BRIGHT LIGHTS, BIG COSMOS

Relying on Blacklight’s shared memory, a team of astrophysicists is running the most sophisticated, largest simulations yet undertaken of when the cosmos first began to blaze with islands of light.

Before there was a Milky Way galaxy, a solar system or planet Earth, the Universe — as if taking a nap after the birth effort of the Big Bang — was wrapped in a blanket of cosmic fog. There were as yet no stars nor galaxies. Cosmologically speaking, it was the Dark Ages.

Initially, in that first mysterious microsecond about 13.7 billion years ago, there was light. And then an instant after the Big Bang, as the prevailing cosmological theory is often called, matter was an expanding soup of elementary particles, quarks and gluons and photons, which in turn evolved into a plasma, an ultrarelativistic plasma of protons, neutrons and electrons — with temperatures too hot for atoms to form. As the plasma cooled and the rapidly growing baby Universe was still very young — around 380,000 years, protons and electrons came together and made neutral hydrogen atoms.

The cosmos had recombined, and by this time the unimaginably hot initial spark had ballooned into immensity and cooled to about 3,000° Kelvin. Besides the shining echoes of the Big Bang, the cosmic background radiation, nothing was hot enough to radiate. The Dark Ages passed, obviously. But how did light come back into the cosmos?

“This is one of major frontiers in astrophysical research,” says Princeton University theoretical physicist and cosmologist Renyue Cen. “When did the first stars, black holes, galaxies and quasars form? These questions are fundamentally important.”

Cen and Carnegie Mellon cosmologist Hy Trac lead a team of physicists — including post-doctoral researchers Nick Battaglia and Aravind Natarajan and graduate student Paul La Plante — undertaking a series of very large-scale computational simulations to help answer these questions. What astrophysicists understand is that, gradually, tiny ripples in matter started a process by which gas coalesced and ultimately collapsed, under the action of gravity, to form the first stars, lit up with nuclear fusion, and quasars, powered by black holes.

“This marks the emergence of the first luminous bodies in the Universe,” says Trac. Over the next few hundred million years, ultraviolet light from these first stars and galaxies converted the gas surrounding them into a much hotter, thinner plasma of protons and electrons — “reionized” it — and the Universe came to look much like it does today: a sea of blackness dotted with islands of light.

In between recombination and the start of reionization, a period that, relatively speaking, didn’t last long — a few hundred million years — things happened by which the Universe began to structure itself into a vast web — sheets, filaments and knots of matter. Within this cosmic web, galaxies formed and processes originated that, over billions of years, led to living organisms and consciousness — which allows scientists in 2012 to try to understand how, out of inanimate energy and matter, we got to where we are.

“We have basically no information,” says Cen. “That period of darkness to the end of reionization is a black box.” To delve into this black box more deeply than has been done until now, Cen and Trac turned to a sophisticated software approach, RADHYDRO, which they developed for these studies. RADHYDRO incorporates physics of three mechanisms involved in shaping the cosmos as it emerged from darkness: gravity, hydrodynamics, and radiation.
EVOLUTION & STRUCTURE OF THE UNIVERSE

of the Universe is in the form of dark matter,” says Trac. “With hydrodynamics, RADHYDRO takes account of cosmic gases, primarily hydrogen and helium, by tracking their evolution as a fluid. At this very large scale, says Trac, rather than thinking of gas as individual hydrogen and helium atoms, it can be effectively treated as an ideal fluid. The microscopic interactions are accounted for in the fluid equations that describe macroscopic properties, including extremes in pressure experienced by gases in space.”

The researchers, nevertheless, have taken to zero in on spectral signatures — the imprint of electrons that describe macroscopic properties, including extremes in pressure experienced by gases in space.

RADHYDRO’s third component, radiation, distinguishes this code from most other cosmological modeling, which generally doesn’t include the physics of electromagnetic radiation. As emitted from normal matter in space, radiation influences the evolution of the reionizing Universe. “We use radiative-transfer algorithms,” says Trac, “that follow the propagation of radiation from early stars and galaxies out into expanding spacetime.”

In volume, the calculations are almost unimaginably vast. Trac and their colleagues have published several papers. “For the first few papers in this series,” says Trac, “we are describing the method and studying how various observable phenomena change when we alter the reionization process.” This will help theorists understand data coming in from current and future telescopes such as the Atacama Cosmology Telescope, Planck Space Observatory, the Low Frequency Array, and the Square Kilometer Array.

“Blacklight makes it possible for us to run the largest simulations of reionization in the world.”

Blacklight makes it possible for us to run the largest simulations of reionization in the world.”

With hydrodynamics, RADHYDRO takes account of cosmic gases, primarily hydrogen and helium, by tracking their evolution as a fluid. At this very large scale, says Trac, rather than thinking of gas as individual hydrogen and helium atoms, it can be effectively treated as an ideal fluid. The microscopic interactions are accounted for in the fluid equations that describe macroscopic properties, including extremes in pressure experienced by gases in space.

RADHYDRO’s third component, radiation, distinguishes this code from most other cosmological modeling, which generally doesn’t include the physics of electromagnetic radiation. As emitted from normal matter in space, radiation influences the evolution of the reionizing Universe. “We use radiative-transfer algorithms,” says Trac, “that follow the propagation of radiation from early stars and galaxies out into expanding spacetime.”

In volume, the calculations are almost unimaginably vast. Trac and their colleagues have published several papers. “For the first few papers in this series,” says Trac, “we are describing the method and studying how various observable phenomena change when we alter the reionization process.” This will help theorists understand data coming in from current and future telescopes such as the Atacama Cosmology Telescope, Planck Space Observatory, the Low Frequency Array, and the Square Kilometer Array.

A Three-in-One Model

Even with the most powerful supercomputers, it isn’t possible to model every atom, proton and photon of light in the entire Universe. The researchers, nevertheless, have taken their work beyond previous efforts at modeling cosmic reionization. Their innovative software RADHYDRO is more comprehensive in the physics it encompasses than previous models, and they are modeling a larger volume of space with higher resolution in the quantity of particles and light rays they represent within that volume.

RADHYDRO includes gravity, which takes into account the invisible substance that comprises most of the mass in the Universe. “Eighty-five percent of the Universe is in the form of dark matter,” says Trac, which interacts with other matter — including the protons, neutrons, and electrons that make up the visible Universe — only through gravity.

The Cosmic Microwave Background

This graphic from the simulations shows temperature fluctuations in the cosmic microwave background (CMB) radiation generated due to cosmic photons scattering with fast-moving electrons during the epoch of reionization. This temperature signal, which registers in milliarcseconds of degrees Kelvin, can be positive (red) or negative (blue) depending on whether the electrons are moving toward or away from us. The square represents a 1° x 1° map of the sky that spans a time period from when the Universe was approximately 200 million to one billion years old. Ongoing experiments such as the Atacama Cosmology Telescope and Planck Space Observatory will measure these temperature distortions in the CMB.

Prizes in Scientific Computing, 2012

Traces of the Dark Ages

Princeton cosmologist Jeremiah Ostriker isn’t involved in this project but is a pioneer in simulating this epoch of the cosmos. The difference in complexity and detail between his own earlier work (first with Cen and then with Princeton collaborator Weilinshu A. Chiu) and Cen and Trac’s simulations, he says, “is in the difference between modeling traffic with bumper cars and modeling it with all the detail of a superhighway. Among cosmology models, this is a real detailed test. When we didn’t have this model and tried to make predictions, we obtained much less accurate answers.”

Although their work is still underway, Cen and Trac and their colleagues have produced several papers. “For the first few papers in this series,” says Trac, “we are describing the method and studying how various observable phenomena change when we alter the reionization process.” This will help theorists understand data coming in from current and future telescopes such as the Atacama Cosmology Telescope, Planck Space Observatory, the Low Frequency Array, and the Square Kilometer Array.

The researchers are working to scale up their model — run efficiently on more processors, for which PSC staff have been crucial. In particular because of RADHYDRO’s incorporation of radiation physics, Blacklight, with its large shared memory, is the best possible machine for this work. PSC scientists Roberto Gomez and Rick Costa helped to overcome obstacles in efficiently using software called OpenMP, which allows the software to communicate among processors. “Because these photons are always moving,” says Trac, “communicating them between different processors is very difficult. Blacklight makes it possible for us to run the largest simulations of reionization in the world.”

With increased resolution, the simulations will, for instance, help to determine what kind of luminous matter first began radiating — stars or black holes — as the Universe reionized. Stars and black holes leave different imprints, says Cen, and the simulations can provide concrete clues that will help to optimize the search strategies of space and ground-based observation.

Eventually, telescope observations and simulations will feed insights back to the other scientists that use them to test the theoretical models. By knowing what we’re looking at, we can better understand how the early Universe worked — and how it became the collection of bright islands of shining stars and galaxies we see today. (MC)

More info: www.psc.edu/science/2012/cosmos/