Astronomers made first measurements of small-scale ripples in primeval hydrogen gas using rare double quasars

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An artist's view of the heart of a quasar. Credit: NASA

The most barren regions known are the far-flung corners of intergalactic space. In these vast expanses between the galaxies there is just one solitary atom per cubic meter—a diffuse haze of hydrogen gas left over from the Big Bang. On the largest scales, this material is arranged in a vast network of filamentary structures known as the "cosmic web," its tangled strands spanning billions of light years and accounting for the majority of atoms in the universe.

Now, a team of astronomers, including UC Santa Barbara physicist Joseph Hennawi, have made the first measurements of small-scale ripples in this primeval hydrogen gas using rare double quasars. Although the regions of cosmic web they studied lie nearly 11 billion light years away, they were able to measure variations in its structure on scales 100,000 times smaller, comparable to the size of a single galaxy. The results appear in the journal *Science*.

Intergalactic gas is so tenuous that it emits no light of its own. Instead astronomers study it indirectly by observing how it selectively absorbs the light coming from faraway sources known as quasars. Quasars constitute a brief hyperluminous phase of the galactic life cycle powered by matter falling into a galaxy's central supermassive black hole. Acting like cosmic lighthouses, they are bright, distant beacons that allow astronomers to study intergalactic atoms residing between the location of the quasar and the Earth. But because these hyperluminous episodes last only a tiny fraction of a galaxy's lifetime, quasars are correspondingly rare and are typically separated from each other by hundreds of millions of light years.

In order to probe the cosmic web on much smaller length scales, the astronomers exploited a fortuitous cosmic coincidence: They identified exceedingly rare pairs of quasars and measured subtle differences in the absorption of intergalactic atoms along the two sightlines.

"Pairs of quasars are like needles in a haystack," explained Hennawi, associate professor in UCSB's Department of Physics. Hennawi pioneered the application of algorithms from "machine learning"—a brand of artificial intelligence—to efficiently locate quasar pairs in the massive amounts of data produced by digital imaging surveys of the night sky. "In order to find them, we combed through images of billions of celestial objects millions of times fainter than what the naked eye can see."

Once identified, the quasar pairs were observed with the largest telescopes in the world, including the 10-meter Keck telescopes at the W.M. Keck Observatory on Mauna Kea, Hawaii, of which the University of California is a founding partner.

"One of the biggest challenges was developing the mathematical and statistical tools to quantify the tiny differences we measured in this new kind of data," said lead author Alberto Rorai, Hennawi's former Ph.D. student who is now a postdoctoral researcher at Cambridge University. Rorai developed these tools as part of the research for his doctoral degree and applied them to spectra of quasars with Hennawi and other colleagues.

The astronomers compared their measurements to supercomputer models that simulate the formation of cosmic structures from the Big Bang to the present. On a single laptop, these complex calculations would require almost 1,000 years to complete, but modern supercomputers enabled the researchers to carry them out in just a few weeks.

"The input to our simulations are the laws of physics and the output is an artificial universe, which can be directly compared to astronomical data," said co-author Jose Oñorbe, a postdoctoral researcher at the Max Planck Institute for Astronomy in Heidelberg, Germany, who led the supercomputer simulation effort. "I was delighted to see that these new measurements agree with the well-established paradigm for how cosmic structures form."

"One reason why these small-scale fluctuations are so interesting is that they encode information about the temperature of gas in the cosmic web just a few billion years after the Big Bang," explained Hennawi.

Astronomers believe that the matter in the universe went through phase transitions billions of years ago, which dramatically changed its temperature. Known as cosmic re-ionization, these transitions occurred when the collective ultraviolet glow of all stars and quasars in the universe became intense enough to strip electrons off atoms in intergalactic space. How and when re-ionization occurred is one of the biggest open questions in the field of cosmology, and these new measurements provide important clues that will help narrate this chapter of cosmic history.

More information: "Measurement of the small-scale structure of the intergalactic medium using close quasar pairs" *Science*, science.sciencemag.org/cgi/doi … 1126/science.aaf9346

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