

Astronomers observe a nascent galaxy stuck to the cosmic web

A strand of the web appears to be conducting gas into the protogalaxy.

The clumpy universe we see today can be traced back to quantum fluctuations during the period of inflation, just after the Big Bang. Cosmologists think that as the universe cooled, the fluctuations seeded emerging matter that then collapsed into giant walls, and within those walls it collapsed further into filaments separated by great voids. The network of filaments, dubbed the cosmic web, is revealed—if indirectly—by astronomical surveys that show galaxies strung across the presumed filaments, with bigger galaxies and galaxy clusters at nodes where filaments intersect.

Direct observation of the filaments themselves is difficult because their constituents, mostly dark matter and cold gas, are either invisible or too faint. But with help from a quasar 10 billion light-years from Earth, Christopher Martin of Caltech and his colleagues have been able to take a close look at a strand of the cosmic web.¹ The astronomers trained the Palomar Observatory's 200-inch (5.1-meter) Hale Telescope on the neighborhood of quasar QSO UM287 and observed, illuminated by the quasar's intense UV radiation, a cosmic-web filament attached to a rotating, actively forming galaxy.

A cosmic flashlight

Astronomers have tried to get around the problem of the cosmic web's faintness by looking at the spectra of background quasars. (See *PHYSICS TODAY*, March 2005, page 19.) The absorption of a quasar's UV light by neutral hydrogen atoms in the intergalactic medium in the foreground shows up as a Lyman- α line.

Unfortunately, the technique is essentially one-dimensional: It only detects hydrogen gas along the line of sight to the quasar. If a foreground galaxy fortuitously lines up with that line of sight and the quasar's absorption spectrum reveals the presence of hydrogen, astronomers can infer the inflow of filamentary gas into the galaxy.² But as Nicolas Bouché of France's Research Institute in Astrophysics and Planetol-

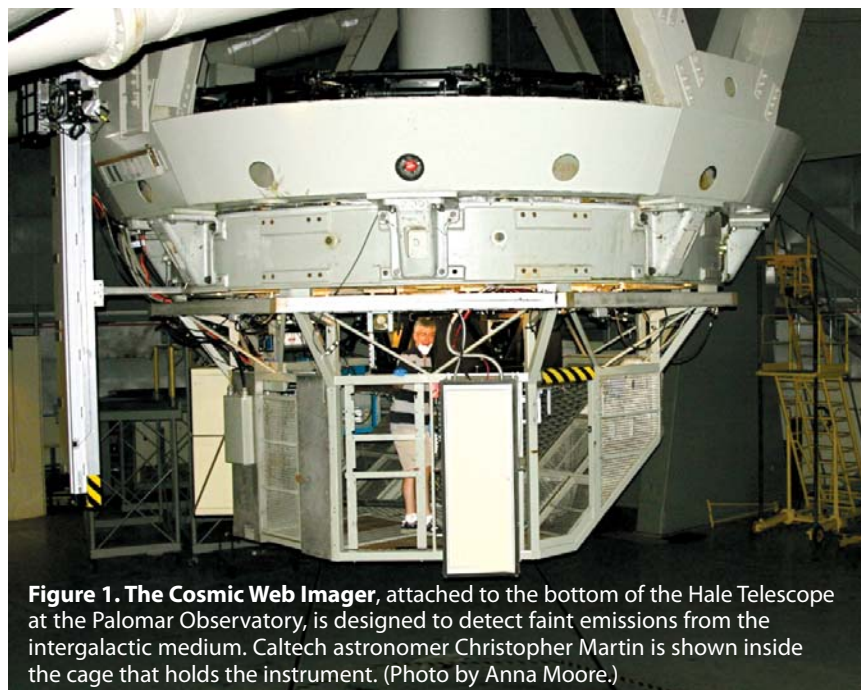


Figure 1. The Cosmic Web Imager, attached to the bottom of the Hale Telescope at the Palomar Observatory, is designed to detect faint emissions from the intergalactic medium. Caltech astronomer Christopher Martin is shown inside the cage that holds the instrument. (Photo by Anna Moore.)

ogy notes, "It is always clearer to see something directly."

Last year a team led by Sebastiano Cantalupo (ETH Zürich) tried a different tactic. The researchers figured that a quasar would be like a cosmic flashlight that could illuminate cosmic-web filaments in its neighborhood. Those filaments in turn would produce faint Lyman- α emissions. Sure enough, Cantalupo's team spotted a glowing thread near QSO UM287. However, the thread was much brighter than one would expect for a cosmic-web filament.³

Enter Martin, who has been thinking

about ways to image the cosmic web since his graduate student days in the 1980s. He and his Caltech team had recently built a new instrument called the Cosmic Web Imager (CWI) for the Hale Telescope. Seen in figure 1, the CWI is a so-called integral field spectrograph that slices up a 2D image, feeds the slices into a spectrometer, and then reconstructs the data into hundreds of images at different wavelengths. By following Lyman- α lines through the different images and matching the wavelengths to redshifts, one can work out the kinematics of an emission source.

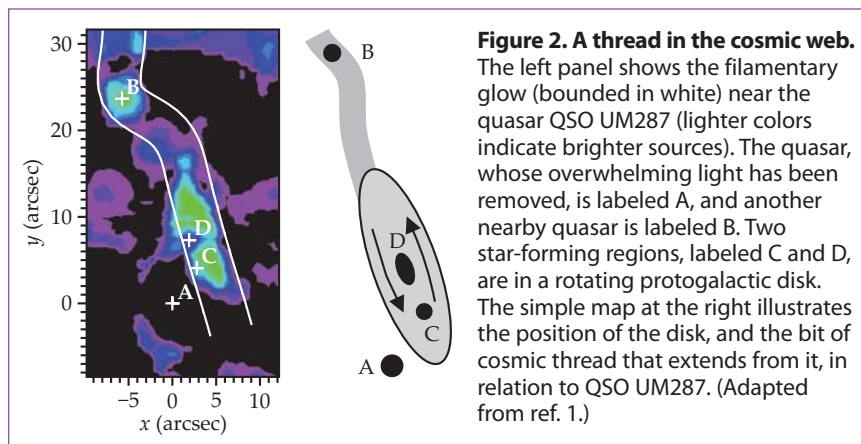


Figure 2. A thread in the cosmic web.

The left panel shows the filamentary glow (bounded in white) near the quasar QSO UM287 (lighter colors indicate brighter sources). The quasar, whose overwhelming light has been removed, is labeled A, and another nearby quasar is labeled B. Two star-forming regions, labeled C and D, are in a rotating protogalactic disk. The simple map at the right illustrates the position of the disk, and the bit of cosmic thread that extends from it, in relation to QSO UM287. (Adapted from ref. 1.)

Martin, Cantalupo, and their coworkers identified the newly found filament as a perfect target for the CWI. “We knew it would be interesting and bright enough to say a lot about,” says Martin. They were right: Attached to the filament was a giant protogalactic disk, 400 000 light-years across.

The disk and filament are shown in figure 2 with the positions of QSO UM287 marked A, another nearby quasar marked B, and two star-forming regions within the disk marked C and D. By analyzing how the redshifts vary along the disk, the group deduced that the disk is rotating. They then fit the protogalaxy’s velocity profile to a rotating disk model and obtained good agreement with a gas disk embedded in a dark-matter halo of some 10^{13} solar masses.

The researchers also ran computer simulations, with the disk’s thickness and brightness as inputs, to estimate the protogalaxy’s baryonic mass. Baryons, the stuff of conventional matter, make up only about 1% of the protogalaxy—well below the cosmic average baryon component of 17%. Apparently, suggest Martin and company, the baryons have lagged behind the collapse of the dark-matter halo and will continue to accrete in the future.

Cold flow

The velocity of the gas in the extended filament is constant and matches that of the upper end of the disk where the two meet. The astronomers speculate that gas flowing down the filament imparts angular momentum to the disk, consistent with the so-called cold-flow model of galaxy formation. Martin likens the filament to a hose streaming water into one side of a circular tub. “The water will spiral down into the drain,” he explains. The group’s modeling indicates a gas temperature of about 30 000 K, much cooler than the plasma of the dark-matter halo and again consistent with the cold-flow model.

The standard model of galaxy formation posits that when a dark-matter halo collapses gravitationally, the conventional matter embedded in the halo heats to high temperatures and then slowly cools to form stars. Any additional gas that falls into the nascent galaxy would also be shock heated to high temperatures. In that picture, galaxies formed slowly in the early universe.

In the alternative cold-flow model, cool gas ready for star formation flows directly from filaments of the cosmic web into galaxies, as seen in figure 3. That scenario has galaxies build up rap-



Figure 3. A snapshot from a cosmological simulation shows relatively cool gas flowing into two rotating protogalactic disks (magenta) from filaments (gray-green) of the cosmic web. Hot ionized gas at temperatures greater than 10^6 K is shown in red. (Courtesy of Philip Hopkins/Caltech.)

idly from large gas disks connected to the cosmic web, much like the one discovered by Martin, Cantalupo, and their colleagues. (See the article by Jeremiah Ostriker and Thorsten Naab, *PHYSICS TODAY*, August 2012, page 43.)

An intrigued Jason Tumlinson of the Space Telescope Science Institute explains that hydrodynamic simulations of galaxy formation show such filamentary inflows of cool gas. He adds, “Detecting them has been a key goal. This one looks filamentary and looks real.”

Martin and his colleagues have considered alternative interpretations of their data—for example, as arising from a galactic merger involving one or both quasars (A and B in figure 2) in the neighborhood. But given the distance between the disk and QSO UM287 (at least 32 000 light-years), the large size of the disk, and the lack of any signs of tidal disruptions, they say those explanations are unlikely.

Tumlinson says the new results are just as interesting for demonstrating a new technique for observing the intergalactic medium. “It’s a pretty heroic measurement,” he remarks. Martin and coworkers are already busy surveying other quasars in search of more giant protogalactic disks.

In addition, the Caltech group is commissioning an improved version of the CWI at the Keck Observatory. And a similar instrument, the Multi Unit Spectroscopic Explorer, is being tested on the European Southern Observatory’s Very Large Telescope. Both new instruments are set to make similar observations but on telescopes larger than the one on Mount Palomar.

Sung Chang

References

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2. N. Bouché et al., *Science* **341**, 50 (2013).
3. S. Cantalupo et al., *Nature* **506**, 63 (2014).

Freestanding solids get stretched

Engineering a phase transformation to proceed in just the right way creates a material that’s permanently under tension.

Negative absolute pressures, though much investigated in liquids (see *PHYSICS TODAY*, January 2011, page 14), have been thought to be impossible to sustain in solids. Informally, materials under negative pressure are said to be under tension. But more specifically, that tension must be isotropic; thin films produced by strain-engineering techniques that stretch them in just one or two dimensions, though useful, don’t qualify.

Now Nava Setter (Swiss Federal Institute of Technology, Lausanne), her former student Jin Wang (currently an

assistant professor at the Tsinghua University Graduate School at Shenzhen, China), and their colleagues have developed a method to create freestanding crystalline nanomaterials stretched in all three dimensions.¹ The researchers synthesized lead titanate nanowires in the material’s so-called PX phase—a low-density, metastable crystal structure shown in figure 1a—and induced them to transform into the denser, stable perovskite phase shown in figure 1b. Because of the dynamics of that transformation, the perovskite nanowires form with their surfaces under positive