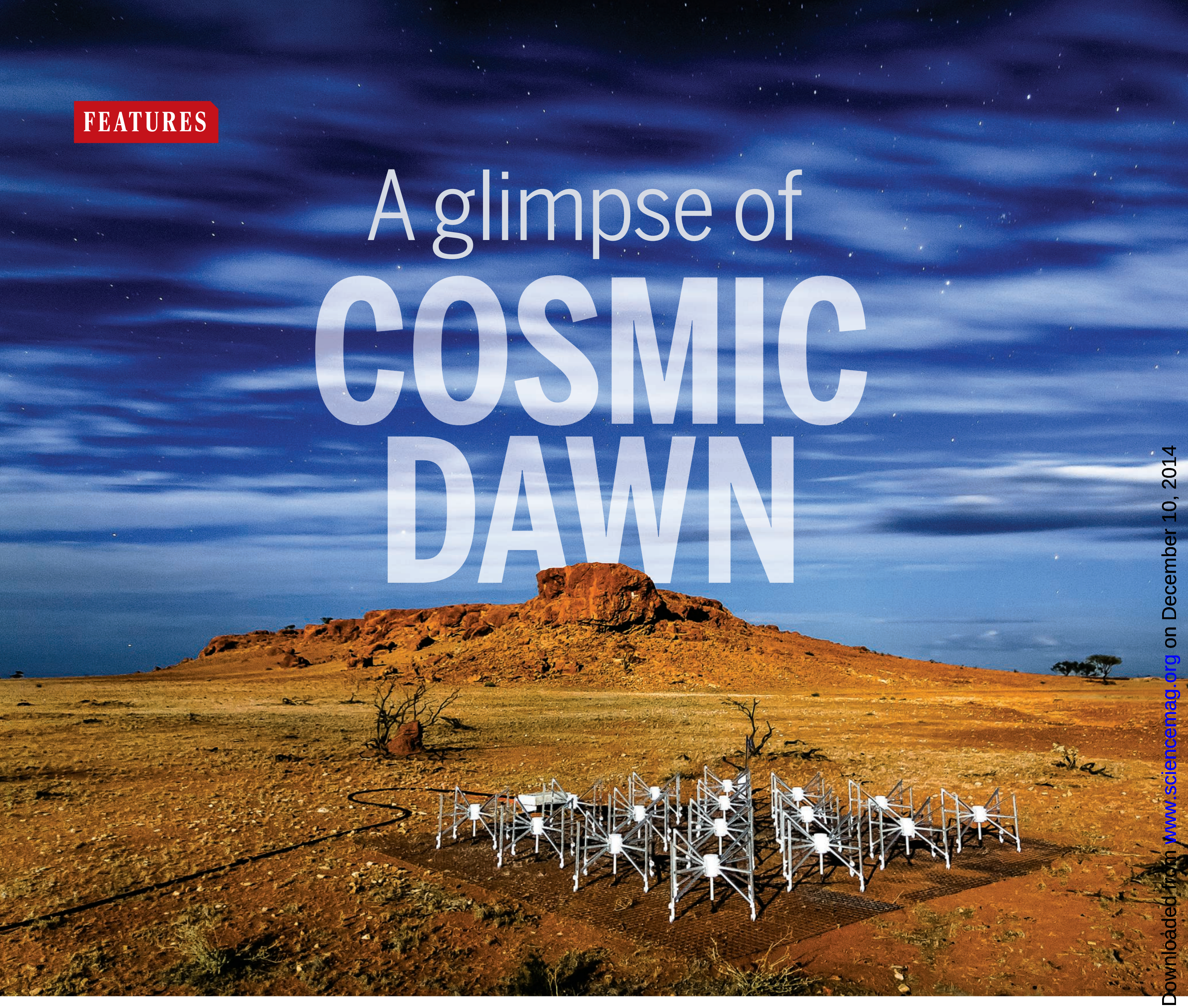


FEATURES

A glimpse of COSMIC DAWN

Astronomers are attempting to look back to when the first stars and galaxies lit up and changed the universe forever

By **Daniel Clery**

They may be the strangest telescopes on Earth. They have no domes, no giant mirrors, no steerable radio dishes—just scattered arrays of simple antennas, some on poles as tall as a person, others resembling robot spiders or bizarre garden furniture. These antenna arrays—one in Northern Europe, one in South Africa, a third in Australia—can't point at particular heavenly targets. Instead, they passively take in whatever signals come their way and feed them to distant supercomputers where the real work of detection is done.

The otherworldly instruments have an otherworldly target. They are probing a time so far back in the universe's history that there was very little to see: just a few of the very earliest stars and galaxies. And their quarry is not the scattered points of light at that early epoch, but the diffuse ocean of gas between them, where a profound change was taking place.

By some 400,000 years after the big bang, the expansion of the universe had cooled the maelstrom of particles and energy formed in the instant of creation. The result was a dark fog of gas, mostly hydrogen. The universe's "dark ages" had begun. It took many millions of years for the gas, which was cool and electrically neutral, to slowly swirl together to form stars and galaxies—and when it did, the gas itself was transformed.

The most distant galaxies astronomers can now see, about a billion years after the

PHOTO: © PETE WHEELER

The Murchison Widefield Array in Australia is using 2000 simple spiderlike antennas and massive computer power to detect the faint signal of the ionization of the universe.

big bang, live in a universe full of ionized hydrogen—bare protons with their electrons stripped away. Just as the lights came on, something must have ionized all the universe's hydrogen. The most likely culprits are the early stars and galaxies themselves, but to do this they would have had to be very different from the stars and galaxies we can see today: bigger, more violent, more exotic. Astronomers are desperate to know more—but not much can be gleaned from scattered lights in a fog more than 13 billion light-years away.

In 1997, however, British astronomer Martin Rees and colleagues Piero Madau and Avery Meiksin suggested that astronomers look for a signal from the early neutral hydrogen itself. In a hydrogen atom, the central proton and the orbiting electron normally have opposite magnetic orientations. When some energy source flips them into the same orientation, the atom quickly relaxes back into its ground state and emits a microwave photon, at a wavelength of 21 centimeters.

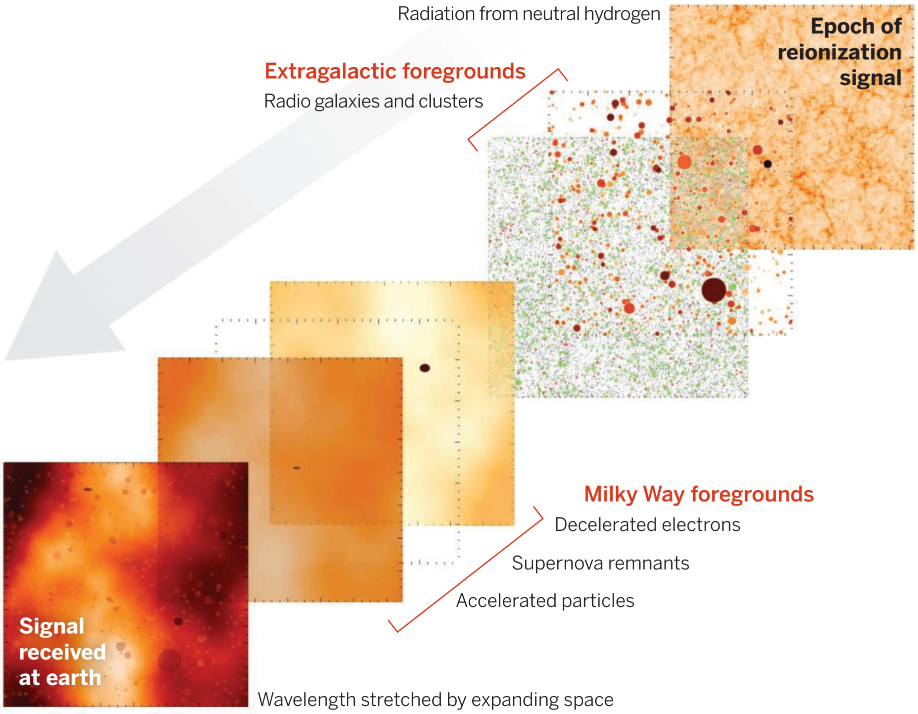
Unlike the neutral gas, ionized hydrogen emits no such radiation. Rees *et al.* suggested that if astronomers could detect the 21-centimeter radiation from the so-called epoch of reionization (EoR), they might see radiation-free "bubbles" of ionized hydrogen around whatever was ionizing the gas. The size and distribution of those bubbles could provide information about the nature of the sources and the timing of reionization.

Astronomers began thinking about what it would take to detect such a signal. As 21-cm radiation from the EoR travels across the universe, cosmic expansion stretches its wavelength to about 2 meters. Conventional radio telescopes are mostly blind to such long wavelengths, and a purpose-built dish would be impractically large. But there was another way: an array of simple antennas and some heavy-duty number crunching. As astrophysicist Don Backer of the University of California (UC), Berkeley, said at the time: "All you need is paperclips and a supercomputer."

Now, several of these paperclips-and-supercomputer telescopes are in hot pursuit of the first detection of the EoR signal. They hope to glimpse something within the next year or two—and the stakes could be enormous. Scientists say the 21-cm radiation could open up a floodgate of information about the astrophysics and cosmology of this unstudied part of the universe's history, perhaps comparable to the discoveries that have flowed from studying the cosmic microwave background left over from the big bang. But detecting the primordial radio signal amid the cacophony of other radio sources, earthbound and astronomical, is akin to hearing a whisper amid a crowd of cheering sports fans. "We're learning all the lessons," says Judd Bowman of Arizona State University, Tempe, chief scientist of one of the new instruments, the Murchison Widefield Array (MWA) in Australia. "We're hopeful and eager."

Signal and noise

The faint radio signal coming from the epoch of reionization is almost drowned out by the "foreground" noise from sources in deep space, our own galaxy, and closer to home.



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The largest of the telescopes in the hunt—the Low Frequency Array, or LOFAR—bristles in the middle of a peat bog in the northern Netherlands. One of its creators, co-principal investigator (PI) Michiel Brentjens of ASTRON, the Netherlands Institute for Radio Astronomy, in Dwingeloo, calls it "the most unimpressive radio telescope in the world." He's right: It's just a thicket of hundreds of white plastic poles about the height of a person, braced by guy ropes. The guys are the antennas, no different in principle from a rooftop TV antenna. Large low boxes under tarpaulin covers contain more, smaller antennas. A few scattered electrical cabinets hum ominously.

LOFAR is an interferometer, a device that combines signals from widely spaced detectors to extract information from the differences between them. The core of the array in and around the peat bog at Exloo has 24 clusters, each containing more than 850 antennas, spanning a 4-kilometer-wide area; another 14 clusters are scattered around the Netherlands, plus another five in Germany and one each in France, Sweden, and the United Kingdom. (More are under construction in Germany and Poland.) Widely spaced stations give the interferometer finer resolution, enabling it to zoom in on smaller patches of sky.

But the location of LOFAR is far from ideal. The Dutch government provided €53 million to build the array so long as its core was sited in the north of the country to help build up high-tech infrastructure there. Besides the boggy terrain, LOFAR has to contend with interference from nearby radio sources, including the 88-to-108 megahertz band of FM broadcasts, which are slap in the middle of the frequencies LOFAR is trying to detect. "The signals from all the radio and TV transmitters in [the FM] band are just phenomenal," says LOFAR PI Ger de Bruyn of ASTRON. "They're a million times brighter [than the EoR signal], so you can't observe there." Fortunately, the team found that the main hunting ground for EoR signals, about 150 MHz, "seemed to be very quiet," he says.

The other main arrays are sensibly situated in remote radio-quiet areas. The

Precision Array for Probing the Epoch of Reionization (PAPER)—Backer's brainchild—is in the semidesert Karoo region of South Africa. Its garden chair–like antennas have been growing in number since 2009 and have now reached 128. The third instrument, MWA, sits on the semiarid plains of Western Australia, a few hundred kilometers north of Perth. MWA was instigated by a group of U.S. institutions that were originally part of the LOFAR project. They parted company with the Dutch over the issue of building LOFAR in the noisy environment of the Netherlands and set out to build their own array, teaming up with researchers in Australia, New Zealand, and India. The resulting telescope has 2048 spider-like antennas arranged in 128 four-by-four tiles. "It's in good shape and running well," Bowman says.

But building the arrays is, in a sense, the easy part. The antennas are "old technology," says theorist Saleem Zaroubi of the University of Groningen in the Netherlands, a co-PI on LOFAR. They have no moving parts and so cannot focus on a particular spot—they simply pick up everything coming from the sky. It falls to distant supercomputers to make sense of the signals, processing them to calibrate the instrument, focus on a part of the sky, and separate the signal from the noise. Such "software telescopes" offer the advantage of becoming more powerful as computers do, even without changes to the antennas on the ground.

The biggest challenge the arrays face is picking out the extremely feeble EoR signal from all the other radio sources at the same frequency. In our Milky Way galaxy, radio waves at those frequencies come from sources including supernova remnants, charged particles accelerated by the galaxy's own magnetic field, and radiation from electrons colliding with ions inside hydrogen clouds. Outside the Milky Way, countless radio galaxies and galaxy clusters also broadcast their own signals. Models of the EoR signal suggest that these other radio sources are between 1000 and 100,000 times brighter—which means astronomers must identify them and strip them out.

> ***"To do what we do, you have to be hopelessly optimistic, but also brutally realistic."***
>
> **Saleem Zaroubi**, University of Groningen

No images or catalogs of sources exist for this poorly studied part of the spectrum; the teams must map it out themselves before they can discount it from their data. "After subtracting all the foregrounds, the signal-to-noise ratio is still one-tenth. You have to understand the noise [and] find out ways to quantify it," says ASTRON's Brentjens.

Once that's done, investigators will be rewarded not with an image of the neutral hydrogen at the EoR, but rather a power spectrum: a statistical analysis of how the radio signal varies across the sky. It will reveal whether the biggest variations occur over small distances or large ones—whether the bubbles of ionized gas were small, the handiwork of individual stars, or galaxy-sized cavities. The teams should also be able to watch reionization unfold over time. The EoR may have lasted millions of years; 21-cm radiation from earlier in its history will have traveled farther and thus will be stretched out to a longer wavelength and a lower frequency than later radiation. So a signal detected at 140 MHz will be from an earlier time than one at 160 MHz.

As interferometers are sensitive to differences, the middle of the EoR—when half the universe is neutral and half ionized—will produce the strongest signal. So the teams will be scanning the frequencies for a signal that has a peak and then drops off farther into the past (when more of the universe was neutral) and farther toward the present (when more of the universe was ionized). "These telescopes hope to learn two basic things: when the EoR happened and how long it lasted," Bowman says. "That should be easy to read when they detect a signal."

All three teams are optimistic that they will soon get their first glimpse of the EoR. "We're getting pretty close to what theorists predict the signal level is, and we expect to do two or three times better with the data that is coming in right now," De Bruyn says. He hopes LOFAR will get a "first-order re-

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sult" by next year. The PAPER and MWA teams are similarly hopeful. But MWA's Bowman adds that those projections are all based on theoretical models of the EoR signal. "If there is no detection by 2020," he acknowledges, "that will be a disappointment for the community."

Because of the amount of signal processing required and the many different assumptions that underlie the calculations, "there'll be no eureka moment. It'll be hard to convince ourselves [of the detection]," Brentjens says. Even harder will be convincing the rival teams. "I worry about this a lot," says Aaron Parsons of UC Berkeley, who is head of PAPER. "I hope journal editors are very careful. It's very important that papers are reviewed by people who are really knowledgeable. And we have to be very careful not to overstate claims."

A confirmed and reliable signal from the time of reionization could amount to what some researchers are calling "a COBE moment" for astrophysics. COBE was the NASA satellite that, in 1992, revealed the size of fluctuations in the microwave background and opened a floodgate of results in cosmology. A glimpse of the EoR would give astrophysicists their own origins story and a starting point for studying the very first things to shine.

Knocking out an electron and ionizing hydrogen takes quite a lot of energy, so any potential ionizing source needs to produce a lot of photons at high energies—ultraviolet or higher. It's expected that the first stars to form in the universe were unlike any that exist now because they were made of almost pure hydrogen, without any of the heavier elements that were forged inside stars as the universe aged. Pure hydrogen stars, known as population III stars, should grow to enormous size before their internal furnaces ignite—hundreds or even thousands of times as massive as our sun. Big stars burn bright, hot, and fast, making them a perfect source of ionizing radiation. But do they form in isolation, or does dark matter draw the hydrogen into galaxies first? Or were bigger, more powerful sources such as quasars—hugely luminous galactic nuclei centered on supermassive black holes—the engine of reionization? Theorists speculating about the EoR have also invoked more exotic drivers, including decaying dark matter and cosmic strings. "We're shooting in the dark. We have no idea what they are," Zaroubi says.

The existing arrays probably won't be able to answer all of these questions. "To really understand how the first stars form and what early galaxies were like needs the next generation of instrument," Parsons says.

The LOFAR team hopes to build up its array with more stations and faster computing. But the PAPER and MWA teams are joining forces to build a new, more powerful instrument called HERA, the Hydrogen Epoch of Reionization Array. HERA's antennas will be static wire-mesh dishes pointing straight up. The joint team has won $2 million to build a test array of 37 dishes in the Karoo, using PAPER's infrastructure. This alone will have up to three times the sensitivity of PAPER, Parsons says. Then the team will seek up to $20 million to build an array of 350 dishes by 2019. "We'll turn the tables on theorists and really start to drive theory, really advance our understanding," he says.

The Square Kilometre Array (*left*, in an artist's conception) will use dishes and static antennas to pick up different radio frequencies. LOFAR (*above*) mingles low-frequency antennas (brown specks) with higher frequency ones (inside dark tiles).

Looming on the horizon is the next generation: the Square Kilometre Array (SKA). This enormous international project will be built mostly in South Africa, starting in 2018, and will target everything from galaxy evolution to signals from extraterrestrial intelligence. But part of the array, to be sited at the Murchison Radio-astronomy Observatory, home of MWA, will collect low-frequency radiation with a quarter of a million antennas spread over 100 kilometers. With its huge collecting capacity, SKA will be able to move beyond statistical observations and produce images. "We'll see the structures themselves directly. That's a huge step," Zaroubi says.

But first the rival teams need to catch that first glimpse of early light. They will have to overcome radio interference, computing challenges, and the deafening noise—and they must hope that theoretical models of the EoR signal are correct. Says Zaroubi: "To do what we do, you have to be hopelessly optimistic, but also brutally realistic. You need both sides." ■

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