Wired up. Low-band antennas of the Low Frequency Array (LOFAR).

ASTRONOMY

Exotic Telescopes Prepare to Probe Era of First Stars and Galaxies

Radio telescopes that substitute antenna arrays for dishes are gearing up to peer to the brink of the billion-year "dark ages" that followed the big bang

All this year, strange structures have been sprouting in the fields of northern Holland. Low gray boxes and what appear squat flagpoles held up by guy wires cluster in geometric patterns that look like landing sites for alien spacecraft. Their real purpose is only slightly less otherworldly: They are components of a giant radio telescope gearing up to probe the early history of the universe. With it and similar instruments, astronomers hope to peer back in time to when some of the earliest stars flared into life, and beyond that into the unexplored "dark age" of the cosmos.

The Low Frequency Array (LOFAR) is the largest of a new breed of telescope that will observe the sky via long-wavelength radio waves. Unlike conventional radio telescopes—huge movable dishes that point in one direction at a time—these new scopes are made of simple cheap antennas that pick up signals from all directions and then use sophisticated digital signal processing to "steer" a beam at the desired patch of sky. In fact, such a telescope can look at many parts of the sky at once, carving the received signal into multiple beams. "The antennas are extremely simple, but there is a lot of technology behind them," says Michiel van Haarlem, LOFAR's managing director. Similar instruments are either starting work or under construction in China, Australia, and the United States.

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These versatile new scopes can survey and catalog the low-frequency sky, monitor fast-changing radio sources, study the sun and space weather, and track ultrahigh-energy cosmic rays as they hit Earth's atmosphere. But the goal that has scientists buzzing is the prospect of venturing into cosmology's terra incognita. The time from the release of the cosmic microwave background (CMB) radiation 400,000 years after the big bang until some 850 million years later, when the superbright galaxies known as quasars became visible, is a closed book to cosmologists. This is a critical period of the universe's development, during which it evolved from a near-uniform cloud of neutral hydrogen gas into a gallery of stars, galaxies, and clusters of galaxies.

Cosmologists can only simulate what might have happened during this time because they have no data. "Simulations can get things wrong. We have no real idea how these things evolved," says Michael Garrett, director of ASTRON, the Netherlands Institute for Radio Astronomy. This ignorance leaves a raft of questions. What were the first luminous objects like, and when did they form? Did large galaxies emerge fully formed from the primordial gas clouds, or did minigalaxies merge to make larger ones? And what, during that unseen period, caused the neutral hydrogen that emerged from the big bang to become ionized again? This era "is a tremendous potential source of information," says Martin Rees, a theorist at the University of Cambridge and Britain's Astronomer Royal.

The creators of LOFAR and its kind are confident they can at least begin to answer these questions. If they succeed, similar but more powerful telescopes will soon follow. Many in the field liken it to the early days of studying the CMB. "The CMB produced several Nobel Prizes. I'd be surprised if [this] didn't do the same," says Garrett.

Into the dark

During the early millennia following the big bang, the universe was a hot, roiling fireball of subatomic particles and photons. Within 400,000 years, it had cooled enough for protons to pair up with electrons and form neutral hydrogen atoms, an era known as cosmic recombination. Neutral hydrogen could not absorb the low-energy photons that then pervaded the universe, and so space became transparent. Those photons—the CMB—are still flying through space and provide a snapshot of that moment in the universe's history. After recombination, things went quiet for a long time because there were no bright sources of light, just a diffuse, almost featureless cloud of hydrogen. "It's one part of cosmic time we don't have any information on," says Garrett.

That quiet gaseous state did not last. Gravity began working very slowly on slight variations in density in the gas cloud, pulling the matter in the denser regions closer together. Theorists believe the major player in this process was dark matter, the unknown substance thought to make up 85% of the universe's mass. Once you get clumps of dark matter as big as 100,000 solar masses, simulations suggest, stars will begin to form within them. According to some models, the first

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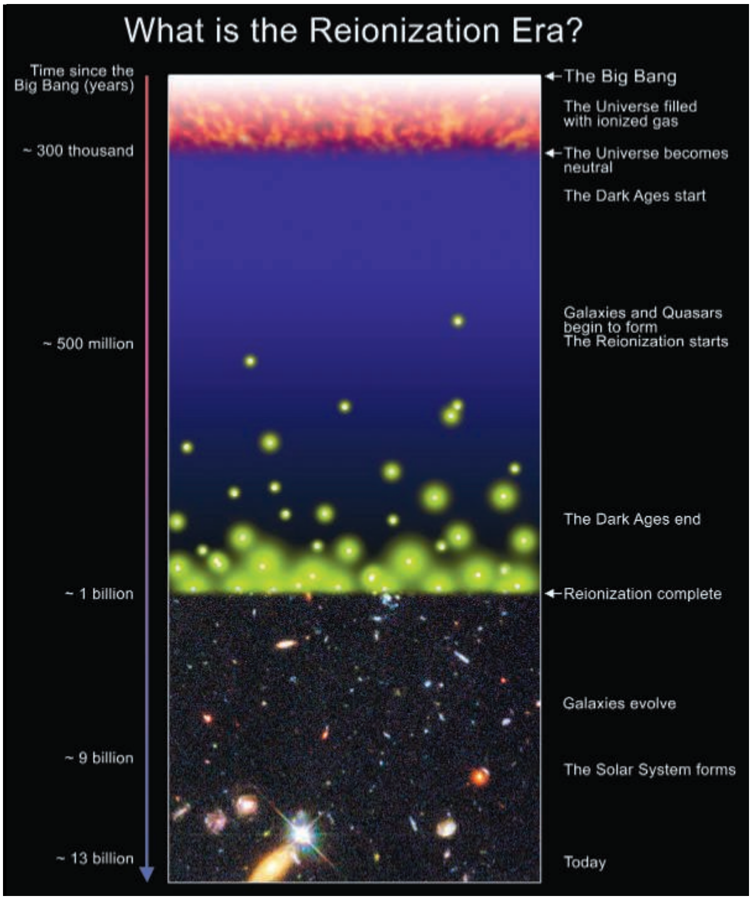
stars may have turned on just 30 million years after the big bang, when the universe was less than 0.25% of its current age.

As the universe continued to evolve, the dark matter clumps got larger and encouraged the growth of galaxies and galaxy clusters. Theorists once thought that the hydrogen gas outside these dark-matter clumps, the intergalactic medium, would remain undisturbed, but observations of the IGM show that it has been ionized as far back as we can see, to when the universe was 850 million years old. So something in the era of the first stars and galaxies shone brightly enough to ionize all the hydrogen in the universe. Suspects include so-called population III stars, stellar giants that burned bright and fast in the early universe; some sort of miniquasars; or even something more exotic such as decaying dark matter. This "epoch of reionization" (EOR) is now one of the main targets of LOFAR and similar instruments. "We want to understand when the first sources turned on, how they formed and where, and how structures formed on a cosmological scale," says theorist Avery Meiksin of the Royal Observatory Edinburgh in the United Kingdom.

Stars and galaxies of that era are too faint for us to see today, but the new telescopes are not looking for starlight. Instead, they aim to detect a subtle difference between neutral hydrogen and ionized hydrogen. Both electrons and protons have a quality referred to as spin, and when they are combined in a hydrogen atom, the two spins can be either parallel or antiparallel. The parallel state has a slightly higher energy than antiparallel, so when the atom flips from the former to the latter, it emits a photon with a wavelength of 21 centimeters. Similarly, absorbing a 21-cm photon will flip the atom from antiparallel to parallel.

Ionized hydrogen, which has no electrons, neither emits nor absorbs 21-cm photons. So, the theory goes, if astronomers used a telescope to look at this 21-cm radiation in the millennia following recombination, first they would see a largely uniform signal from the neutral hydrogen, then later it would appear riddled like Swiss cheese with "bubbles" of ionized gas surrounding early stars and galaxies. Eventually, these bubbles would merge and finally fill all of space with ionized gas. By mapping the history of reionization in this way, astronomers could refine their theories about what caused it. "Because of the complex astrophysics within galaxies, it's not really predictable how the transition happened. The observations could surprise us," says theorist Rennan Barkana of Tel Aviv University in Israel.

LOFAR and its kin won't look for the 21-cm photons that hydrogen molecules emit; those signals are so weak they would be swamped by closer sources of radiation. Instead, astronomers will watch for signs that hydrogen is absorbing 21-cm radiation. To spot such "absorption lines," they will need another source of radiation to act as a backlight. One possibility is the CMB, a small part of which has a wavelength of 21 cm; another is to use radio-loud quasars that formed early in the EOR to illuminate stages that came later. Because the universe is expanding, the redshift will have stretched the 21-cm radiation to a wavelength of 1.5 to 10 meters by the time the signal reaches Earth—exactly the range in which telescopes such as LOFAR are most sensitive.



Terra incognita. Astronomers and cosmologists have no data about the "dark ages," when the first stars, galaxies, and large-scale structures formed. The new generation of long-wavelength radio telescopes will try to peer into the era of the first galaxies.

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A new kind of telescope

The idea of trying to detect the 21-cm signal has been kicking around for decades, but astronomers had largely ignored this part of the spectrum because the long wavelengths would require huge dishes and would achieve poor results in angular resolution. Also, this frequency range is riddled with terrestrial noise, in particular the FM radio waveband, which is slap in the middle of it. But a number of theory papers in the 1990s and advances in digital signal processing encouraged astronomers to take a shot at it. In the late 1990s, astronomers at the ASTRON institute in Dwingeloo, the Netherlands, designing the Square Kilometer Array (SKA), a radio telescope to be built in Australia or South Africa starting in 2014, latched on to the idea of building a prototype scope for 21-cm radiation. They teamed up with several research groups in the United States to form the original LOFAR collaboration.

In 2003, the Dutch government offered the ASTRON team €70 million to build the telescope in northeast Holland. Some of the U.S. partners had favored remote sites in New Mexico or Australia to avoid FM interference. But the ASTRON team reckoned that with clever design and signal processing, it would be possible to operate LOFAR in the noisy environment of the Netherlands. Their partners thought the risk too great, and the collaboration broke up. "It was affected by politics. What can you do?" asks Barkana.

ASTRON pushed ahead, testing antenna designs in the field, before beginning main construction this year. The plan is for ASTRON to build 36 antenna stations, each the size of a football field; 18 will form a compact core near the town of Emmen, and another 18 will be positioned across northern Holland. Each station sports 96 low-band (30–80 MHz) antennas, the squat flagpoles, and 48 high-band (120–240 MHz) antenna tiles, the low gray boxes, each containing 16 antennas. New international

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partners—Germany, the United Kingdom, France, Sweden, and perhaps others—will host additional stations to increase the baseline area of the telescope, improving its angular resolution. "It's a plug-and-play system. If you have a fast connection and a field, you can join in," says Rob Fender of the University of Southampton, head of the U.K. LOFAR team.

Getting the antennas in position, however, is the easy part. Managing the flood of data is when it gets hard. The full set of antenna stations, Fender says, will produce as much raw data as CERN's Large Hadron Collider particle accelerator. LOFAR does not have the computing resources to archive that much data, so computers at each station will validate and process data on the fly, winnowing it down by more than 90%. The resulting data streams are sent via a fiber-optic network to the University of Groningen, where an IBM Blue Gene/P supercomputer correlates them and begins the complex task of subtracting various foreground signals, leaving data products that astronomers can study.

Garrett says six stations, including the first of five German stations, are complete and sending data. "Each few weeks more stations come online," he says, adding that the telescope should be completed next year. The Groningen computer has constructed LOFAR's first images, of bright radio sources at cosmological distances. "The data look fantastic. The quality is breathtaking," Garrett says. Some frequencies are affected by interference, he says, but he's confident that LOFAR's digital processing can handle them. Conventional radio astronomy will start soon; collecting enough data to distinguish the faint EOR signal will take longer. "We will learn over years how [interference] will affect sensitive measurements like the EOR," Garrett says.

Meanwhile, other telescopes are also gearing up to search for the 21-cm signal. LOFAR's nearest rival may be the Murchison Widefield Array (MWA), a telescope being built in Western Australia. The project is led by some of the original LOFAR collaborators at the Massachusetts Institute of Technology's Haystack Observatory, now teamed up with other researchers in the United States, Australia, and India. Colin Lonsdale, director of Haystack, says they have built a "late-stage prototype" and plan to finish the array during 2010. LOFAR's huge collecting area and high resolution make it a general-purpose, low-frequency observatory, Lonsdale says. MWA, by contrast, is optimized for the EOR. Although it has lower angular resolution, its wider field of view is better matched to collecting statistical information about reionization, Lonsdale says.

Another contender is the 21 Centimeter Array (21 CMA) in western China. Originally the brainchild of Jeffrey Peterson of Carnegie Mellon University in Pittsburgh, Pennsylvania, and Ue-Li Pen of the Canadian Institute for Theoretical Astrophysics in Toronto, the array began as a collaboration with Chinese researchers who eventually took over the project. The 21CMA was completed in 2006 and has been taking data, but Peterson says funding problems have made its observations sporadic.

IN SEARCH OF REIONIZATION

	Location	No. of antennas	Baseline	Completion
Low Frequency Array (LOFAR)	The Netherlands	44,160	1500 km	2010
Murchison Widefield Array (MWA)	Australia	8,192	3 km	2010
21 Centimeter Array (21CMA)	China	10,287	6 km	2006
Long Wavelength Array (LWA)	New Mexico, U.S.A	12,800	400 km	2010
Precision Array to Probe Epoch of Reionization (PAPER)	Australia	32		2009
Experiment to Detect the Global EOR Signature (EDGES)	Australia	1		2009–2012
PROPOSED				
Hydrogen Epoch of Reionization Array (HERA II)	Australia	5,000		2017
Square Kilometer Array (SKA)	Australia or S. Africa	50 million	3000 km	2018–2022
Lunar Radio Array (LRA)	Far side of the moon	~ 100,000	10 km	2020–2030

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Cosmological tomography

Although these first-generation low-frequency telescopes will be able to form images of closer radio-emitting objects, they probably won't collect enough photons to image any features in the 21-cm signal. But their statistical measurements will still provide valuable information for cosmologists. The longer radiation spends traveling through space, the more the redshift lengthens its wavelength. So by looking at the 21-cm signal in different wavelengths, astronomers can effectively follow it forward and backward in time. Measuring the signal's intensity at different wavelengths should enable them to track the disappearance of the universe's neutral hydrogen during the EOR.

Researchers also hope to extract power spectra, measures of how the signal power varies over different angular scales. These spectra can reveal a number of things, such as the extent of clumps of hydrogen collapsing under gravity, the size of bubbles of ionized gas around the first galaxies, and areas where early sources have heated up the intergalactic hydrogen. Such information, Lonsdale says, will help theorists to improve their theories of the history of the EOR. "It'll take at least 3 years to accumulate data and understand it. We'll get detection but not details," says Meiksin.

Such results will likely just whet cosmologists' appetite to delve deeper into the EOR with bigger, more powerful telescopes. "If we detect the EOR, anything can happen," says Garrett. One obvious candidate for a second-generation machine is the SKA, whose design—which is still in development—will include antennas designed for low frequencies. An EOR telescope of that size would take observations to a whole new level. It would be able to image the ionized bubbles as they formed around new galaxies. And by varying the wavelength of the images, researchers can perform tomography, imaging slice after slice at different distances to build up a three-dimensional map of the ionizing universe. "With SKA we'll really start answering questions," Meiksin says.

And astronomers are already thinking about what might come after that. In a worst-case scenario, LOFAR and its kind "could illustrate that we can't do this from the ground," says Joseph Lazio of the Naval Research Laboratory in Washington, D.C. So several groups are starting to design telescopes for the far side of the moon. Such a project could make use of NASA's upcoming Ares heavy-lift launcher to deliver a package of material to land robotically on the far side. An autonomous rover would then distribute antennas over a 10-kilometer area, leaving a central processing and communications center at the landing site. There, far from earthbound radio transmitters and the distorting effects of the ionosphere, astronomers could peer straight into the heart of the universe's dark age. "It would allow us to see hydrogen before it became complicated by stars, galaxies, and quasars—a complex astrophysical brew—when the imprint of cosmological processes would be much easier to measure," says Lonsdale. From such a vantage point, we would get a view of the universe before stars were born.

–DANIEL CLERY