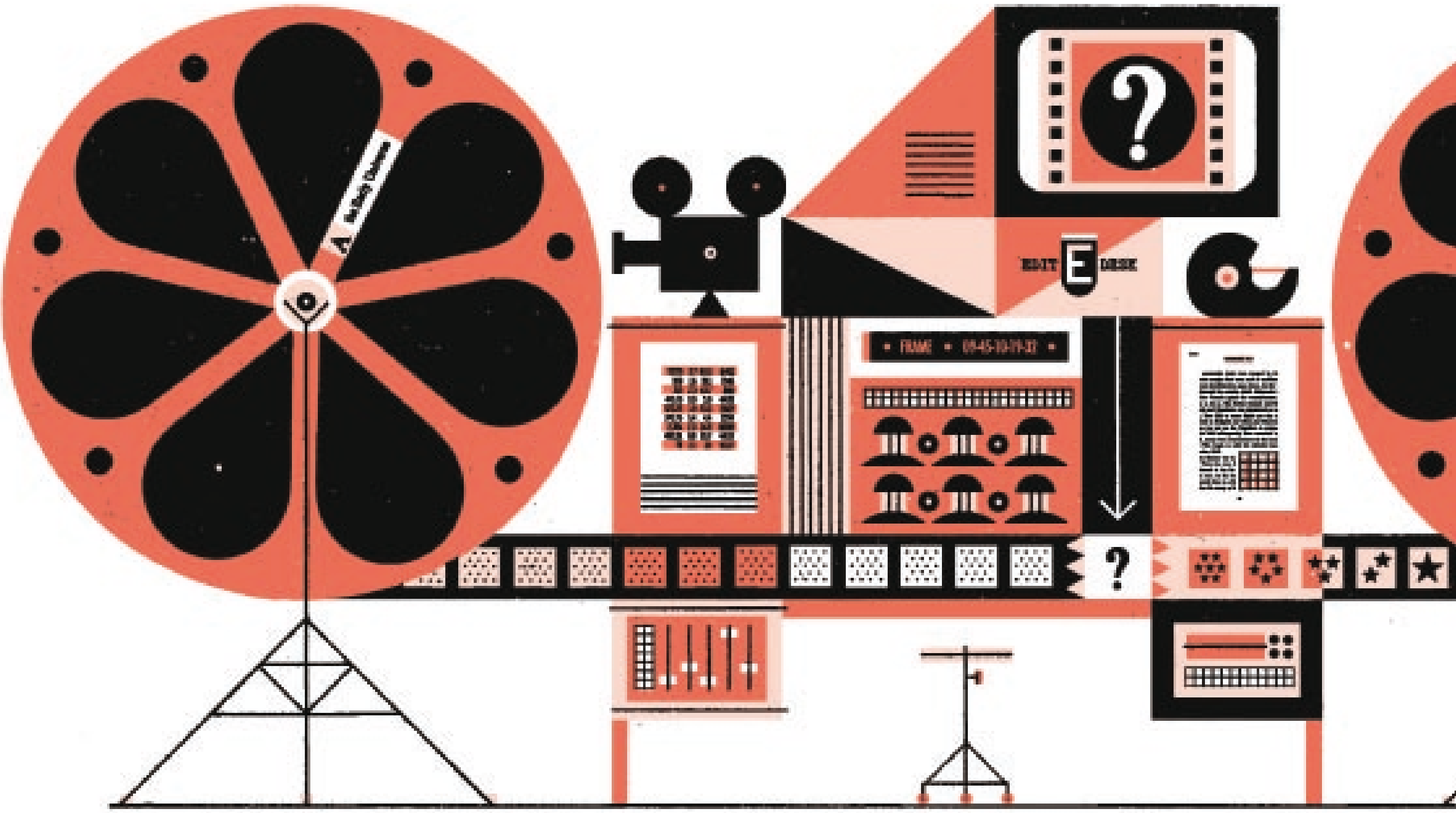

The missing reel

The universe's story is a true epic – but up till now we have been lacking some decisive early scenes, say astrophysicists **Abraham Loeb** and **Jonathan Pritchard**

ASTRONOMERS have a great advantage over archaeologists: they can see the past. The finite speed of light means that the further away a cosmic object is, the longer its light takes to reach us. An image recorded by our telescopes today tells us how that object looked long ago when its light was emitted.

Using our most powerful telescopes on Earth and in space, we can now trace the universe's story back to a time it was just 500 million years into its 13.7-billion-year life. Meanwhile a single flash that bathed the cosmos in light 400,000 years after the big bang provides us with an isolated exposure of the universe in this infancy.

This infant universe is, like a new-born baby, almost featureless, yet to assume the characteristics that will mark it out in later life. When our telescopic cameras pick up its story again, however, it is recognisably its adult self – stars, galaxies and clusters of galaxies already populate its reaches.

What happened in between, during the universe's turbulent, formative adolescent years? That has long been a matter of conjecture. Now, thanks to a combination of new instruments and refined observational techniques, the missing reel of the universe's story is about to be slotted in – presented in the crackle and hiss of giant radio waves.

We already have a rough storyboard for the universe's missing adolescence. Clues are encoded in the cosmic microwave background, that radiation suddenly liberated 400,000 years into the universe's existence. At this "epoch of recombination" the cosmos had cooled enough for protons and electrons to form neutral hydrogen that scattered light in all directions. Tiny variations in this radiation's temperature show that the atoms were spread not uniformly, but in almost imperceptible clumps. Gravity's pull, our story

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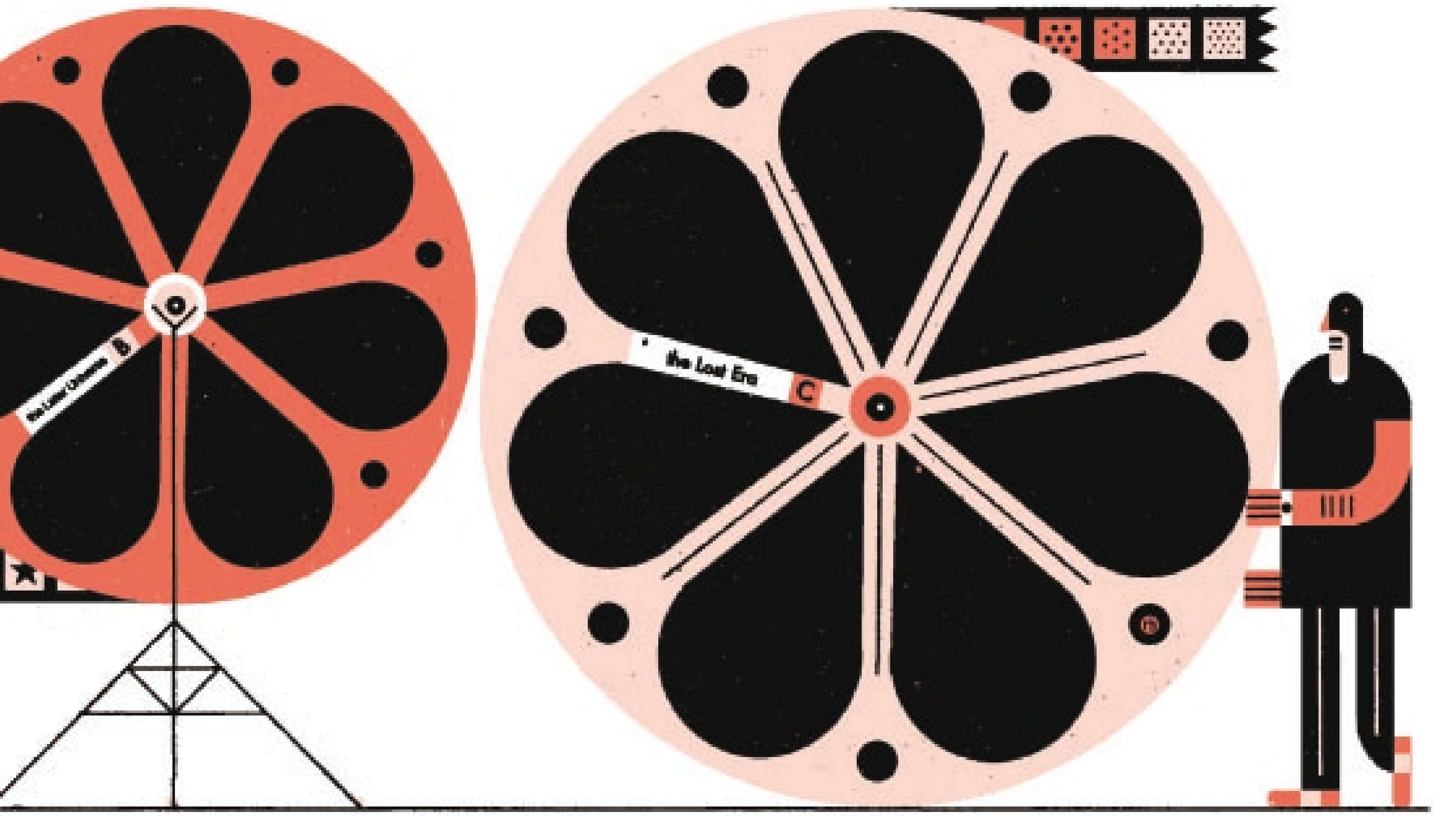

goes, caused these lumps to consolidate and grow and eventually ignite into stars. These stars, in turn, felt a mutual attraction, slowly – over the course of a few hundred million years – forming ever-larger galaxies.

As they did so, the universe underwent a final shift in its character: high-energy radiation broke down hydrogen formed at the epoch of recombination, freeing up electrons and protons. This "epoch of reionisation", which is thought to have ended some 700 million years after the big bang, marked the coming-of-age of the cosmos we see today.

Convincing as this plot development is, in the absence of observational evidence it is a tale too confidently told. Many significant details of the universe's evolution remain sketchy – and in some cases wholly obscure.

For a start, what made the first galaxies? The first stars, one might reasonably think. But the first stars must have been oddballs. Unlike every subsequent generation, they grew up in a pristine environment consisting solely of hydrogen and helium, the only elements the big bang forged in large quantities. Nuclear reactions within these pioneering stars created the heavier elements such as carbon, oxygen and silicon that went into the mix for later stars such as our sun – and, ultimately, our planet and ourselves.

From what we can tell, these first stars were bloated monsters up to 100 times the size of our sun that lived fast, burned bright and died within a few million years. Was that really long enough to form their own galaxies, or to influence their formation – or was it their less flamboyant successors that first found safety and stability in numbers?

Cosmic monsters that have survived into our times also pose puzzles. The centre of the Milky Way, and every galaxy like it, seems to host a black hole with a mass millions or even billions times that of the sun. How did they get that big? One theory is that they began as star-sized black holes, produced when massive stars exploded and fell in on themselves, and then slowly grew by sucking in gas and surrounding stars. Yet a typical supermassive black hole would need longer than the age of the universe to swallow enough material. An alternative theory is that they were simply born big, produced directly by the collapse of massive amounts of primordial gas.

"When our telescopes pick up the universe's story again , it is already recognisably its adult self"

And was it ultraviolet light from the first stars or X-rays emitted by these black holes as they fed that caused the epoch of reionisation? Our Milky Way was a product of the universe's dark ages – so asking these questions is again an investigation into our own origins.

How can we find the answers? We might build even larger, more sensitive telescopes to look even further back towards the big bang, but at least in the foreseeable future, that can only give us a partial view: the objects of interest are so far away that even the most gargantuan telescopes currently planned will see only the very brightest.

An alternative is to capture radio emissions from hydrogen atoms. Neutral hydrogen gas was an abundant, if diffusely spread, feature of the cosmos between the epochs of recombination and reionisation, and it gives off a faint signal of its presence. The lone electron and proton within each atom act

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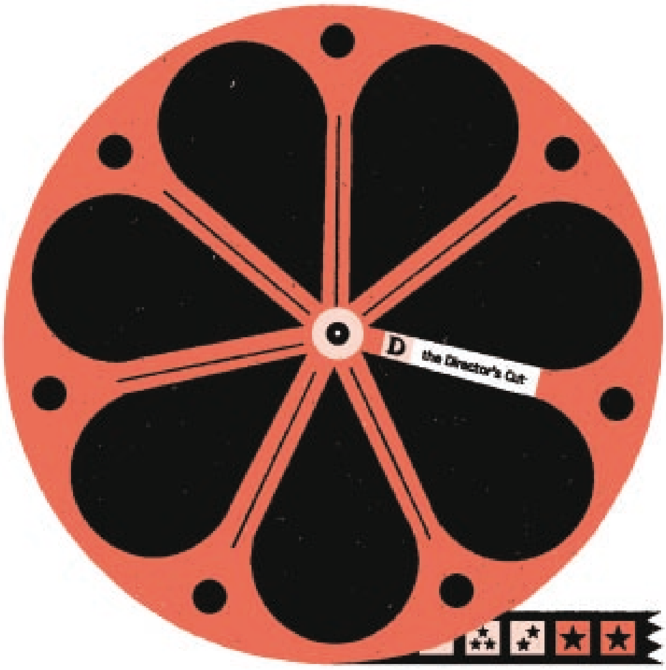


like two bar magnets that can lose energy by "flipping" so that their magnetic moments, or spins, point in opposite directions. When an atom flips, it releases energy as a photon with a defined radio wavelength of 21 centimetres. Equally, a hydrogen atom can flip into the higher-energy, aligned state by absorbing a passing photon of the same wavelength.

Either way, the emission or absorption of 21-cm radiation over patches of sky is a sure sign that hydrogen atoms are present. Because hydrogen is ionised by high-energy radiation – whether from brightly burning stars or from supermassive galactic black holes – maps of where it is should provide a detailed picture of where stars and galaxies are not.

The hydrogen signal was predicted by Dutch astronomer Hendrik van de Hulst in 1942, and first picked up from the Milky Way in 1951 by Harold Ewen and Edward Purcell, who placed a horn antenna through a window of the physics department at Harvard University. Since then it has been used to detect warm hydrogen gas in our galaxy and other nearby galaxies – for example, to measure Doppler shifts to higher or lower wavelengths and so find out what parts of galaxies are moving towards and away from us.

A similar Doppler-like shift can be used to record the evolution of hydrogen in the early universe. As the universe expands over time, so does the wavelength of radiation that travels through it. The further away a region is, and so the earlier in cosmic time we see it, the more stretching the radiation undergoes. This allows us to map the ancient hydrogen in three dimensions: two across the sky and, by tuning our receivers to different stretched wavelengths, a third that is equivalent to distance or "look-back time".

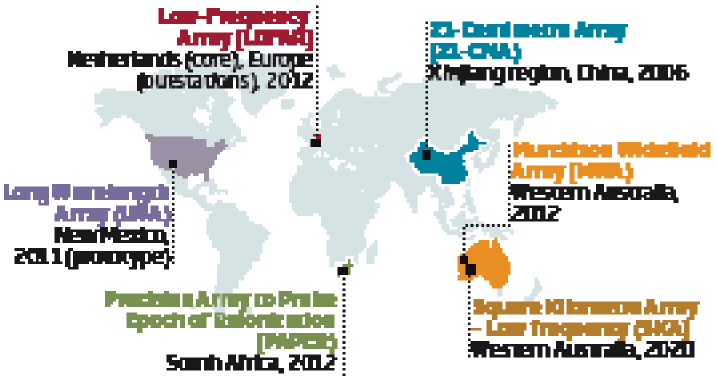
The result will be a film reel of the universe's missing years that can confirm – or, indeed, disprove – our general theoretical picture and answer many of those nagging questions. Fine details in the patterns of the 21-cm signal over time should reveal whether first-generation stars were a long-lasting feature in galaxy evolution, or brief candles that flickered once, never to be seen again. Different patterns of ionisation are expected from ultraviolet and X-ray emission, so that should tell us whether stars or black holes were the main agents of reionisation. If black holes were significant participants, the size of the ionised bubbles they created around them should reveal whether they ate their way to supersize or were simply born big.

Clues to a host of problems in fundamental particle physics might also be contained in the new hydrogen movies (see "Visible in radio", right). So why have we not made them before? Put simply, it has not been technically feasible. Hydrogen emissions from the first billion years after the big bang are stretched to wavelengths of around two metres, several million times longer than a typical visible wavelength. The larger the wavelength, the larger the telescope required to capture it with the necessary resolution. For the sort of radio telescope that springs to most people's mind – an overgrown satellite dish – the size rapidly becomes unfeasibly large. The world's largest

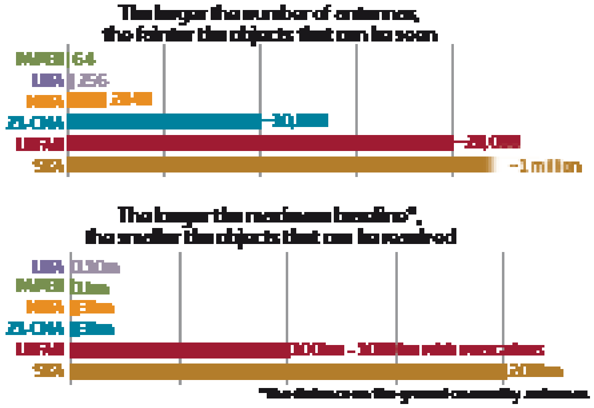
Radio multi-eyes

Arrays of radio antennas tuned to extremely long radio wavelengths will extend our vision back into the universe's crucial first billion years

Where are they?



How big are they?



*The distance on the ground separating antennas single radio telescope – a dish 305 metres in diameter built into a mountainside near Arecibo, Puerto Rico – does not come even close to the sensitivity required.

That is why the newest generation of radio telescopes takes a different approach. In an optical telescope, photons are generally separated by much more than their short wavelengths. The telescope is really just a bucket in which we collect individual photons to count them. In a radio telescope, by contrast, incoming photons from a distant source overlap and are recorded as a single continuous wave. This wave can be sampled at different points by many widely distributed small radio antennae and the samples combined by computer algorithms into a single, coherent signal.

One such array, the 30-antenna Giant Metrewave Radio Telescope, has been up and running since 1996, but has proved too small: it was designed in a data-starved era when there was believed to be much more hydrogen in the universe than we now know to be the case. The more antennas within a given area, the greater the telescope sensitivity. The bigger the "baseline" of the telescope – the maximum distance on the ground covered by the antennas – the smaller the size of the distant objects you can resolve. Imagine several thousand TV antennas connected to a supercomputer and you have an accurate image of a series of huge, long-wavelength radio arrays that are about to sharpen our view of the deep cosmic past (see diagram, below).

These arrays still won't have it easy. Earth's ionosphere interferes with radio waves as they pass, distorting the position and shape of distant sources and creating an effect that is like trying to perform optical astronomy from the bottom of a swimming pool. This must be corrected by referencing coordinates to a network of radio "pulsars", fast, rotating neutron stars that send regular, pinpointed pulses of radiation our way. Individual bright radio sources and diffuse radio emissions from our own galaxy, which are 10,000 times brighter than the ancient cosmic signal, must also be peeled away – not to mention the busy noise of our own radio transmissions.

"Radio astronomy on Earth's surface is a bit like optical astronomy from the bottom of a swimming pool"

The theoretical and computational tools to overcome such difficulties are now largely in place, and the first definitive detection of hydrogen from the epoch of reionisation is expected within the next five years. These first pictures will still be a little fuzzy. For a finer-grained view, all eyes will be on the Square Kilometre Array (SKA), on which construction is due to start in South Africa and western Australia in 2016. The long-wavelength (low-frequency) part of the SKA, to be completed in Australia by about 2020, will consist of around one million radio antennas, yielding a collecting area of a square kilometre, plugged to one of the world's fastest supercomputers. It should help to unravel the nature of the very first galaxies that formed in the first few hundred million years after the big bang.

Looking even further ahead, NASA is examining the possibility of 21-cm experiments on the far side of the moon, thus avoiding the problems both of Earth's ionosphere and of human radio activity. The idea is not as fanciful as it sounds. After all, in comparison to hulking a weighty conventional telescope with mighty mirrors into orbit, a simple radio array would be little more than a few wires connected to a supercomputer and a power source. Not much for the ultimate cinematic record of the universe's history. ■

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VISIBLE IN RADIO

Hydrogen's 21-centimetre radio emissions should illuminate the universe's dark adolescence (see main story), but address some deeper questions too.

What was inflation?

The 21-cm observations ultimately measure variations in cosmic density seeded at the period of inflation, a breakneck expansion of space thought to have occurred a split second after the big bang. The cosmic microwave background radiation provides a single 2D projection of these fluctuations 400,000 years after the big bang. The 21-cm observations will give us a far richer, 3D source of information on what physics looked like under extremely hot, dense conditions far beyond those recreated in earthly accelerators.

How massive are neutrinos?

That neutrinos have a mass comes as a surprise to the standard model of particle physics - but they do, albeit a tiny and as yet unmeasured one. Characterising these elusive particles is important for understanding physics beyond the standard model, but it is a frustrating process using detectors on Earth. Measuring their influence on the formation of structure in the universe is a surprisingly effective alternative. The passage of neutrinos smoothes the distribution of matter and the scales on which this smoothing occurs at different times tells us how far and fast neutrinos have travelled since the big bang - and hence their mass.

What is dark matter?

Invisible dark matter is thought to make up 80 per cent of cosmic matter, and is needed to explain why galaxies rotate as fast as they do. Most particles postulated to be dark matter can annihilate each other, releasing energy and heating their surrounds. This would make an imprint in the hydrogen 21-cm radiation, so measuring its pattern across the early cosmos will narrow down where dark matter was - and possibly reveal its nature.

ow far back can they look?

ach array is tuned to a different span of the Universe's early years