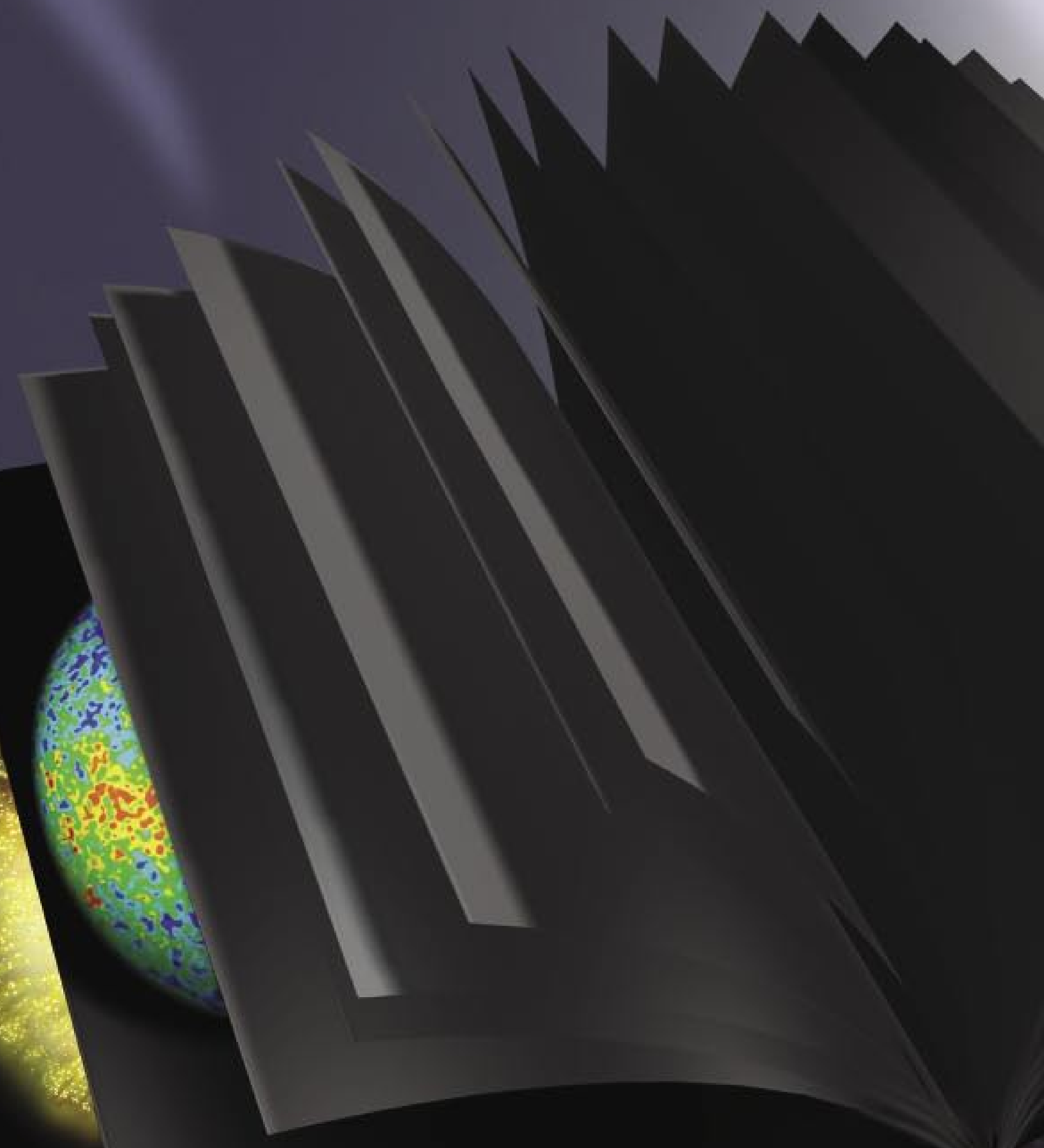
THE DARK AGES



of the Universe

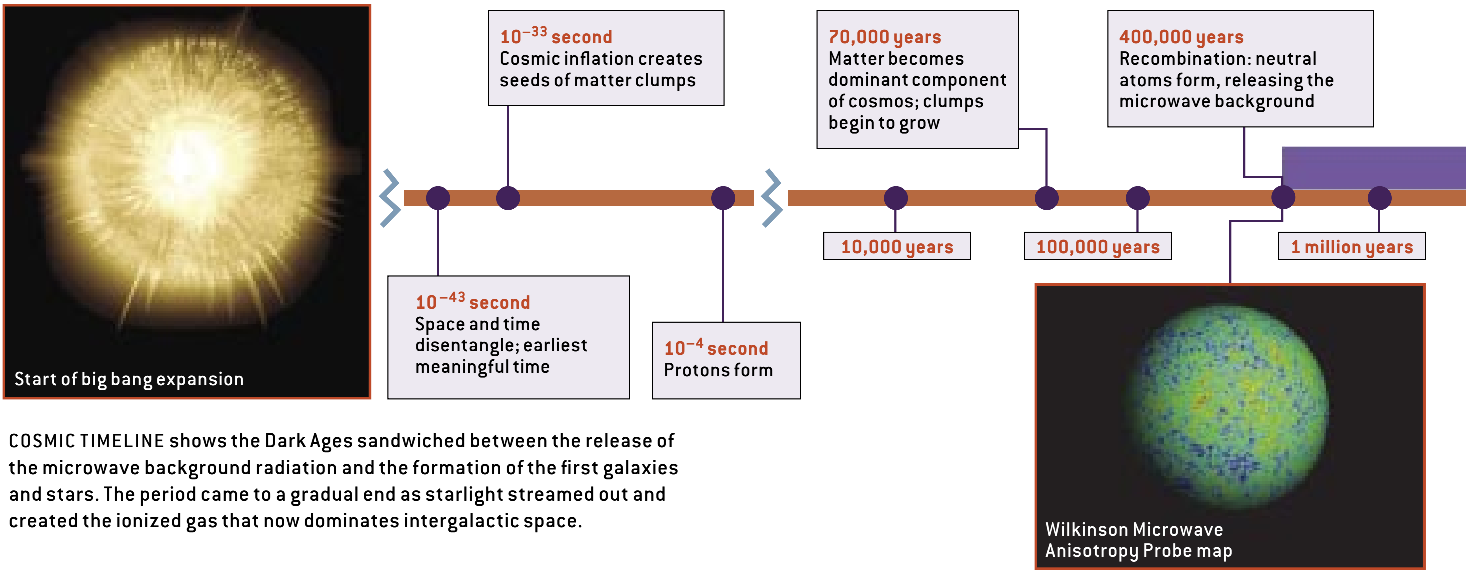
Astronomers are trying to fill in the blank pages in our photo album of the infant universe

By Abraham Loeb

When I look up into the sky at night, I often wonder whether we humans are too preoccupied with ourselves. There is much more to the universe than meets the eye on earth. As an astrophysicist I have the privilege of being paid to think about it, and it puts things in perspective for me. There are things that I would otherwise be bothered by—my own death, for example. Everyone will die sometime, but when I see the universe as a whole, it gives me a sense of longevity. I do not care so much about myself as I would otherwise, because of the big picture.

Cosmologists are addressing some of the fundamental questions that people attempted to resolve over the centuries through philosophical thinking, but we are doing so based on systematic observation and a quantitative methodology. Perhaps the greatest triumph of the past century has been a model of the universe that is supported by a large body of data. The value of such a model to our society is sometimes underappreciated. When I open the daily newspaper as part of my morning routine, I often see lengthy descriptions of conflicts between people about borders, possessions or liberties. Today's news is often forgotten a few days later. But when one opens ancient texts that have appealed to a broad audience over a longer period of time, such as the Bible, what does one often find in the opening chapter? A discussion of how the constituents of the universe—light, stars, life—were created. Although humans are often caught up with mundane problems, they are curious about the big picture. As citizens of the universe we cannot help but wonder how the first sources of light formed, how life came into existence and whether we are alone as intelligent beings in this vast space. Astronomers in the 21st century are uniquely positioned to answer these big questions.

What makes modern cosmology an empirical science is that we are literally able to peer into the past. When you look at your image reflected off a mirror one meter



COSMIC TIMELINE shows the Dark Ages sandwiched between the release of the microwave background radiation and the formation of the first galaxies and stars. The period came to a gradual end as starlight streamed out and created the ionized gas that now dominates intergalactic space.

away, you see the way you looked six nanoseconds ago—the light's travel time to the mirror and back. Similarly, cosmologists do not need to guess how the universe evolved; we can watch its history through telescopes. Because the universe appears to be statistically identical in every direction, what we see billions of light-years away is probably a fair representation of what our own patch of space looked like billions of years ago.

The ultimate goal of observational cosmology is to capture the entire history of the universe, providing a seamless picture of our descent from a shapeless gas of subatomic particles. We have a snapshot of the universe as it was 400,000 years after the big bang—the cosmic microwave background radiation—as well as pictures of individual galaxies a billion years later. By the middle of the next decade, NASA plans to launch a new space telescope, named the James Webb Space Telescope (JWST), that should be able to pick up the first galaxies, which theorists predict formed at a cosmic age of hundreds of millions of years.

Overview/*Epoch of Reionization*

- Much of the attention in cosmology over the past several years has focused on the cosmic microwave background radiation, which provides a snapshot of the universe at an age of 400,000 years. But between this moment and the appearance of the first galaxies was a period of almost total darkness, broken by not so much as a glimmer of starlight. Hidden in the shadows of this era are the secrets of how galaxies took shape.
- Clearly, it is hard to probe a period that is by its very nature practically invisible. The key is to look for the feeble radio waves emitted by electrically neutral hydrogen gas as it interacts with the background radiation. Observers are now starting to do so.
- The result should be an even more interesting map than that of the microwave background. It will be fully three-dimensional and will show, step by step, how form emerged from formlessness.

But that still leaves a tremendous gap. In between the release of the microwave background and the first rays of starlight was a period when the universe was dark and the microwave background no longer traced the distribution of matter. It might sound like a languid, gloomy time, a boring interlude between the immediate aftermath of the big bang and the bustling cosmos of the present day. Yet a great deal happened in these Dark Ages: the primordial soup evolved into the rich zoo of celestial bodies we now see. Within the inky blackness, gravitational forces were assembling objects in the cosmos.

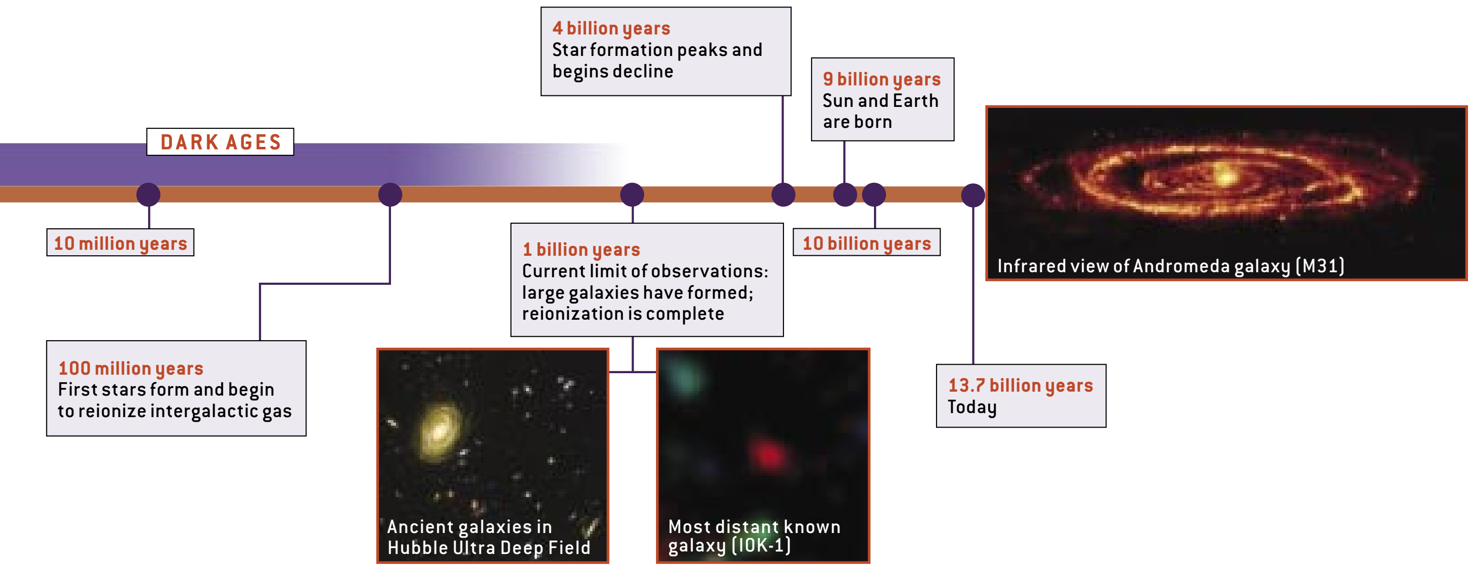
The situation that astronomers face is similar to having a photo album of a person that contains the first ultrasound image of him or her as an unborn baby and some additional photos as a teenager and an adult. If you tried to guess from these pictures what happened in the interim, you could be seriously wrong. A child is not simply a scaled-up fetus or scaled-down adult. The same is true with galaxies. They did not follow a straightforward path of development from the incipient matter clumping evident in the microwave background. Observations hint that the universe underwent a wrenching transition during the Dark Ages.

Astronomers are currently searching for the missing pages of the cosmic photo album, which will show how the universe evolved during its infancy and made the building blocks of galaxies like our own Milky Way. A decade ago, when I started to work on this effort, only a handful of researchers were interested in it. Now it motivates a major fraction of future observational projects and promises to be one of the most exciting frontiers in cosmology over the next decade.

From Ions to Ions

ACCORDING TO the big bang theory, the early universe was filled with hot plasma—a cauldron of protons, electrons and photons, with a smattering of other particles. The freely moving electrons interacted with photons through a process known as Thomson scattering, which coupled matter and

JEAN-FRANCOIS PODEVIN (*preceding pages and start of big bang, this page*); MAX TEGMARK *Massachusetts Institute of Technology* (*WMAP*)



NASA, EUROPEAN SPACE AGENCY, STEVEN BECKWITH *Space Telescope Science Institute* AND HUBBLE ULTRA DEEP FIELD TEAM (*ancient galaxies*); M. IYE AND K. OTA, © SUBARU TELESCOPE, NATIONAL ASTRONOMICAL OBSERVATORY OF JAPAN (*IOK-1*); NASA/JPL (*M31*)

radiation tightly together. As the universe expanded in size, it cooled, and when temperatures fell to 3,000 kelvins, the protons and electrons combined to make electrically neutral hydrogen atoms. The Thomson scattering process ended, and the photons ceased interacting with matter so intensively, becoming the microwave background. Cosmic expansion continued to cool the gas, so one might expect that the cosmic gas would still be cold and neutral today.

Surprisingly, it is not. Although the world around us is composed of atoms, the bulk of the universe's ordinary matter today is in the form of plasma, located deep in intergalactic space. The observed spectra of the most distant (and hence oldest) known quasars, galaxies and gamma-ray bursts indicate that this diffuse cosmic hydrogen was fully ionized by a cosmic age of one billion years [see "The Emptiest Places," by Evan Scannapieco, Patrick Petitjean and Tom Broadhurst; Scientific American, October 2002]. A tantalizing hint of what happened came three years ago, when the Wilkinson Microwave Anisotropy Probe (WMAP) confirmed that the microwave background radiation is slightly polarized. Neutral hydrogen does not polarize this radiation; only ionized hydrogen does. The amount of polarization suggests that the gas was ionized as early as a few hundred million years after the big bang. Thus, the atoms must have been broken back down into their constituent protons and electrons as the Dark Ages came to an end.

Most researchers associate this process of reionization with the first generation of stars. Ionizing an atom of hydrogen takes an energy of 13.6 electron volts, an amount delivered by a photon of ultraviolet light. It is not a great deal of energy—equivalent to about 10^9 joules per kilogram of hydrogen, much less than the 10^{15} joules released by the nuclear fusion of the same amount of hydrogen. If just one millionth of the gas in the universe underwent fusion inside stars, it would have produced enough energy to ionize all the rest. Other researchers conjecture that material plummeting into black holes gave off the ionizing radiation. Falling into a black hole releases as much as 10^{16} joules per kilogram, so only a 10-millionth of the cosmic hydrogen would need to fall into black holes to ionize the rest.

Stars and black holes arise within galaxies, so before reionization could take place, galaxies must have formed. Although most people think of galaxies as collections of stars, cosmologists regard them simply as large clumps of matter in which stars are relative latecomers. In fact, galaxies consist mostly of dark matter, an as yet unidentified type of material that is inherently invisible. Galaxies are thought to have formed when a region of the universe that started slightly denser than average pulled itself together by its own gravity. Although the region initially expanded like the rest of the universe, its extra gravity slowed its expansion down, turned it around and made the region collapse on itself to create a bound object: a galaxy.

According to current models, dwarf galaxies started to take shape when the universe was 100 million years old. They merged and built up bigger galaxies as time went on. A modern galaxy such as the Milky Way involved the coalescence of a million such building blocks. Within the embryonic galaxies, gas cooled and fragmented to create stars [see "The First Stars in the Universe," by Richard B. Larson and Volker Bromm; Scientific American, December 2001]. The stars' ultraviolet radiation leaked into intergalactic space, broke electrons out from their atoms and created an expanding bubble of ionized gas. Ever more bubbles appeared as new galaxies took root, and the intergalactic gas looked like Swiss cheese. The

The universe underwent a WRENCHING TRANSITION during the Dark Ages.

bubbles started to overlap and eventually filled all of space.

Although the above sequence of events sounds plausible, its only residence so far has been in the minds of theorists. Practical cosmologists would like to see direct evidence for the reionization epoch before adding the missing chapter to their textbooks. Moreover, only observations can settle whether stars or black holes dominated reionization and what the properties of the dark matter were. But how are such observations possible if, initially at least, the Dark Ages were dark?

Seeing in the Dark

FORTUNATELY, EVEN COLD HYDROGEN can emit a form of light. Subatomic particles have an intrinsic orientation known as spin, which can point in one of two directions, conventionally called "up" and "down." The electron and proton in a hydrogen atom can point either in the same direction (aligned) or in opposite directions (antialigned). In the antialigned state the atom has a lower energy. If, for example, both the electron and proton point up, and the electron then flips so that it points down, the atomic state will decrease in energy and give off a photon with a wavelength of 21 centimeters. Conversely, if the atom absorbs a photon of this wavelength, the electron will flip up.

A 21-centimeter photon is much less energetic than the photons typically emitted by hydrogen as electrons jump between orbits. For this reason, the spin-flipping process was able to operate even when no stars yet shone. Energy from the microwave background radiation and from collisions among the atoms would have sufficed to flip electrons and induce the hydrogen to glow feebly. The relative numbers of atoms with aligned and antialigned spins defined the so-called spin temperature of the gas. A high spin temperature, for example, would indicate that a high fraction of atoms were aligned.

Theory therefore indicates that the Dark Ages were defined by three distinct temperatures: the spin temperature (a measure of the relative abundance of atoms with different spin states); the ordinary, kinetic temperature (a measure of the motions of the atoms); and the radiation temperature (a measure of the energy of the background photons). These three temperatures could deviate from one another, depending on which physical processes operated.

In a strange ménage à trois, the spin temperature matched first the kinetic temperature, then the radiation temperature and finally the kinetic temperature once again [*see box on opposite page*]. As space expanded, both the gas and the radiation cooled. Left to its own devices, the gas would have cooled faster, but initially a small residual number of free electrons left over from the formation of hydrogen atoms counteracted this tendency. These electrons acted as middlemen to convey energy from the microwave background to the atoms, keeping all three temperatures equal. Ten million years after the big bang, however, the electrons faltered in their role because the microwave background had become too dilute. The equilibrium between gas and radiation broke down, and the gas started to cool rapidly. Atomic collisions kept the kinetic and spin temperatures equal. In this phase the hydrogen was a net absorber of 21-centimeter photons and soaked up energy from the microwave background (though never enough to restore equilibrium).

One hundred million years after the big bang, a second transition occurred. Cosmic expansion had diluted the density of the gas to the point where collisions were too infrequent to equalize the spin and kinetic temperatures. The spins then picked up energy from the microwave background. When the spin temperature returned to equilibrium with the radiation temperature, hydrogen was neither a net absorber nor a net emitter of 21-centimeter photons. During this period the gas could not be seen against the microwave background.

When the first stars and black holes lit up, a third transition took place. The x-rays they gave off raised the kinetic temperature. Their ultraviolet light was absorbed and reradiated by the hydrogen, and the ensuing hopscotching of electrons among atomic orbits brought the spin and kinetic temperatures into equilibrium. The spin temperature increased beyond the microwave background temperature, so the hydrogen outshone the background. Flipping electrons takes much less energy than ionizing atoms, so galaxies caused the hydrogen to glow well before they reionized it. Eventually, as the hydrogen became ionized, it gave off light by different means and the intergalactic 21-centimeter emission faded away.

The new map may carry MORE INFORMATION than even the cosmic microwave background radiation.

THE AUTHOR

ABRAHAM LOEB is a world leader in the theoretical study of the first stars and black holes and the epoch of reionization. What drives him, he says, is an interest in ancient philosophical questions; these inspired him to enter physics as a young person. He is now an astronomy professor at Harvard University and a visiting professor at the Weizmann Institute of Science in Rehovot, Israel. Loeb has also been a pioneer of the detection of extrasolar planets by gravitational microlensing and the production of gamma rays in intergalactic space. He served on the first science working group for the James Webb Space Telescope and received a Guggenheim Fellowship in 2002.

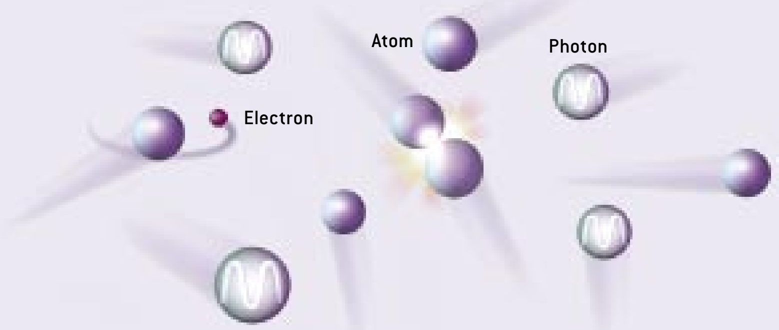
Primeval Tomography

BECAUSE OF THIS MÉNAGE À TROIS, the 21-centimeter sky will be either brighter or darker than the microwave background, depending on time and location. Another phenomenon that observers need to take into account is that cosmic expansion has stretched the photons to longer wavelengths.

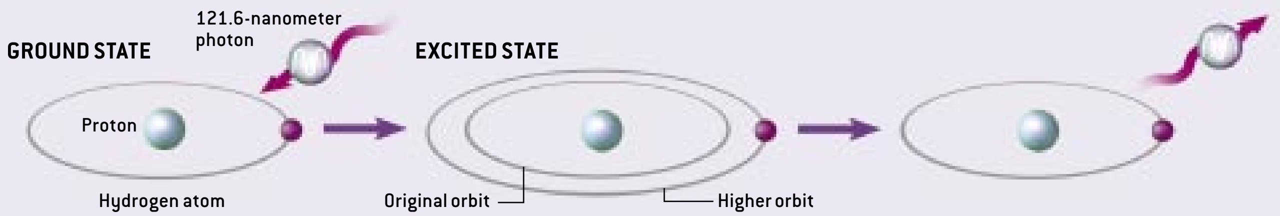
HOW TO SEE IN THE DARK

Despite the lack of stars, the Dark Ages were not completely dark. A rare process caused hydrogen gas to glow dimly.

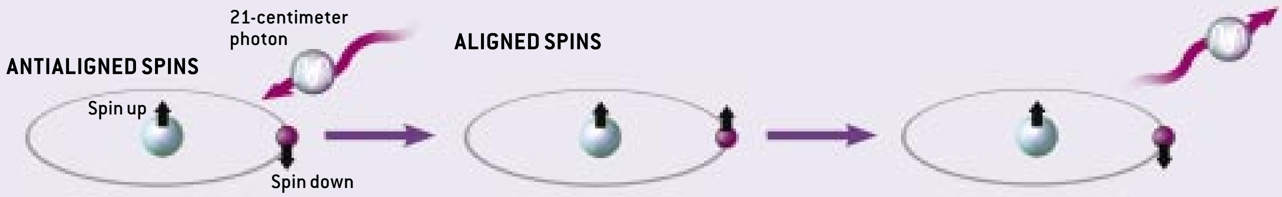
For hydrogen to glow, there had to be a source of energy. The only available ones were the atoms' own kinetic energy (released by collisions between atoms) and the photons of the cosmic background radiation. A smattering of unattached electrons was available to help transfer energy between the atoms and the photons.



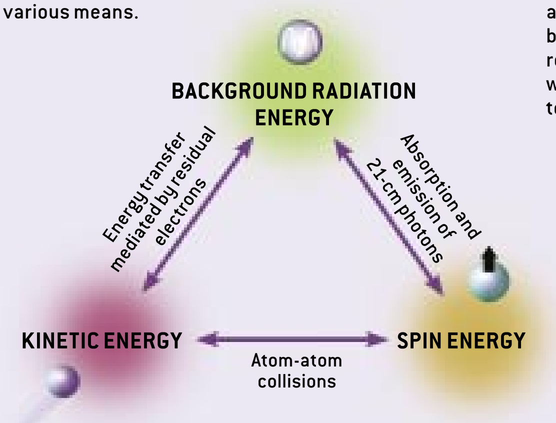
Neither source, however, was strong enough to cause the hydrogen to glow by the usual means, in which an electron gets bumped into a higher orbit (a so-called excited state) and falls back down, releasing a photon.



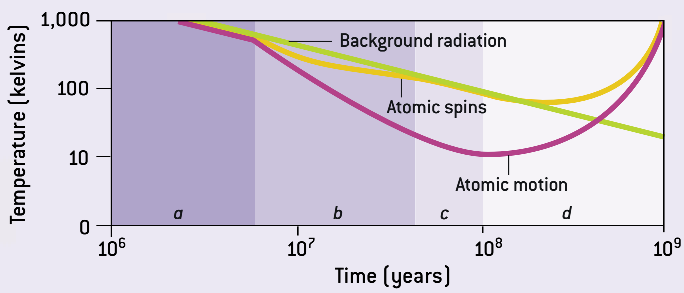
The collisions and photons did, however, pack just enough punch to flip an electron so that its spin pointed the same way as the proton's. When the electron flipped back, it released a photon with a wavelength of 21 centimeters.



The kinetic energy, photon energy and spin energy were three reservoirs that interchanged energy by various means.



The amount of energy in each reservoir can be represented in terms of temperature: the higher the temperature, the greater the energy. At the start of the Dark Ages, all three temperatures were the same (*a*). Then the kinetic and spin temperature began to fall faster than the photon energy (*b*). After a while, the spin temperature returned to equilibrium with the photon temperature (*c*). Finally, stars and quasars warmed the gas, pumping up the kinetic and spin temperatures (*d*). The relative temperatures determine how (and whether) the hydrogen can be observed.



GEORGE RETSECK (*illustrations*); DANIELA NAOMI MOLNAR (*graph*)

Since the start of the Dark Ages, the universe has expanded in size by a factor of 1,000, so a 21-centimeter photon emitted at that time arrives on earth with a wavelength of 210 meters. A photon emitted toward the end of the Dark Ages is shifted to a wavelength of one to two meters.

This range of wavelengths falls into the radio part of the electromagnetic spectrum. The emission can be picked up by arrays of low-frequency antennas similar to those used for television and radio communications. Several groups are currently constructing such arrays. The Mileura Widefield Array (MWA) in Western Australia will consist of 8,000 antennas scattered across a region 1.5 kilometers long and sensitive to a wavelength of one to 3.7 meters. It has an angular resolution of a few arcminutes, which corresponds to a physical scale of about three million light-years during the Dark Ages. Other efforts include the Low-Frequency Array (LOFAR), the Primeval Structure Telescope (PaST) and, in the more distant future, the Square Kilometer Array (SKA).

By scanning across wavelengths, these arrays will probe the 21-centimeter emission at different times in cosmic history. Astronomers will be able to build a three-dimensional map of the neutral hydrogen distribution. They will be able to watch density fluctuations of one part in 100,000 (as in the microwave background) become orders of magnitude greater. At the locations of greatest density, galaxies should take shape and create bubbles of ionized hydrogen. The bubbles will proliferate and merge, eventually clearing intergalactic space of neutral hydrogen [*see box at right*]. The sharpness of the bubbles' boundaries will answer the question of whether reionization was caused by massive stars or by black holes. Massive stars pour out most of their energy in ultraviolet light, which is readily blocked by intergalactic hydrogen, whereas black holes generate mostly x-rays, which penetrate deeply into the gas. So black holes produce fuzzier boundaries.

For several reasons, the 21-centimeter map may carry more bits of information than any other survey in cosmology—more than even the cosmic microwave background. First, whereas an image of the microwave background is two-dimensional, because it originated at a single moment in time (when the universe cooled below 3,000 kelvins), the 21-centimeter map, as mentioned above, will be fully three-dimensional. Second, the microwave background is somewhat blurry because its release did not occur at the same time everywhere. The universe went through a period when it was neither fully opaque nor fully transparent, like a fog that dissipated gradually. During that time, the radiation diffused across short distance scales, smearing the fine print in the microwave background sky. In contrast, when 21-centimeter radiation emerged from hydrogen atoms, nothing blocked its propagation through space, so it traces the gas distribution without such blurring. Third, the microwave background carries information about the matter density fluctuations that seeded galaxies, whereas the 21-centimeter map will depict both the seeds of galaxies and the effect that the galaxies, once formed, had on their surroundings.

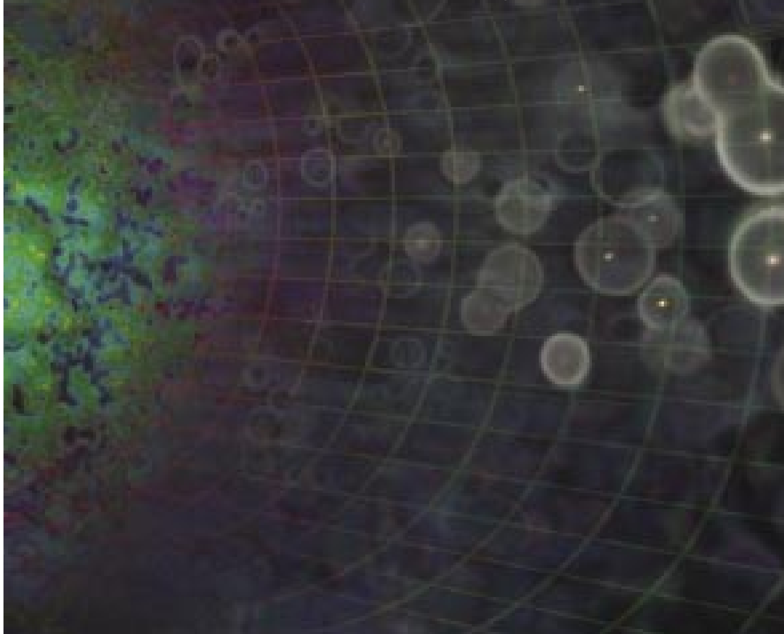
To detect the 21-centimeter signal, observers will have to overcome numerous challenges. Low-frequency radio broadcasts on earth have to be filtered out. Even more difficult will be dealing with foreground radio emission from our galaxy, which is 10,000 times more intense than the signal from the epoch of reionization. Fortunately, the galactic noise is roughly the same at slightly different wavelengths, whereas the signal fluctuates with wavelength, reflecting the spatial structure of the ionized bubbles. This difference makes it possible to extract the signal. Astronomers should be able to compare the 21-centimeter maps with images from instruments such as JWST. The galaxies seen in infrared light should correlate with ionized bubbles in the neutral hydrogen.

In addition to the above observational challenges, a number of tasks remain for theorists. Most important, they need to run bigger computer simulations to track events in a volume of space large enough (a billion light-years across) to be a representative statistical sample of our universe and with high enough resolution to capture dwarf galaxies. The simulation also needs to trace the propagation of the ionizing radiation from the galaxies through the surrounding gas, a process modeled only very crudely so far. Observers may well see reionization before theorists are able to forecast what they should see.

This combined observational and theoretical effort should shed light on various mysteries that now plague the theory of galaxy formation. One set of questions concerns the massive black holes in the centers of galaxies. Over the past decade astronomers have realized that almost every galaxy in the present-day universe, including our own Milky Way, hosts a massive black hole. These holes are believed to be fed with gas in episodic events, triggered by mergers of galaxies. During these

LIGHTING UP THE COSMOS

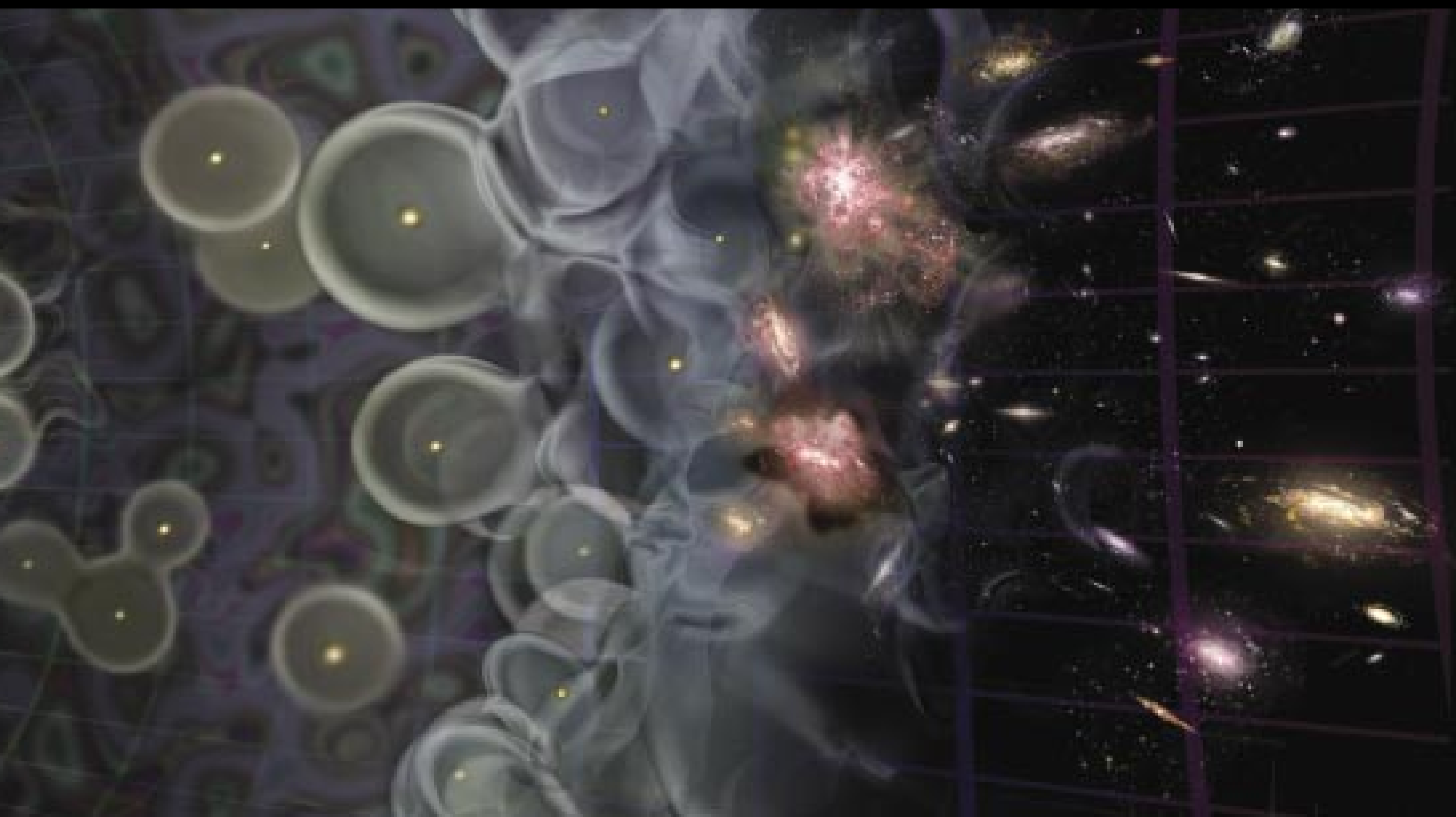
In the beginning of the Dark Ages, electrically neutral hydrogen gas filled the universe. As stars formed, they ionized the regions immediately around them, creating bubbles here and there. Eventually these bubbles merged together, and intergalactic gas became entirely ionized.



Time:
Width of frame:
Observed wavelength:

Simulated images of 21-centimeter radiation show how hydrogen gas turns into a galaxy cluster. The amount of radiation (*white is highest; orange and red are intermediate; black is least*) reflects both the density of the gas and its degree of ionization: dense, electrically neutral gas appears white; dense, ionized gas appears black. The images have been rescaled to remove the effect of cosmic expansion and thus highlight the cluster-forming processes. Because of expansion, the 21-centimeter radiation is actually observed at a longer wavelength; the earlier the image, the longer the wavelength.

JEAN-FRANCOIS PODEVIN (*illustration*); STEVEN FURLANETTO, AARON SOKASIAN AND LARS HERNQUIST *Harvard University* (*simulations*)



210 million years
2.4 million light-years
4.1 meters
All the gas is neutral. The white areas are the densest and will give rise to the first stars and quasars.

290 million years
3.0 million light-years
3.3 meters
Faint red patches show that the stars and quasars have begun to ionize the gas around them.

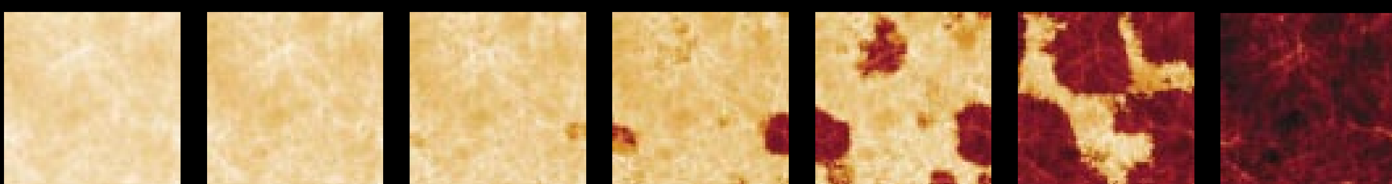
370 million years
3.6 million light-years
2.8 meters
These bubbles of ionized gas grow.

460 million years
4.1 million light-years
2.4 meters
New stars and quasars form and create their own bubbles.

540 million years
4.6 million light-years
2.1 meters
The bubbles are beginning to interconnect.

620 million years
5.0 million light-years
2.0 meters
The bubbles have merged and nearly taken over all of space.

710 million years
5.5 million light-years
1.8 meters
The only remaining neutral hydrogen is concentrated in galaxies.



growth spurts, the accreting gas shines much more brightly than the entire rest of the galaxy, producing a quasar. The Sloan Digital Sky Survey has revealed that quasars with black holes of more than a billion solar masses already existed at a cosmic age of one billion years. How did such massive black holes come to exist so early? Why did they stop growing?

Another set concerns the size distribution of galaxies. Theorists believe that the ultraviolet radiation produced by dwarf galaxies during the epoch of reionization heated the cosmic gas and suppressed the formation of new low-mass galaxies. How did this suppression unfold over time? Which of the dwarf galaxies we find today were already in existence at the beginning? These are only a few of the many questions whose answers lie in the Dark Ages. SA

MORE TO EXPLORE

Measuring the Small-Scale Power Spectrum of Cosmic Density Fluctuations through 21 cm Tomography Prior to the Epoch of Structure Formation. Abraham Loeb and Matias Zaldarriaga in *Physical Review Letters*, Vol. 92, No. 21, Paper No. 211301; May 25, 2004. Preprint available at **arxiv.org/abs/astro-ph/0312134**

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Chasing Hubble's Shadows: The Search for Galaxies at the Edge of Time. Jeff Kanipe. Hill and Wang, 2006.

Cosmology at Low Frequencies: The 21 cm Transition and the High-Redshift Universe. Steven Furlanetto, S. Peng Oh and Frank Briggs in *Physics Reports* (forthcoming). **arxiv.org/abs/astro-ph/0608032**