LIGHTING UP THE DARK AGES

by Marcus Y. Woo

NOT LONG AFTER THE BIG BANG—a mere 370,000 years later—the universe entered what astronomers now call the dark ages. The cosmos had yet to see the light of stars and galaxies; in fact, a cloak of hydrogen haze smothered almost any photon that might have tried to illuminate the infant universe.

After about 200 million more years, however, that hydrogen gas began to coalesce into increasingly dense clouds—coaxed together by the gravitational pull of dark matter, the unseen and unknown stuff that accounts for most of the universe's mass. Those hydrogen clouds eventually collapsed into dense balls that were hot enough to ignite nuclear fusion, thus giving birth to the first stars.

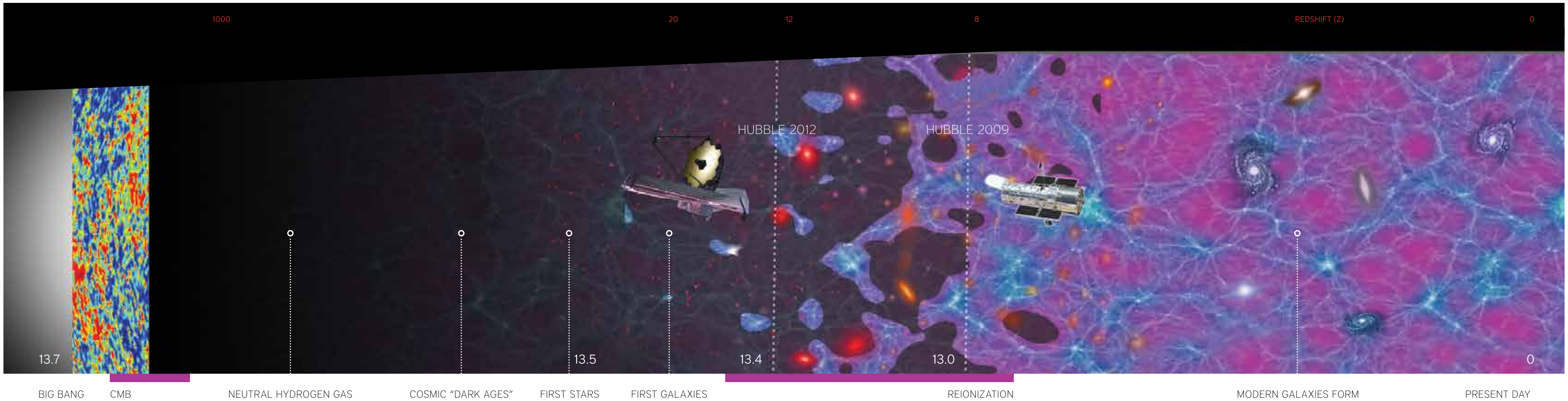
Over the course of another couple of hundred million years, more and more stars flared into existence and galaxies formed, flooding the universe with high-energy photons—ultraviolet light that carried enough energy to strip the single electrons from the hydrogen atoms that pervaded the cosmos. At this time, most of the hydrogen gas in the universe was electrically neutral—a single electron joined with a proton—and neutral hydrogen blocks light by absorbing it. But with the influx of ultraviolet light, the neutral hydrogen lost its electrons and became ionized. Without neutral hydrogen to absorb them, photons could now travel freely.

This epoch—the one that saw the first stars and galaxies and the ionization of hydrogen—is known as the cosmic dawn, and its light brought an end to the dark ages. Together, both periods represent the last frontier of observational cosmology—an era so distant and therefore so faint that it's out of reach (though only just so) of today's telescopes. But because astronomers, ever the pioneers, love a good frontier, scientists like Caltech's Richard Ellis are pushing the limits of those present-day telescopes, trying to capture images of the first generation of stars right after they formed.

Recently, they got tantalizingly close when Ellis led an international team of astronomers as they discovered seven of the earliest galaxies ever seen—the first-ever census of such primitive galaxies. The observations offered a glimpse of the cosmic dawn, setting the stage for the next generation of telescopes to peer even deeper into this mysterious era of cosmic history. "It's exciting," he says. "We're very close now."

FILLING THE GAP

The universe is roughly 13.8 billion years old—a staggering number compared to our human timescales. But, remarkably, scientists have been able to sketch out its general history pretty well. The beginning of the dark ages, for instance, is marked by the omnipresence of the cosmic microwave background (CMB)—a microwave-frequency glow that provides a snapshot of the universe when it was 370,000 years old. Studying the CMB allows astronomers to piece together a blow-by-blow account of the early universe beyond that snapshot, down to the first fractions of a second after the Big Bang. There have been a variety of increasingly advanced experiments,



such as the balloon-borne BOOMERanG project, which was led by Caltech's late Andrew Lange at the turn of the century, as well as other Caltech-led balloon and Earth-based programs at the South Pole, and experiments on the Planck spacecraft (whose U.S. participation is based at JPL). Thanks to these efforts, astronomers have been able to probe the CMB and the baby universe with startling precision over the last couple of decades.

While such experiments are telling, telescopes offer the ability to actually peer back into different stages of cosmic history. The light that reaches astronomers' telescopes is an image from the past: the more distant a galaxy, the longer its light will have to travel; so the farther away the object, the more primitive it is. Bigger and better telescopes have allowed astronomers to chronicle periods of cosmic history deeper into the past—as far back in time as about 12.8 billion years ago. But, until recently, telescopes hadn't been able to reach much farther than that.

Between the window the CMB gives us into the earliest days of the universe and the telescopic record going back more than 12 billion years from today, however, there's a gap. And in that gap are the dark ages and the cosmic dawn. As Ellis says, "it's the last uncharted period of cosmic history."

Which isn't to say that nobody's tried to chart it, nor that they haven't had some success. In 2009, for instance, a team of astronomers led by Garth Illingworth of UC Santa Cruz and Rychard Bouwens of Leiden University pointed the Hubble Space Telescope at what's known as the Hubble Ultra Deep Field. Hubble had first observed this tiny patch of sky in the constellation Fornax—only about 1/50th the area of the moon as it appears in the sky—between 2003 and 2004. The astronomers had chosen that region because it lacked bright foreground stars and nearby galaxies, which would have overwhelmed the faint galaxies they wanted to study. During that original set of observations, which were made almost 10 years ago now, the astronomers had kept the telescope trained on that same region for 400 orbits—amounting to 11.3 days of total exposure time. Only with such a long exposure time could they hope to see the cosmic dawn.

What they found was an impressive initial haul of galaxies, containing a total of about 10,000 of the most distant galaxies ever seen—which meant they were some of the earliest ever detected. But astronomers weren't quite able to see back to the cosmic dawn. By the fall of 2009, however, astronauts had upgraded Hubble with the Wide-Field Camera 3 (WFC3); Ellis says its larger field of view, smaller pixels, and overall improvements made it 40 times more efficient at taking astronomical surveys than its predecessor. Using this new instrument, Illingworth and Bouwens's team was able to observe galaxies that were even more distant—including about three dozen from a time when the universe was just under 800 million years old. The astronomers were also able to pinpoint one galaxy that appeared to be from 480 million years after the Big Bang, making it the single most distant galaxy ever seen.

The astronomers were able to date these newly discovered, very distant galaxies by measuring their colors. Astronomers can determine the colors of galaxies using filters that block light at certain wavelengths. For instance, massive stars that quickly burn through their nuclear fuel are hotter, and therefore bluer, than others. Since they use up their fuel so fast, they die faster as well—after only a few hundred million years, compared to the lifespans of other stars that last billions of years. If you see a blue star, then, it must necessarily have been young—i.e., caught early in its lifespan—otherwise, it would already have died. Redder stars, which burn slower, will have lived longer and therefore must be older, caught later in their lifespans. Because the galaxies in the 2009 observations appeared blue, they were likely newborns. That the galaxies were also extremely distant led the scientists to ask whether they might be the long-sought first-generation galaxies of the cosmic dawn.

PUSHING THE FRONTIER

To see if this was truly the case—and to see if they could reach even further back in time—Ellis and his colleagues pointed Hubble at the same area once again in 2012, taking more exposures over the course of two months and thus gathering an additional 128 orbits of data. They used an additional filter to better narrow down the colors—and therefore the ages—of the galaxies.

The team also used a "drop-out" filter technique to confirm that the distant galaxies were indeed extremely far away. The neutral hydrogen gas that permeated the early universe absorbed any light that was bluer than a wavelength of 121.6 nanometers. Because the expansion of the universe stretches the wavelength of light, the more distant a galaxy is, the more its light's wavelength gets shifted—a phenomenon known as the cosmological redshift.

To measure this shift, the astronomers use different filters to observe each galaxy at shorter and shorter wavelengths until the galaxy is no longer visible—because the hydrogen around it has completely absorbed its light. At that point, the galaxy is said to have "dropped out." The wavelength at which a galaxy drops out tells the astronomers how much its light has redshifted, which tells them how far away it is. Caltech's Lee A. DuBridge Professor of Astronomy Chuck Steidel was the first to demonstrate this technique on a large sample of galaxies at the Palomar and Keck Observatories.

The results of the 2012 observations, Ellis says, were a breakthrough. The team doubled the 2009 number of known galaxies that existed less than 800 million years after the Big Bang—there are now a total of 74 such galaxies. More importantly, he says, the team found seven new galaxies that date from just 500 million years after the Big Bang. With the better data, the 480-million-year-old galaxy that had been previously identified as the most distant galaxy ever spotted now looks as if it came into being when the universe was a mere 380 million years old. (At least for now, says Ellis. Because this galaxy is especially faint, the astronomers aren't as confident about its age; in the future, more

Above: A timeline of the history of the universe, with the numbers denoting billions of years. The location of Hubble 2012 and Hubble 2009 represents the era targeted by the Hubble Ultra Deep Field in 2012 and 2009.

Above: Richard Ellis (left) and Matthew Schenker are leading the way to find the very first galaxies.

powerful telescopes may help them pin it down for sure.)

These observations—and, in particular, the sighting of the seven galaxies dating back to no more than 500 million years after the Big Bang—are as close to the cosmic dawn as anyone has ever gotten. "It's truly amazing that we can look this far back," Ellis says.

What's even more surprising (and slightly disappointing), he adds, is that the galaxies his team found in 2012 aren't as blue as those measured in the 2009 observations. This means they are older, containing stars that had already been shining for 100 million to 200 million years. "These galaxies are not, sadly, the very earliest galaxies," he says. What's less sad is that the findings suggest astronomers are close to finally capturing the earliest galaxies. And they tell us that the cosmic dawn must have happened earlier than we thought—perhaps as early as 200 million years after the Big Bang.

Unfortunately, that's a time beyond the reach of today's telescopes. With the 2012 observations, Ellis and his team pushed Hubble to its limits. To finally capture the cosmic dawn will require the next generation of telescopes: the James Webb Space Telescope (JWST), which is slated for launch in 2018, or the Thirty Meter Telescope (TMT) in Hawaii, scheduled to start observations by 2022. But the current data already hint at what these higher-tech scopes might see—and possibly provide a rich hunting ground for finding even earlier galaxies.

For instance, the 2012 observations show a steady decline in the number of galaxies the further back in time you go. That means the birth of the first stars and galaxies must have been a gradual process—not a single dramatic event that suddenly flooded the cosmos with light. The future telescopes should be able to track this entire transition.

Astronomers also expect JWST and TMT to help solve a related mystery about a cosmic event called reionization. When hydrogen first formed after the Big Bang, it was ionized, i.e., missing an electron. As the universe expanded and cooled, the hydrogen nuclei joined up with their lost electrons to form the so-called neutral hydrogen gas that blanketed the universe during the dark ages. It was only when that gas became ionized (or *re*ionized, since the hydrogen was initially in an ionized form) that the fog of the dark ages lifted. Today, almost all of the hydrogen gas in the universe is ionized. According to scientists' observations of the CMB, this ionization happened sometime after the cosmic dawn, as more and more galaxies began to populate the universe.

The question is, how did all that hydrogen become reionized in the first place? The process would have required a flood of ultraviolet light, which many astronomers think simply radiated from the growing number of galaxies that characterized the cosmic dawn. But were there enough galaxies to do the job?

The data from the Hubble Ultra Deep Field seem to say that there weren't enough galaxies—not at all. But there's a catch: the galaxies sighted in 2012 are among the biggest and brightest ever seen. And yet it was the faintest of those bright galaxies—the ones at the very limits of Hubble's galaxy-finding abilities—that appeared to be most numerous. That could mean that there's a large population of small, dim galaxies out there that Hubble just can't see. According to Ellis and his colleagues, there should have been enough of these feeble galaxies—as they call them—to have reionized all the hydrogen gas in the universe.

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If future telescopes fail to find these feeble galaxies, Ellis says, astronomers will then have to consider more exotic sources of ultraviolet light—such as massive black holes that produce high-energy radiation as they gobble up gas and dust. But for now, he says, "galaxies are the best bet."

BEYOND THE HUBBLE

To study this epoch of reionization more closely and pinpoint exactly when the universe emerged from its dark ages, Matthew Schenker, a graduate student at Caltech working with Ellis, has been using the Keck observatory in Hawaii and, more specifically, its multi-object spectrometer for infrared exploration, or MOSFIRE—a state-of-the-art instrument built by Caltech's Chuck Steidel and instrument expert Keith Matthews along with a team from UCLA. Together, Schenker and Ellis have been measuring a specific wavelength of light from galaxies, called the Lyman-alpha emission line, which corresponds to the wavelength of light that's absorbed by neutral hydrogen—the same 121.6-nanometer feature used to determine galactic distances in the drop-out filter technique.

Reionization and the end of the dark ages go hand in hand, it turns out. This is because the dark ages were characterized by the presence of that neutral, nonionized hydrogen gas. Once ultraviolet light appeared on the scene, the hydrogen became ionized again (which made it transparent to—or unable to absorb—ultraviolet light), more photons were able to light up the universe, and the dark ages were no more.

And so, by measuring how readily the 121.6-nanometer light was absorbed by neutral hydrogen over the course of cosmic history, Schenker and Ellis are able to gauge how the amount of neutral hydrogen waned over time, and thus witness—in a sense—the ushering out of the dark ages. What they've found so far is that at around 1 billion years after the Big Bang, the emission line, which had appeared in 50 percent of the galaxies previously, dropped to only 10 percent—a sudden decline that marks the end of the dark ages.

In addition to Hubble and Keck, Ellis and his colleagues are also using the Spitzer Space Telescope to probe the cosmic dawn. While Hubble is good at detecting those younger, bluer stars, Spitzer—which observes in longer, redder wavelengths—is good at detecting the relatively older stars. Old stars are important because they reveal the past rate of star formation, which is how much "star stuff"—the combined mass of stars—has been produced over time. For example, if you see a bunch of stars that are 200 million years old and collectively weigh as much as a billion suns, then that means the equivalent of a billion suns is formed over the course of 200 million years, a rate of five suns per year (by comparison, the Milky Way is forming stars at a rate less than one sun per year).

And while Hubble has already been pushed to its limits, Ellis says, Spitzer has not. The astronomers have applied for telescope time to point Spitzer at the Hubble Ultra Deep Field soon to gather data on older stars and complement the census of younger stars taken during the 2012 Hubble observations.

In addition, astronomers working at the Atacama Large Millimeter/submillimeter Array (ALMA), an array of dishes in Chile that began operation in 2011, will conduct their own survey to find the first stars and galaxies. Because the first-generation galaxies are so distant, their light has been stretched to millimeter and submillimeter wavelengths, making them prime targets for ALMA.

Still, despite the promising data that ALMA and Spitzer may soon yield, astronomers will have to wait until the next generation of telescopes before they can completely explore the dark ages and the cosmic dawn. They'll look for the first stars with JWST and TMT and try to map the neutral hydrogen throughout the dark ages with radio telescopes such as the Square Kilometre Array—an arrangement of radio dishes to be built in South Africa and Australia that won't start observations until after 2021—and the Owens Valley Long Wavelength Array in eastern California. These radio telescopes will be used to try to reveal how clouds of gas in the infant universe clumped together to form the very first stars. And then, hopefully, astronomers will finally be able to answer some of the most profound questions about cosmic history. After all, Ellis says, "finding the very first objects is, in essence, exploring our very origins." E&S

Richard Ellis is the Steele Family Professor of Astronomy. *This work is funded by the Space Telescope Science Institute.*