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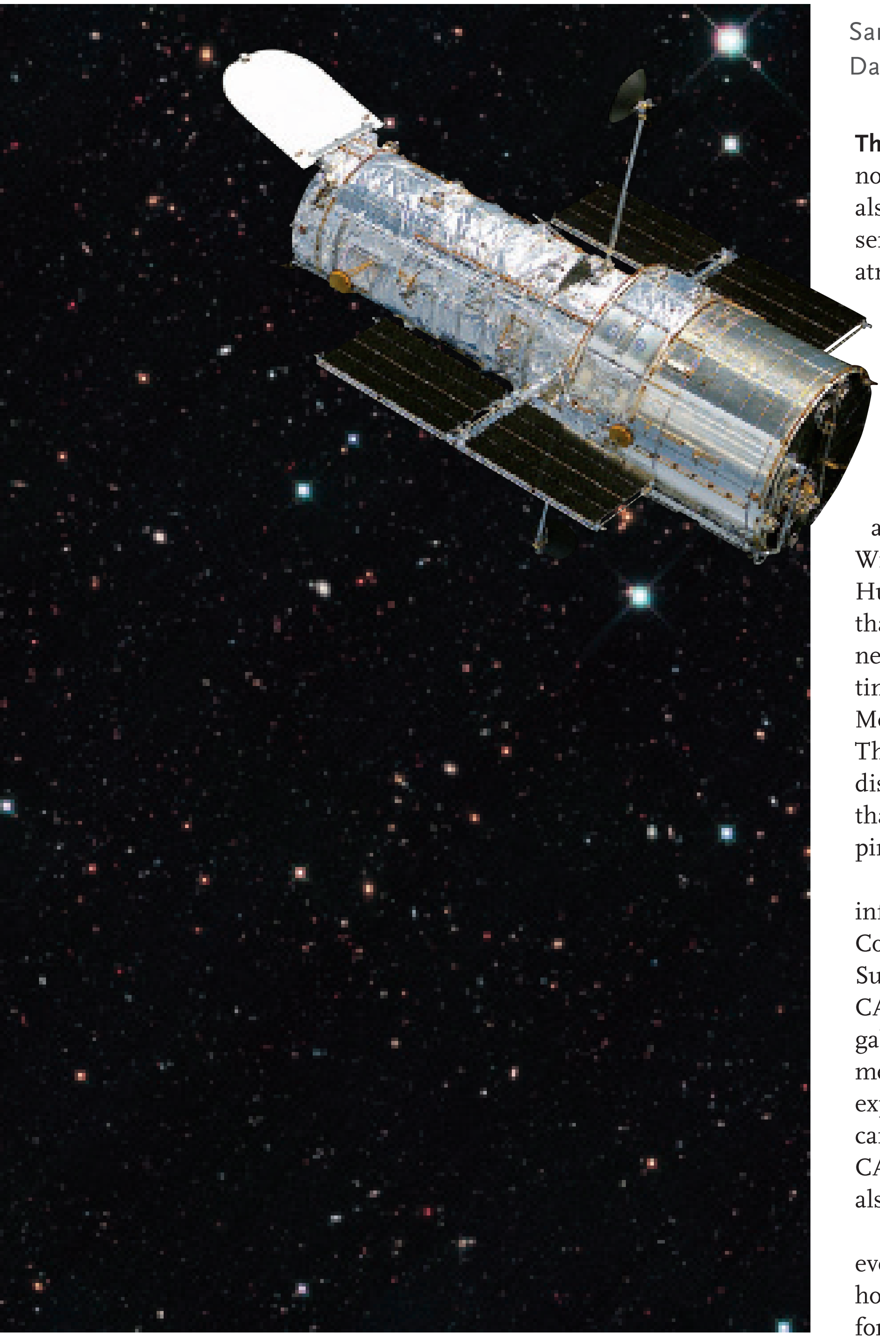
Staring Back to

Hubble's single largest observing program is detecting the earliest galaxies, finding the most distant

COSMIC SURVEY As part of the CANDELS survey, the Hubble Space Telescope scanned a small patch of Cetus for a total of 61 hours. The 61 hours were divided among 352 separate exposures spread across a mosaic of 44 different telescope pointings. The picture reveals a few foreground stars in our galaxy, and thousands of galaxies ranging from the local universe to a time when the universe was less than 1 billion years old.

Cosmic Dawn

supernovae, and revealing the fireworks-like peak of star formation at cosmic high noon.



NASA / ESA / A. VAN DER WEL / H. FERGUSON / A. KOEKEMOER / CANDELS TEAM

Sandra M. Faber, Henry C. Ferguson,
David C. Koo, Joel R. Primack & Trudy E. Bell

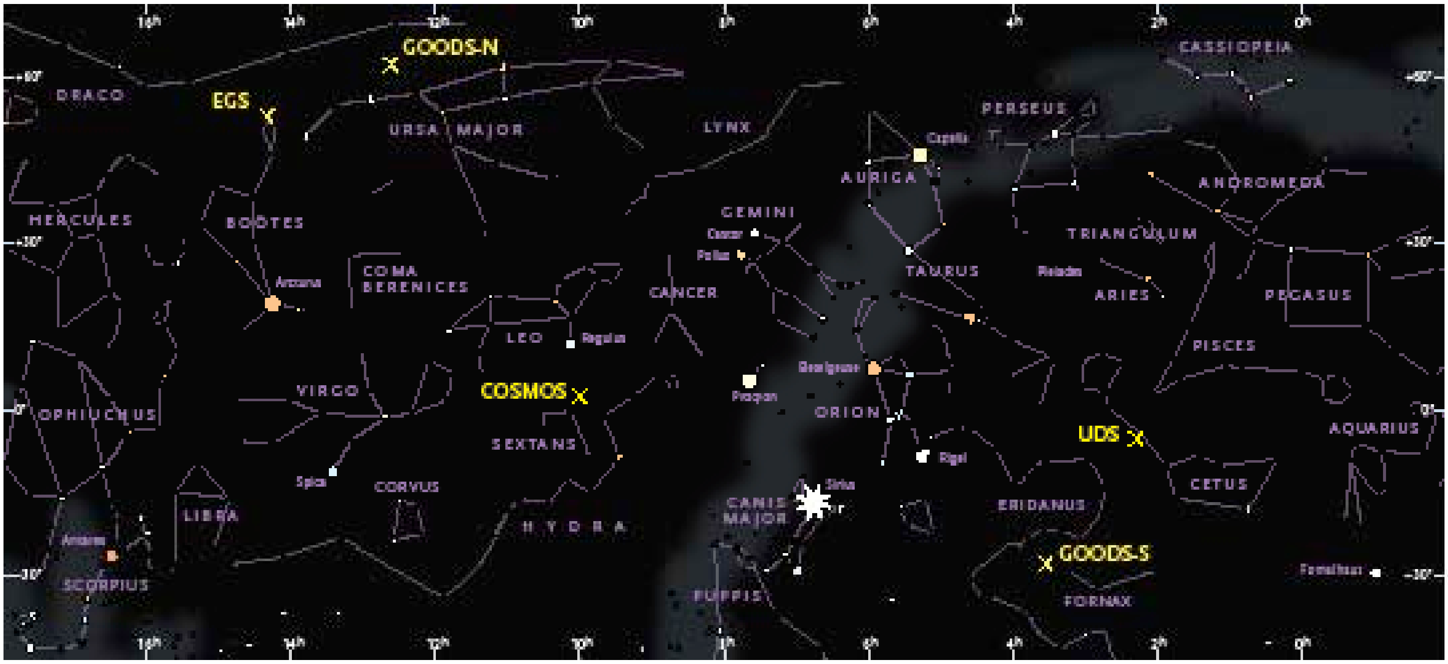
The Hubble Space Telescope is a time machine, staring not only billions of light-years into the depths of space but also billions of years back in time. With its extraordinarily sensitive detectors above Earth's shrouding and blurring atmosphere, HST can witness the peak of star formation at cosmic high noon, which ended about 5 billion years after the Big Bang. And at the outer limits of its capabilities, we wondered if it could detect the faintest candles of creation: the earliest galaxies made of the earliest stars at cosmic dawn, when the universe was less than a billion years old.

Those were the hopes of two of us authors (Faber and Ferguson) after NASA astronauts installed HST's Wide-Field Camera 3 (WFC3) in 2009, which enabled Hubble to survey the infrared sky about 30 times faster than before. Within a few months, Hubble pointed the new camera at the Hubble Ultra-Deep Field (HUDF) — a tiny region in Fornax only a tenth the diameter of the full Moon — and took exposures totaling about three days. Those deep HUDF images revealed some of the most distant galaxies ever found, which look very different than nearby galaxies. But the HUDF represented just a pinprick poke at the universe.

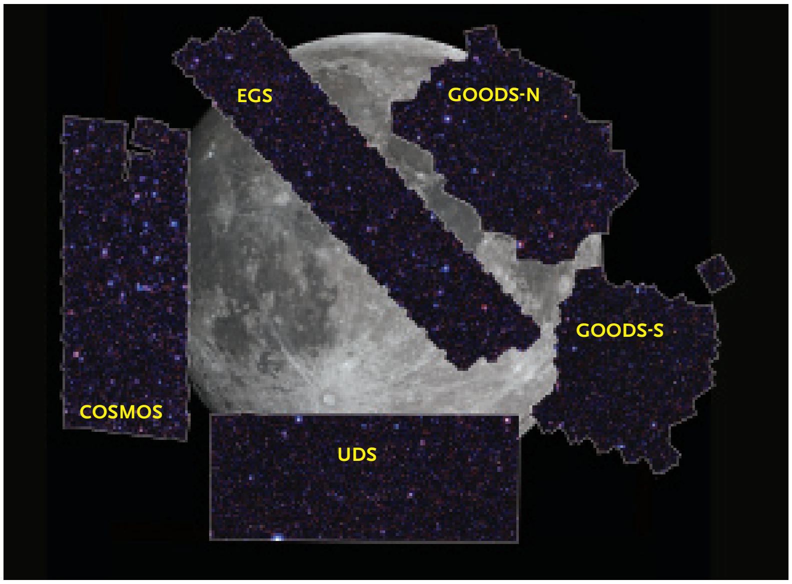
So we began an ambitious program at visible and near-infrared wavelengths as a natural successor to HUDF: the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS), pronounced "candles." We designed CANDELS primarily to document the first one-third of galaxy evolution. The program also would enable astronomers to search for the most distant Type Ia supernovae — exploding white dwarfs that are the best-known standard candles for measuring the universe's recent expansion rate. CANDELS could thus test whether Type Ia supernovae are also a valid yardstick for the early universe.

CANDELS became the largest observing program ever undertaken by Hubble. The telescope devoted 600 hours — fully 10% of its observing time — to CANDELS for three years, surveying an area of sky 60 times larger

To view more images related to this article, visit skypub.com/CANDELS.



S&T: GREGG DINDERMAN; SOURCE: CANDELS TEAM



CANDELS TEAM; MOON PHOTO: S&T: DENNIS DI CICCO

CANDELS FIELDS The CANDELS survey targeted five different fields at various depths and wavelength coverage. Even though the combined fields cover only about the area of the full Moon, they provide representative samples of the deep universe.

than the HUDF, albeit to brighter limiting magnitudes (about 27 for CANDELS compared to 30 for the HUDF). CANDELS targeted five patches of the northern and southern skies, each about one-fourth the angular size of the Orion Nebula (M42). Each patch has been well studied from radio to X rays, giving plenty of complementary data across the electromagnetic spectrum.

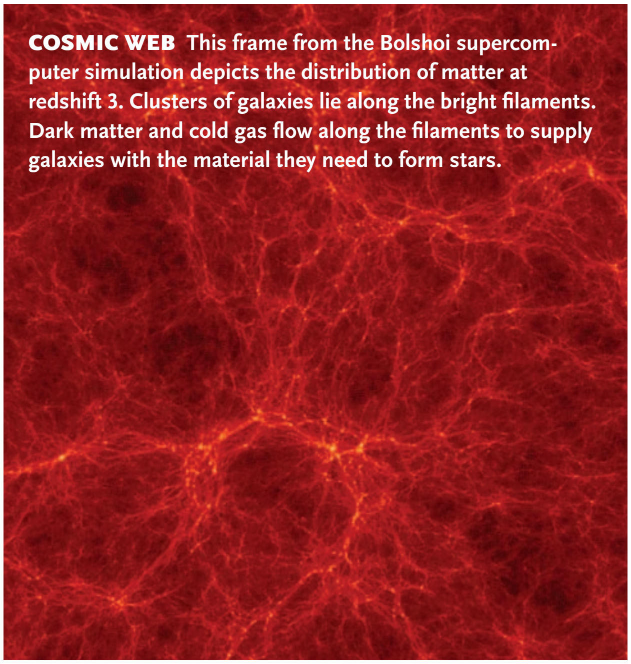
Because remote galaxies are so faint, the five target areas were away from our Milky Way's star-studded plane. Much as pollsters and medical researchers learn about the human population as a whole by studying carefully selected samples of a small number of individuals, we chose the five target areas because they're physically representative of the universe at large.

Depending on the field, CANDELS took multiple images with exposure times ranging from 40 minutes to roughly 3 hours through each of two or three infrared filters. Although CANDELS surveyed a total area only about that of the full Moon, the long exposures looked so deep into the cosmos that they recorded roughly a quarter-million ancient galaxies in enough detail to reveal their sizes, shapes, and even gross internal structures. Such a rich treasure trove provides powerful new data for statistical studies of galaxy growth and evolution.

Astrophysicists will continue to analyze the wealth of observations for years to come. The data have already led to new findings and mysteries about the early universe.

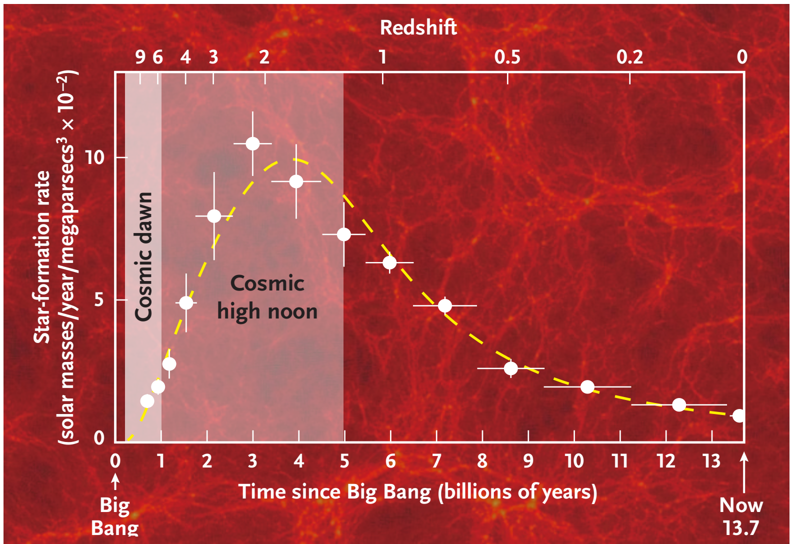
Red, Blue, and "Green" Galaxies

In the nearby and moderately distant universe, most galaxies tend to be red or blue. Red galaxies are commonly elliptical and relatively featureless, and they stopped forming stars more than a billion years ago. Most of their light is emitted by red giants near the end of their lives, and they have little or no cold gas from which new stars can form. An example is M87, the biggest galaxy in the Virgo Cluster. In contrast, blue galaxies commonly have flat disks and spiral arms possessing lots of cold gas and stars of different ages. A small fraction of newborn stars are short-lived blue supergiants, which are so luminous that star-forming regions appear blue. A nearby example is the beautiful Whirlpool Galaxy (M51) in Canes Venatici.



COSMIC WEB This frame from the Bolshoi supercomputer simulation depicts the distribution of matter at redshift 3. Clusters of galaxies lie along the bright filaments. Dark matter and cold gas flow along the filaments to supply galaxies with the material they need to form stars.

ANATOLY KLYPIN / STEFAN GOTTLÖBER



STARBIRTH RATE Using data from many surveys, including CANDELS, astronomers have plotted the rate of star formation through cosmic history. The rate climbed rapidly at cosmic dawn and peaked at cosmic high noon.

S&T: GREGG DINDERMAN; SOURCE: KENNETH DUNCAN (UNIVERSITY OF NOTTINGHAM) / CANDELS, ET AL.

At the present day, only a few galaxies lie between the peaks of the blue and red galaxies, in the so-called "green valley" (so named because green wavelengths are midway between red and blue in the spectrum). A blue galaxy that is vigorously forming stars will become green within a few hundred million years if star formation is suddenly quenched. On the other hand, a galaxy that has lots of old stars and a few young ones can also be green just through the combination of the blue colors of its young stars and the red colors of the old ones. The Milky Way probably falls in this latter category, but the many elliptical galaxies around us today probably made the transition from blue to red via a rapid quenching of star formation. CANDELS lets us look back at this history.

Most galaxies of interest to astronomers working on CANDELS have a look-back time of at least 10 billion years, when the universe was only a few billion years old. Because the most distant galaxies were relatively young at the time we observe them, we thought few of them would have shut off star formation. So we expected that red galaxies would be rare in the early universe. But an important surprise from CANDELS is that red galaxies with the same elliptical shapes as nearby red galaxies were already common only 3 billion years after the Big Bang — right in the middle of cosmic high noon.

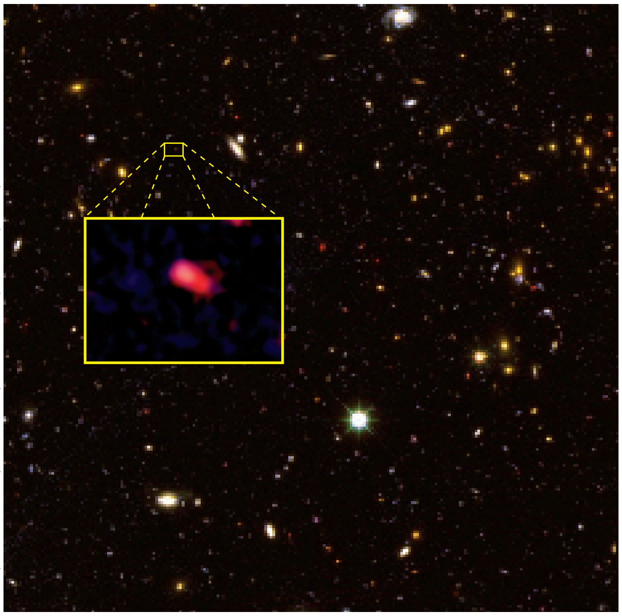
Puzzlingly, however, elliptical galaxies from only about 3 billion years after the Big Bang are only one-third the size of typical elliptical galaxies with the same stellar mass today. Clearly, elliptical galaxies in the early universe must have subsequently grown in a way that increased their sizes without greatly increasing the number of stars or redistributing the stars in a way that would change their shapes. Many astronomers suspect that the present-day red ellipticals with old stars grew in size by "dry" mergers — mergers between galaxies having older red stars but precious little star-forming cold gas. But the jury is still out on whether this mechanism works in detail to explain the observations.

The Case of the Chaotic Blue Galaxies

Ever since Hubble's first spectacular images of distant galaxies, an enduring puzzle has been why early star-forming galaxies look much more irregular and jumbled than nearby blue galaxies. Nearby blue galaxies are relatively smooth. The most beautiful ones are elegant "grand-design" spirals with lanes of stars and gas, such as M51. Smaller, irregular dwarf galaxies are also often blue.

But at cosmic high noon, when stars were blazing into existence at peak rates, many galaxies look distorted or misshapen, as if galaxies of similar size are colliding. Even the calmer-looking galaxies are often clumpy and irregular. Instead of having smooth disks or spiral arms, early galaxies are dotted with bright blue clumps of very active star formation. Some of these clumps are over 100 times more luminous than the Tarantula Nebula in the Large Magellanic Cloud, one of the biggest star-forming regions in the nearby universe. How did the chaotic, disordered galaxies from earlier epochs evolve to become the familiar present-day spiral and elliptical galaxies?

Because early galaxies appear highly distorted, astrophysicists had hypothesized that major mergers — that is, collisions of galaxies of roughly equal mass — played an important role in the evolution of many galaxies. Mergers can redistribute the stars, turning two disk galaxies into a single elliptical galaxy. A merger can also drive gas toward a galaxy's center, where it can funnel into a black



V. TILVI / S. FINKELSTEIN / C. PAPOVICH / A. KOEKEMOER / CANDELS / STSCI / NASA

RECORD HOLDER Astronomers discovered the earliest known galaxy (*inset*), as of March 2014, in this CANDELS frame. Using the 10-meter Keck 1 telescope, the team spectroscopically measured a redshift of 7.51, meaning we see the galaxy as it existed just 700 million years after the Big Bang. The galaxy, designated z8_GND_5296, appears red due to its extreme redshift. It's forming stars at a rate about 100 times greater than our Milky Way.

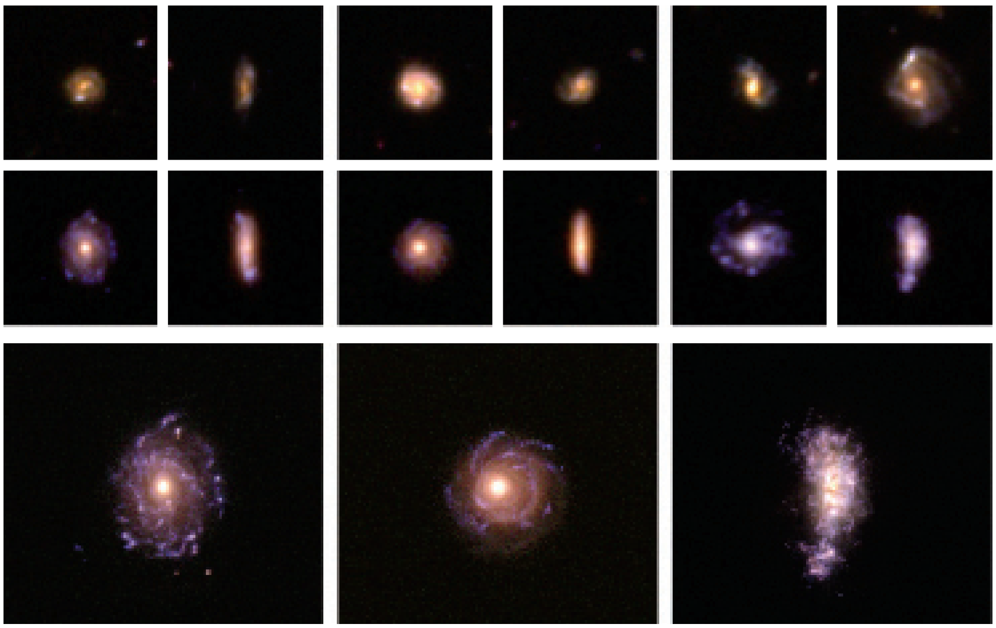
hole, building up its mass and triggering a huge outflow of energy that can heat or eject any remaining gas, thus quenching further star formation. Mergers, then, seemed to explain why elliptical galaxies look like they do and why they stopped forming stars.

But CANDELS revealed that major mergers appear to be less important in galaxy evolution than we had thought. Instead, when combined with supercomputer simulations, the CANDELS observations are beginning to tell a very different story. After the Big Bang, the universe was a nearly uniform sea of dark matter and of gaseous hydrogen and helium. But it wasn't perfectly uniform. As the universe expanded, the denser regions of dark matter and gas expanded more slowly, held back by their own gravity. Eventually, the gas and dark matter in denser regions collapsed into smaller structures: first sheets and filaments known as the "cosmic web," and then into denser blobs of gas and dark matter at the intersections of dark matter filaments. These structures later collapsed to form the seeds of galaxies.

More cold gas flowed along the dark matter filaments into galactic disks, where it became gravitationally unstable and formed clumps. Nearby galaxies have comparatively little gas, so star-forming clumps of gas generally won't grow beyond about a million solar masses. But in early galaxies, the gravity of the much more abundant gas formed gigantic clumps — up to about a billion solar masses — and rapidly formed stars. Then fairly quickly — in only a few hundred million years according to computer simulations — the clumps migrated inward and merged into the central bulge. The CANDELS observations support this theoretical picture: most of the giant clumps in ancient galaxies are young, with older clumps tending to lie closer to galaxy centers. This process presumably fueled quasar activity and led to the rapid growth of supermassive black holes.

Cosmic Dawn

We sought to identify hundreds of primordial galaxies at cosmic dawn, when the universe was only 500 million to 2 billion years old and the first stars were igniting



CANDELS TEAM (15)

CLUMPY GALAXIES *Top row:* Six galaxies from CANDELS are seen when the universe was 4 to 6 billion years old. *Middle row:* These computer simulation frames show three disk galaxies as if imaged by CANDELS when viewed roughly face-on (*left of pair*) and edge-on (*right*). *Bottom row:* This is how these galaxies would appear if we could see them closer up from one angle. All three are about 4 billion years old and have large clumps of rapidly forming stars ignited by instabilities in their disks.

in the first galaxies. We wanted to see enough detail to reveal the galaxies' sizes, shapes, and star-formation rates. Giant 8- to 10-meter ground-based telescopes are already spectroscopically measuring precise redshifts (distances) and helping to nail down the masses of the brightest of these galaxies. Prospects will be even more exciting once 20- to 30-meter behemoths become available next decade, complementing the data we'll be getting from NASA's James Webb Space Telescope.

CANDELS has produced the largest sample of candidate galaxies that formed within the first 1 billion years of the universe's existence. As of March 2014, the spectroscopic record-holder is a galaxy at a redshift of 7.51, corresponding to a time just 700 million years after the Big Bang. Despite being less than a tenth the mass of our Milky Way, this diminutive galaxy is churning out stars at a rate about 100 times higher.

Combined with data from the HUDF and a few other surveys, the CANDELS observations have given us a much more detailed view of the first billion years of galaxy formation. The overall star-formation rate in the universe 500 million years after the Big Bang was about the same as it is today. The fireworks came later, reaching a peak when the universe was 3 to 4 billion years old, with a rate about 10 times higher. But the galaxies we see at cosmic dawn were tiny — about 10% the diameter of our Milky Way — so they packed a lot of star formation into a much smaller volume.

CANDELS is also helping to solve a big mystery about the rarefied gas between galaxies. Most of this gas in the nearby universe is ionized — that is, the electrons of most of the hydrogen atoms are stripped from their protons. As a result, the intergalactic medium is utterly transparent to ultraviolet light for billions of light-years. But observations of the cosmic microwave background and of light from the most distant quasars show that in the early universe — roughly from about 400,000 years to 1 billion years after the Big Bang — the intergalactic medium was mostly neutral (that is, in atomic form). If you existed then and had eyes sensitive to ultraviolet light, the universe would have been filled with a gray fog!

Clearly something big must have happened. Neutral hydrogen can be ionized by absorbing ultraviolet light — but reionizing most of the atoms throughout the entire intergalactic medium a billion years after the Big Bang would have required a phenomenal influx of ultraviolet radiation. What could have produced so much UV energy? Evidence from CANDELS and other recent observations suggest that the earliest galaxies alone — not some other exotic explanation, such as the decay of dark matter — were responsible for such widespread reionization of the universe because their early stars were particularly massive, energetic, and blue. Such stars produce UV light in prodigious quantities.

CANDELS' Standard Candles

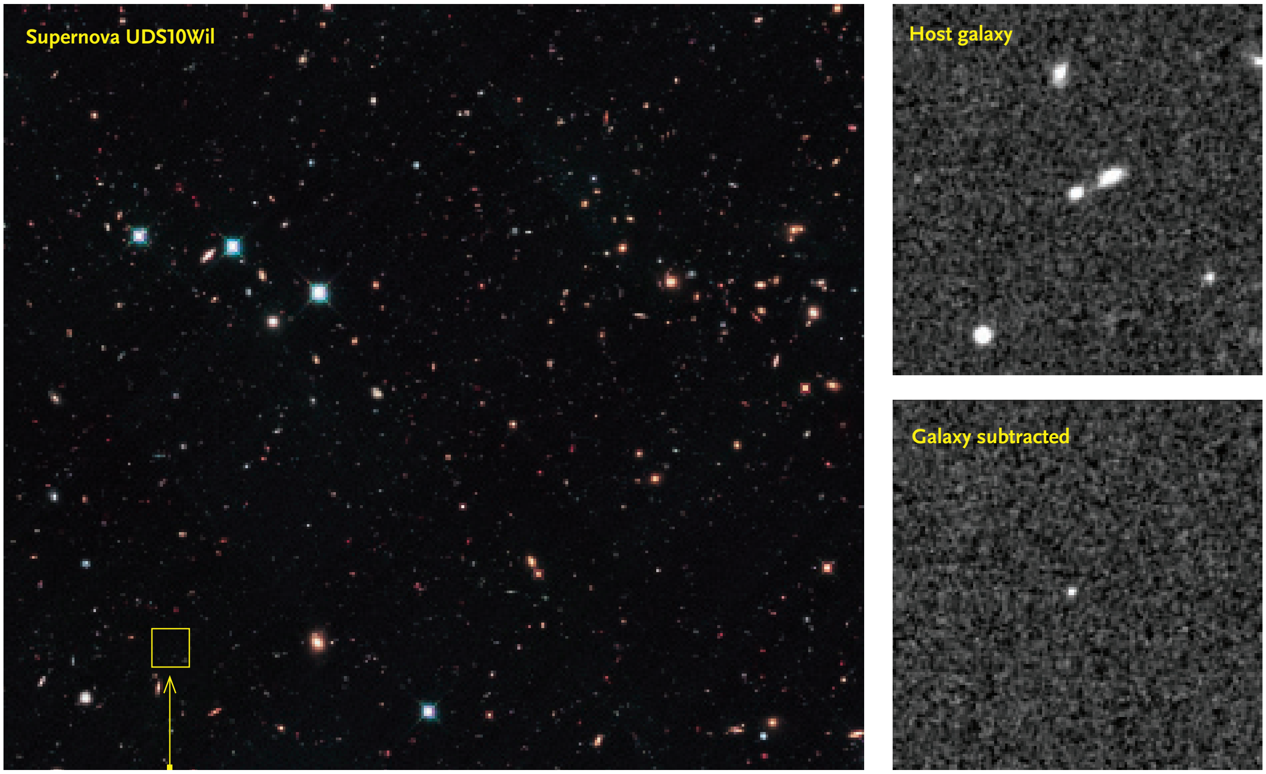
Instead of acquiring a single long time exposure of each tiny target patch of sky, the CANDELS survey typically took two or more exposures about 60 days apart. For studying galaxies, the two exposures were stacked (combined) on a computer to create a longer exposure that revealed more detail. But subtracting one image from the other enables astronomers to see anything that changed. Specifically, we were looking for distant Type Ia supernovae, from exploding white dwarfs.

Type Ia supernovae are remarkably useful because their brightness is correlated with the supernova's color and fade time. Because we can measure a Type Ia supernova's absolute brightness, its apparent brightness depends on its distance. Thus, Type Ia supernovae have become a powerful tool allowing astronomers to determine the universe's expansion history.

NASA / ESA / HUBBLE HERITAGE TEAM (STSCI/AURA)

NASA / ESA / S. BECKWITH / HUBBLE HERITAGE TEAM (STSCI/AURA) (2)

RED AND BLUE GALAXY **The elliptical galaxy M87 (*left*) and the spiral galaxy M51 (*right*) are classic nearby examples of red and blue galaxies, respectively. Despite M87's enormous size, it's devoid of gas and has thus stopped forming new stars. Its light is dominated by old, reddish stars. In contrast, the spiral arms of M51 are ablaze with the brilliant blue light of newborn hot stars.**



NASA / ESA / A. RIESS / D. JONES / S. RODNEY (3)

DISTANT SUPERNOVA *Left:* Astronomers spotted the most distant supernova ever detected in this CANDELS field. *Top right:* Zooming into the boxed region reveals the host galaxy. *Above right:* A Type Ia supernova is seen once the host galaxy is subtracted. The supernova occurred at a redshift of 1.9, meaning the explosion took place 3.5 billion years after the Big Bang. Studying such distant supernovae will help astronomers determine the universe's expansion history, providing clues to the nature of dark energy.

Major surveys before CANDELS revealed that cosmic expansion was decelerating until about 5 billion years ago. But measurements of Type Ia supernovae convinced astronomers in 1998 that cosmic expansion has been accelerating ever since, research that led to the 2011 Nobel Prize in physics. Astronomers hope that studying Type Ia supernovae identified by CANDELS at various distances will reveal more about the details of this transition from decelerating to accelerating expansion, and thus yield precious information about the nature of the enigmatic dark energy responsible for the acceleration.

But to improve the precision of such cosmological measurements, astronomers need to understand Type Ia supernovae better. For example, do they come from a single exploding white dwarf, or from merging white dwarfs? Scientists also need to see if there is a systematic trend in supernova luminosity that correlates with cosmic age. After all, early stars were poorer in elements heavier than helium. Moreover, the typical white dwarf in the early universe was more massive than a typical white dwarf today because in the early universe only the most massive, fast-burning stars had enough time to evolve into white dwarfs. CANDELS can detect supernovae when the universe was only 3 billion years old, so astronomers can test for such trends.

Stay Tuned!

The proposers of a Hubble observation normally have sole access to the data for a year. But the CANDELS raw images were made public within hours of being downlinked, and the CANDELS team has been providing carefully calibrated images to the astronomical community within a few months of the observations. The team includes more than 150 collaborators from 45 different institutions in 12 countries. Nevertheless, roughly a third of the papers published so far using the CANDELS data have come from outside the team. The pace of discovery shows the power of combining data from across the spectrum, and having observers work with theorists and computer models. Watch for new findings during the years to come! ✦

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