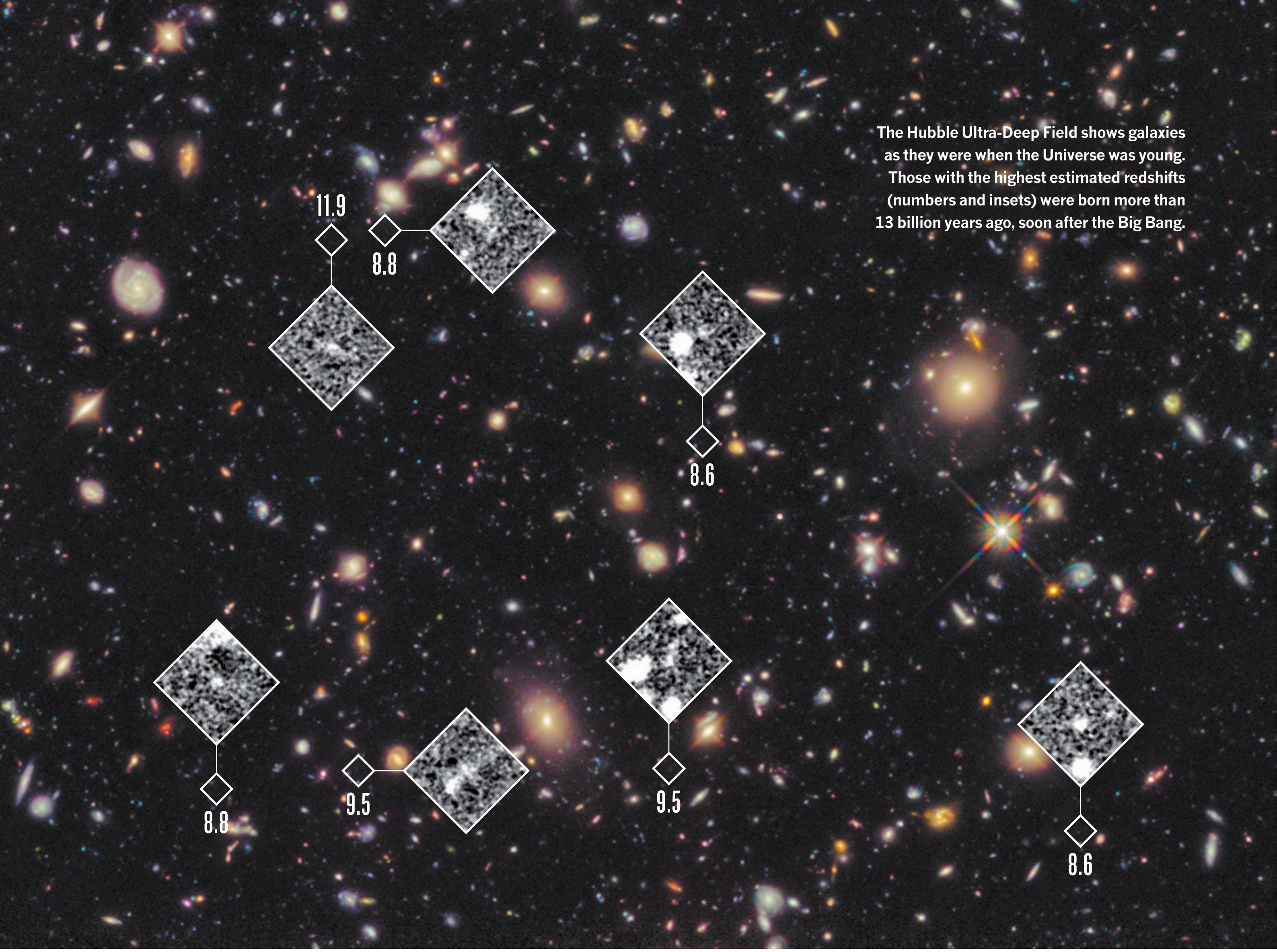

The Hubble Ultra-Deep Field shows galaxies as they were when the Universe was young. Those with the highest estimated redshifts (numbers and insets) were born more than 13 billion years ago, soon after the Big Bang.

COSMIC DAWN

The Hubble Space Telescope is giving astronomers a glimpse of the Universe's first, tumultuous era of galaxy formation.

BY RON COWEN

For one sleepless week in early September 2009, Garth Illingworth and his team had the early Universe all to themselves. At NASA's request, Illingworth, Rychard Bouwens and Pascal Oesch had just spent the previous week staring into their computer screens at the University of California, Santa Cruz, scanning through hundreds of black-and-white portraits of faint galaxies recorded in a multi-day time exposure by a newly installed infrared camera on the Hubble Space Telescope. NASA simply wanted the three astronomers to preview the images and make sure that the camera was working correctly, before the agency released the data more widely.

But Illingworth, Bouwens and Oesch were hoping that they would find more — that at least some of those smudges of light would prove to be among the first galaxies to form in the Universe, less than 1 billion years after the Big Bang. Even a faint glimpse of such objects could provide fresh insights into some of the biggest questions in cosmology, ranging from the nature of the first stars to the tumultuous beginnings of galaxy formation.

That week, the astronomers began to focus on two dozen tiny candidate images — each so dim and grainy that they might easily be noise in the camera's digital sensors. But as their analysis proceeded, it became clear that these patches of light had the right colour, appearing only in the camera's reddest filters — exactly what would be expected of newborn galaxies seen at a very great distance and very high redshift. And

NASA, ESA, R. ELLIS (CALTECH), UDF 2012 TEAM

when the three colleagues started digitally adding together exposures of each candidate, says Illingworth, "suddenly there they were" — fuzzy, but undeniable images of galaxies. "That week in September was one of the most exciting times of my career!"

By the week's end, he, Bouwens and Oesch had posted two draft papers to the arXiv preprint server[1,2], detailing their first-ever collection of more than 20 galaxies from the age of galaxy formation, some 13 billion years ago, when the cosmos was only 600 million to 800 million years old. Since then, other researchers have made further observations of the same small patch of sky, known as the Hubble Ultra-Deep Field (HUDF), and four other larger regions. They have expanded that initial roster to some 1,400 young galaxies, from the same era.

The data from this growing catalogue are already hinting at a still-unseen time — an infant Universe thronged with countless small galaxies and lit by primordial stars so massive that they burned out and blew up in a cosmic eye-blink. And a new generation of instruments promises to bring that era into clear view. They include the Atacama Large Millimeter/submillimeter Array (ALMA) of radio telescopes in Chile, which is already beginning such observations; and Hubble's successor, the infrared James Webb Space Telescope (JWST), which is set for launch in late 2018.

It's a heady time for early-Universe astronomers, says cosmologist Avi Loeb of Harvard University in Cambridge, Massachusetts. "We're looking at our origins," he says. "The first galaxies were the building blocks of the Milky Way, and the desire to understand them is a search for our roots."

DEEP BACKGROUND

Over the past few decades, observers have developed a general storyline describing how galaxies formed (see 'Dawn's early light'). Astronomers know, for example, that the raw material was a hot, ionized plasma of hydrogen and helium that emerged from the Big Bang, then rapidly cooled as the Universe expanded. Once its temperature had fallen far enough, about 370,000 years after the Big Bang, protons and electrons combined to make neutral atoms and created a light-absorbing haze that plunged the Universe into a cosmic 'dark ages'.

Astronomers also know that this cosmic haze was almost perfectly uniform at the start — but immediately began to clump together as gravity began to magnify slight fluctuations in the material's density. And they are reasonably sure that, after several hundred million years, the densest of the growing clumps began to form the first stars, which ignited by thermonuclear fusion and reionized the neutral gas that remained. The veil of gas became a transparent plasma again, bringing the cosmic dark ages to a spectacular end (see *Nature* **490,** 24–27; 2012).

"SUDDENLY THERE THEY WERE — FUZZY, BUT UNDENIABLE IMAGES OF GALAXIES."

But from this point onwards, very little is certain. The formation of succeeding generations of stars and galaxies was a swirling chaos of heating and cooling gas clouds, detonating supernovae, black-hole accretion and fierce stellar winds strong enough to eject matter from small galaxies — a process far too messy and complex to understand without extensive observations.

Such observations are a major goal of the HUDF project, which aims to gather enough images of distant galaxies to discern patterns in their sizes, shapes and colours. Located south of Orion in the constellation Fornax, and measuring just one-tenth of the diameter of the full Moon as seen from the ground, the HUDF is an otherwise typical patch of dark sky that happens to be relatively devoid of foreground stars and galaxies. But just as astronomers expected, an 11.3-day time exposure of the field taken by Hubble in late 2003 and early 2004 revealed that it was, in fact, filled with a multitude of faraway galaxies seen as they were billions of years ago.

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In August and September 2009, the field was re-examined in an additional two-day exposure taken by Hubble's Wide Field Camera 3 (WFC3): an instrument installed by astronauts the previous May that is exquisitely sensitive at infrared wavelengths — exactly where visible and ultraviolet light from the farthest galaxies is expected to end up after being redshifted by the cosmic expansion.

These were the images that Illingworth, Bouwens and Oesch saw. Knowing that the WFC3 could detect distant galaxies about 30 times fainter than its predecessor could, or about 4 billion times fainter than anything visible to the human eye, the astronomers initially thought that they might have caught one of the very first generations of galaxies in the act of being born. When they estimated the objects' distance and composition by examining their colours in three different filters — the faint smudges were far too dim for Hubble to get a spectrum — the team found that they were relatively blue, exactly as expected of extremely young galaxies glimpsed in their first frenzy of star formation.

But this conclusion was far from ironclad. Testing the idea was a prime motivation for a team of astronomers led by Richard Ellis at the California Institute of Technology in Pasadena. In 2012 they re-examined a small part of the centre of the HUDF, this time with an additional colour filter and a time exposure totalling about 23 days.

These newer observations, which Ellis's team reported in January this year at a meeting of the American Astronomical Society in Long Beach, California[3–5], reveal that the galaxies are in fact redder, and therefore contain older stars, than initially calculated. The very youngest galaxies that Hubble has identified, imaged as they appeared 560 million to 780 million years after the Big Bang, contain stars that are 100 million to 200 million years old. So these galaxies had already been around for at least that long.

The new HUDF observations also reveal puzzling features of the tumultuous era of reionization, as explained at the January meeting by Brant Robertson of the University of Arizona in Tucson. This was the time when the first galaxies were growing bigger and more numerous, and when ultraviolet light from the first stars was becoming strong enough to ionize the veil of thick hydrogen gas that enveloped them. Other observations show that reionization began roughly 250 million years after the Big Bang, and that it was complete at a cosmic age of roughly 1 billion years — at which point starlight could stream freely into space and the cosmos was mostly transparent, just as we see it today.

But although the galaxies Hubble saw in the 2012 (and the 2009) HUDF observations were presumably the largest and brightest ones around all those billions of years ago, there simply were not enough of them to reionize the Universe. This means, according to Ellis, Robertson and their colleagues, that there must have been a large population of unseen small fry that did most of the work — a conclusion also reached by Illingworth and his team[6].

"We now know there's a whole population of small galaxies at even earlier times" than Hubble's detectors can record, says Ellis — which leads to an exciting set of questions for the newer telescopes such as ALMA and JWST, including how these bodies formed and how they coalesced into the larger galaxies that came later.

Another set of questions relates to the very first generation of stars, which coalesced from almost pure helium and hydrogen forged in the Big Bang. Theory suggests that they were more than 100 times as massive as our Sun — far larger than any stars that form today. If so, then theory also suggests that these monsters were so short-lived that none of them would have survived in the galaxies that Hubble can see. Their extreme size would have caused these stars to destroy themselves in spectacular supernova explosions after only some 2 million years. But did they? And did their death throes delay the birth of the next generation of stars, by disrupting the thick interstellar gas clouds in which new stars were forming?

The HUDF data already suggest that the answer to the last question

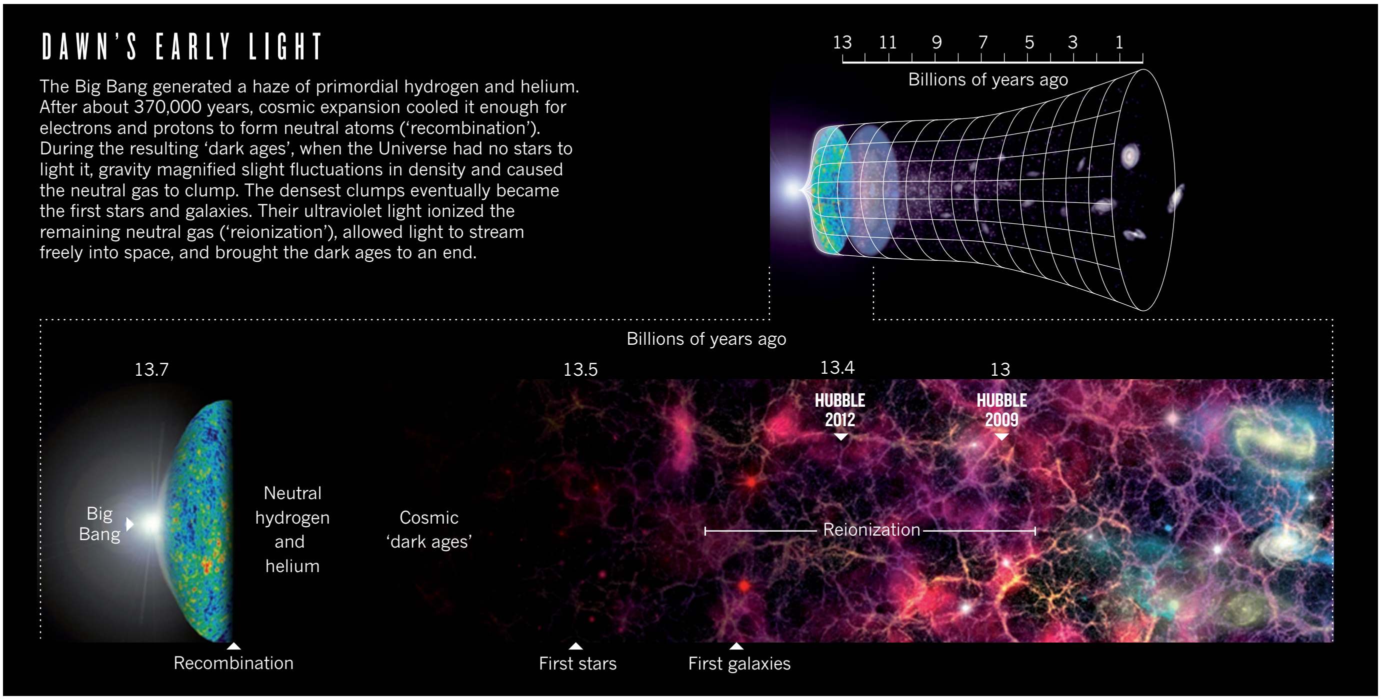

ILLUSTRATION: NIK SPENCER; SOURCES: NASA/WMAP SCIENCE TEAM; R. ELLIS (CALTECH)

is 'No', says theorist Volker Bromm at the University of Texas at Austin, who was not involved in the 2009 and 2012 HUDF studies. Because the colours of the galaxies seen in the ultra-deep field indicate that they had been forming stars for at least 100 million years already, this suggests that there was little or no lag between the death of the very first generation of stars and the birth of the second, he says. The generations may even have overlapped. But untangling exactly what happened will be a job for future telescopes.

THE NEXT FRONTIER

In the meantime, Hubble astronomers haven't been idle. NASA is pursuing a tactic that could turn the observatory into a telescope as powerful as the JWST will be, along some limited fields of view.

To achieve this, astronomers are scanning the heavens to select six fields of view that, unlike the HUDF, each contains a high-mass cluster of foreground galaxies. As first predicted by Einstein, such clusters act as cosmic zoom lenses, gravitationally magnifying and brightening images of distant galaxies that lie directly behind them.

Hubble's visible-light and infrared cameras will take turns at looking through these lenses, which should reveal distant galaxies 10 to 50 times fainter than any previously known — among them the multitude of small fry whose existence is indicated by the reionization data. Collection of data from the first four 'frontier fields' is scheduled to be completed over the next two years, says Mark Dickinson of the National Optical Astronomy Observatory in Tucson, Arizona.

In Chile, ALMA will join the hunt for distant galaxies from this summer (see *Nature* **495,** 156–159; 2013). In contrast to Hubble, which records starlight, ALMA's microwave measurements will reveal the gas and dust that gives rise to stars in these remote bodies. Paradoxically, says James Dunlop of the University of Edinburgh, UK, a member of the 2012 HUDF team, this will allow ALMA to make the most accurate measurement yet of starbirth at such distances. Newborn stars radiate most of their light at ultraviolet wavelengths, he explains, but much of that light is absorbed by gas and dust and reradiated at infrared wavelengths, which are then redshifted by cosmic expansion into ALMA's millimetre range.

In addition, ALMA's high spatial resolution will enable the array to break radio emissions into their component wavelengths and therefore record the actual redshifts — bona fide measurements of distance — of many of the remote galaxies that Hubble has studied, says Chris Carilli at the National Radio Astronomy Observatory in Socorro, New Mexico. Astronomers can then translate those distance measurements into ages, which will give them a much better handle on where these objects fit in cosmic history.

"Hubble has been amazing at finding candidate galaxies from redshift 7 to 10, but none of these has been confirmed with spectra and the potential for [spurious candidates] is severe," says Carilli.

Carilli and his collaborators reported[7] in February that ALMA can measure redshift-7 galaxies (objects 3,955 megaparsecs or 12.9 billion light years from Earth) using just 20 of its eventual complement of 66 antennas. A report from another team in *Nature*[8] provides further evidence. ALMA will "quickly make the jump to redshift 8" by the end of the year, says Carilli, and if the array gets a new set of receivers — a possibility still several years in the future — it could study and measure distances to galaxies out to redshift 11. These objects would be seen as they appeared just 425 million years after the birth of the Universe. ALMA could become the "redshift machine of choice" for the first galaxies, he says.

Nevertheless, most astronomers are eagerly awaiting the 6.5-metre JWST, whose *raison d'être* is to image the faint, primitive bodies that Hubble can only glimpse — but that were the earliest ancestors of modern galaxies such as the Milky Way (see *Nature* **467,** 1028–1030; 2010). Hubble's observations provided "the first hints of the first galaxies", says Ellis, but "we really need the JWST to push back into that even earlier period from 200 million years to 500 million years after the Big Bang".

Back in 2009, even as NASA astronomer and astronaut John Grunsfeld glimpsed the first images of distant galaxies from the infrared camera he had helped to install on Hubble, the JWST had come to his mind. "I couldn't help but feel awed by the power of Hubble," Grunsfeld recalls, but "the views of the HUDF also gave me great satisfaction that the JWST would have plenty to see." ■

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