Mining the Deep Field

A year ago, the Hubble Space Telescope took the most probing look ever out into space and back in time. Now astronomers are unearthing cosmic history from the image

Astronomers, by their own admission, can be a secretive bunch. "There's a long-standing tradition of loners going to the mountaintop and then coming back and sitting on their data," says astronomer Craig Hogan of the University of Washington. Even at the Space Telescope Science Institute (STScI) in Baltimore, where hundreds of people operate the orbiting Hubble Space Telescope (HST), standard procedure is to keep hard-earned data and images under wraps for a year while the researchers who made the observation have time to analyze and publish their work. But a year ago, Robert Williams, the STScI director, broke with that tradition.

Williams knew the data he and his colleagues were collecting were too rich to keep to themselves. They had programmed the HST to point at a tiny patch of sky near the Big Dipper for 10 days straight last December—the most probing look ever at any point in space. A month later, they released a stunning image, showing the faintest galaxies ever seen, and offered the accompanying data to any astronomer who wanted to analyze it.

The result: The past year—ordinarily the gestation period of a single paper—has seen a fruitful free-for-all that has already yielded more than 30 publications. As released last January, the image was a two-dimensional picture, a colorful confetti of galactic blobs and spirals—more than 3000 of them, seen in a patch of sky about the width of a grain of sand held at arm's length. But compressed within that picture may be at least 90% of the history of the universe, back to some of its earliest stars and galaxies. Over the last year, astronomers have worked to unearth that history from the Deep Field.

With other instruments that can gather more light or pick up wavelengths invisible to the HST, they have scrutinized the galaxies for clues to their distances, ages, and natures. By combining new observations with the original data set, they have chronicled how the universe turned primordial gas into stars and galaxies, spotted possible concentrations of galaxies in the early universe (*Science*, 18 October, p. 343), and picked out individual objects that may be the most distant ever seen. "For so many years, we could never see more than [halfway across the universe]," says University of California, Berkeley, astronomer Marc Davis. "Now we've just broken the floodgates and can see all the way."

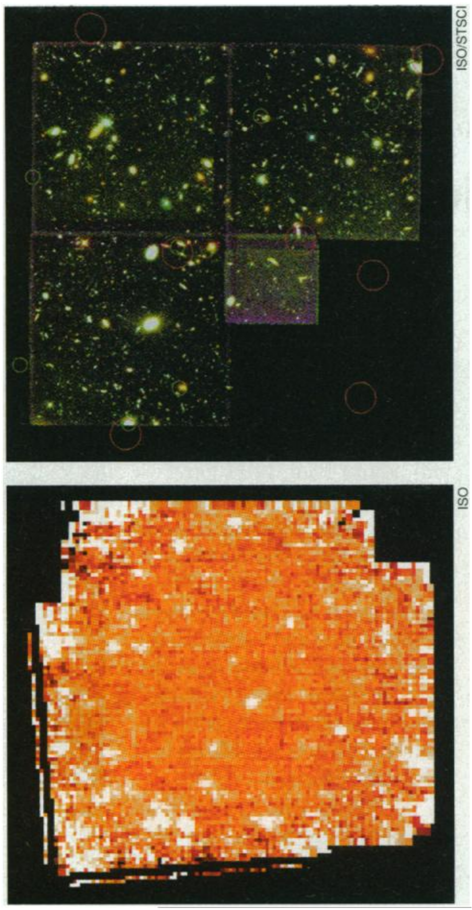
Many of the Deep Field results have accelerated a field that was already in high gear, says Hogan: piecing together the universe's history of star formation, a process that takes place mainly in young galaxies. Astronomers knew that starbirth in our present-day universe is long past its peak (*Science*, 7 June, p. 1434). They had also caught glimpses of distant galaxies whose blue color, the hue of hot young stars, pointed to an era of more active star formation perhaps 8 billion years ago. But identifying a peak is difficult unless you can see both sides of it, and astronomers didn't have a clear enough view into the young universe to detect an early increase in star formation. The Deep Field, however, fills in the early chapters, perhaps revealing the first major population of stars to form. "This may be all the light there is," says Hogan. "We're not seeing quite back to the dark ages, but we are seeing the renaissance."

Just this week, astronomer Piero Madau of STScI and several colleagues reported that they had combined a study of the Deep Field galaxies with a ground-based survey of nearer galaxies made by astronomers from Canada and France to chronicle star formation over much of that renaissance—and the subsequent decline. As a first step, Madau and his colleagues, who published their findings in the *Monthly Notices of the Royal Astronomical Society*, had to arrange the most distant galaxies in the Deep Field along a time line. They relied on an astronomical shortcut.

Astronomers ordinarily determine distances to faraway light sources by measuring the redshift of their light. As the universe expands, the light traveling through it is stretched, shifting it to longer—redder—wavelengths. The farther light travels, the greater the redshift. Usually researchers determine redshifts from detailed spectra, but the number and faintness of the objects in the Deep Field make that approach impractical. Instead, Madau and his colleagues enlisted a technique for deriving a "poor man's redshift" by taking advantage of another property of far-traveled light.

On its journey to Earth, light is not only stretched but also absorbed by clouds rich in hydrogen gas. Hydrogen absorbs the shortest—ultraviolet—wavelengths, essentially erasing one end of the object's spectrum. This so-called Lyman break is redshifted along with the rest of the light—all the way to the visible range for the most distant objects. Madau and his colleagues compared each galaxy's brightness in different Deep Field exposures, made with filters of different colors. By watching for galaxies that appeared dim in the bluest filters, they singled out ones whose Lyman break fell within two redshift ranges: from 2 to 3.5 and from 3.5 to 4.5. The team then gauged the rate of star formation during each redshift span by summing the galaxies' brightnesses at a near-ultraviolet wavelength right next to the Lyman break, where young stars shine especially brightly.

Even at a redshift of about 4, about a billion years after the big bang, the Madau group found that galaxies or their precursors were already forming stars about twice as fast as in today's universe. By a redshift of 2, about 2 billion years later and 10 billion years ago, star formation had risen to five times the current rate. Later, at a redshift of 1—about 8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ISO

Stars are born. Infrared sources (*above*) in the Hubble Deep Field (*top*, with sources outlined) may reveal galaxies forming 10 to 1000 new suns per year.

billion years ago—the Canada-France survey shows galaxies churning out stars 10 times as fast as our Milky Way. The slope then declines to the present day.

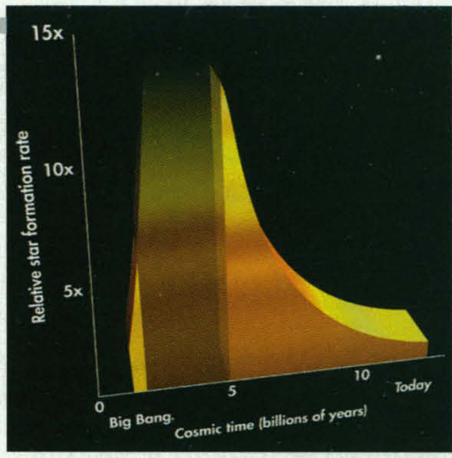
The two studies seem to bracket a time when star formation likely peaked, says Madau. But the height of the peak is still a mystery, because the record has a gap between redshifts of 1 and 2. In objects at these distances, the Lyman break doesn't reach the visible spectrum, putting the galaxies out of reach of the redshift shortcut. At the same time, ground-based observers have a hard time pinpointing redshifts greater than 1.

Michael Rowan-Robinson, an astronomer at Imperial College in London, thinks that the star formation record has another kind of gap as well. Madau and his colleagues deduce star formation from ultraviolet light shifted into the visible range. But when it comes to tracing star formation, Rowan-Robinson says, "there is more than meets the eye."

He and several colleagues have imaged the Deep Field with the orbiting Infrared Space Observatory (ISO), and they have found several sources with infrared emissions more than 10 times stronger than their optical output. The objects' age puts them near Madau's peak, but to Rowan-Robinson their infrared brightness suggests that the starbirth rate may have been much higher than most astronomers guess. Thick blankets of dust, common in star-forming galaxies, are known to absorb the bluish light from young stars and re-emit it in infrared wavelengths. Rowan-Robinson thinks that the ISO sources may be spawning stars 10 to 1000 times faster than our galaxy is today. But Max Pettini, an astronomer at the Royal Greenwich Observatory in the U.K., cautions that "we still don't know if [such violent starbursts are] the story everywhere or if it is just these few."

Another view of the Deep Field, this one in radio wavelengths, may have revealed episodes of starbirth well before the surge 10 billion years ago. In one of the most sensitive radio surveys ever conducted, graduate student Eric Richards and astronomer Kenneth Kellermann of the National Radio Astronomy Observatory spent 100 hours peering at the Deep Field with the Very Large Array (VLA), a set of radio telescopes in New Mexico. Almost all of the 17 faint radio sources they detected match galaxies seen in the Hubble image, and about half match the starbursting galaxies spotted by ISO at a redshift of 1.

But Richards believes a few of the radio signals may originate from "one of the Holy Grails of astronomy": primeval galaxies—the first normal galaxies to form in the soup of gas left by the big bang. Detailed spectra of these galaxies, collected at the Keck Telescope in Hawaii, show that they are at redshifts of 3 or more—some of the most distant objects in the field. And their spectral signatures and radio emissions are typical of young, star-forming galaxies.



Cosmic baby boom. A Deep Field study combined with a ground-based survey traces the universe's rate of star formation.

Even more intriguing is one primeval galaxy candidate that does not have a counterpart in the Hubble image. Richards suggests that the galaxy is so distant that its visible light has been redshifted to a wavelength too far in the infrared for the HST to detect. "That would place it at a redshift of at least 7," he says, "which would be the most distant object ever found." Indeed, it would be nearly twice as far away as the current record-holder, at a redshift of 4.9.

An object at a redshift of 7 "is indeed a possibility," says Mark Dickinson of STScI, but "I would suspect there are more mundane possibilities as well." He suggests that the VLA may have detected a radio-producing plasma lobe, offset from the center of the galaxy that emits it, which may be throwing off attempts to identify the parent galaxy.

Even as astronomers struggle to make sense of the Deep Field data, an effort Richards likens to "drinking from a fire hose," plans for a second round are under way. STScI director Williams and his colleagues are choosing a site for Deep Field South, which will be visible to ground-based telescopes in the Southern Hemisphere. The new data set, says Williams, will be released in the same way as the first one was a year ago. "After all is said and done," he says, "we did it exactly right."

–Gretchen Vogel

GAMMA-RAY ASTRONOMY

Repeated Bursts Puzzle Astronomers

Last week, a U.S.–Russian team announced that four space-based detectors have picked up what might be a vital clue in one of the biggest mysteries of modern astronomy—or a statistical fluke. In the space of 2 days in late October, the detectors, aboard spacecraft including the Compton Gamma-Ray Observatory (GRO) and Ulysses, recorded four gamma-ray spikes from the same small patch of sky. The spikes were immediately identified as signaling gamma-ray bursts—seconds-long blasts of gamma rays that come about once a day from random directions. No one knows what produces gamma-ray bursts, in part because none has ever been correlated with any visible source. And every burst to date has apparently occurred in splendid isolation.

The implication of the new observations—that a single source produced repeated bursts—is a startling one, say researchers. "How can something produce emission over a 2-day period?" asks team member Charles Meegan of NASA's Marshall Space Flight Center in Huntsville, Alabama. At the same time, the new observation may end up giving astronomers their first break in the case. It suggests, say some, that the bursts must come from the neighborhood of our galaxy and not, as other astronomers believe, from the fringes of the universe.

The researchers, who announced the observations in an International Astronomical Union publication on the Internet, are fairly certain that the first two short spikes, seen on 27 October, represent two distinct bursts. Not so the pair of spikes that came 2 days later, just 23 minutes apart. "We are convinced those two come from the same source and that it's one real long burst," says Meegan—the longest ever recorded.

A repeating gamma-ray burst might allow astronomers to eliminate some of the rival explanations for these events. One theory holds that bursts are caused by coalescing neutron stars in the distant universe, but that process "could not make something that would burst again 2 days later," says Meegan. And for any source to produce the intense bursts repeatedly, it cannot be far away, argues team member Bonnard Teegarden of NASA's Goddard Space Flight Center in Greenbelt, Maryland.

Then again, the multiple burst could be a coincidence: several different sources that happened to be in the same patch of sky. "It seems to be unlikely to be due to chance, although we still need to work real hard to make sure," says Meegan. But Ralph Wijers of Cambridge University's Institute of Astronomy has analyzed the numbers and has come to his own conclusions. "BATSE [a GRO instrument] has been observing the sky for five-and-a-half years, and you would in fact expect about one time in that whole list to have three bursts from roughly that size area of sky within a few days," he says. "If you go back and look at the hard numbers, it is not as remarkable as you might think."

–Andrew Watson

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