Found: Primeval Galaxies

An abundance of ancestral galaxies revealed

By RON COWEN

Somewhere deep in space and far back in time, the vast reserves of hydrogen and helium gas in young galaxies collapsed into clouds. These gaseous cocoons soon became stellar nurseries, setting the galaxies aflame with the first blush of starlight. After a journey lasting several billion years, the faint light finally reached Earth.

For nearly 2 decades, astronomers have sought these primeval glimmers—baby pictures of the oldest galaxies in the universe. Despite occasional successes, their quest for a population of primitive galaxies proved a spectacular failure.

That's why Charles C. Steidel, a young astronomer at the California Institute of Technology in Pasadena, is elated—and a bit humbled—about his team's sudden embarrassment of riches. Using a novel technique to ferret out faraway galaxies, Steidel and his colleagues in a few months have discovered 23 galaxies so distant from Earth that the light they emit took 85 percent of the age of the universe to get here.

That means that if the cosmos is 15 billion years old (estimates vary widely), the starlight emitted by these galaxies traveled for 13 billion years to reach Earth. It therefore reveals how galaxies looked when they were mere toddlers. Indeed, the astronomers find that starlight from each of the newly discovered galaxies has a pronounced bluish color, indicating that the stars are young and that these galaxies are still in the first throes of starbirth.

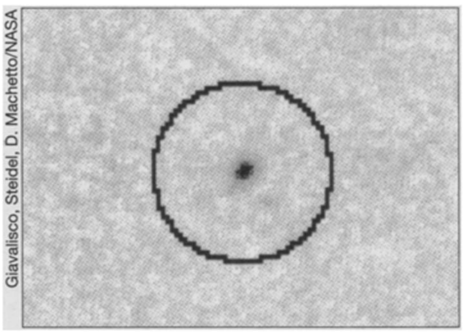
"This is an amazing discovery. They have found a group of galaxies that people have been seeking for the past decade," says Richard G. McMahon of the University of Cambridge in England. "It's one of the most important findings in astronomy in the last 5 years."

Moreover, Steidel and his colleagues argue that the galaxies they've discovered represent the early ancestors of two stellar populations believed to be the oldest in the universe—the football-shaped elliptical galaxies and the central part of spiral galaxies like the Milky Way.

Multicolor images of 120 other intriguing galaxies have also been captured by Steidel and his collaborators, who include Mauro Giavalisco of the Carnegie Observatories in Pasadena, Max Pettini of the Royal Greenwich Observatory in Cambridge, Mark Dickinson of the Space Telescope Science Institute in Baltimore, and Kurt L. Adelberger of Caltech.

Although the distances to these galaxies have yet to be measured, their portraits put them into the same category as the other young galaxies.

For most astronomers, the team's findings fit the description, or nearly so, of one of the Holy Grails of astronomy: a collection of primeval galaxies. Although the galaxies discovered by Steidel's team had already fully assembled, the heavenly snapshots caught them at an extremely early stage of development.



Giavalisco, Steidel, D. Machetto/NASA

Mug shot of a distant galaxy (in circle) taken with the Hubble Space Telescope.

Nonetheless, Steidel all but refuses to classify his objects as primeval. Indeed, he scrupulously avoids using the "p" word in his team's upcoming article in the Astrophysical Journal Letters.

"Whether you want to call these 'primeval' galaxies is up to you," says Steidel, noting that different astronomers define "primeval" in different ways.

On another point, however, Steidel pulls no punches. He and his coauthors cite two lines of evidence supporting their contention that the newly discovered galaxies are the forerunners of elliptical galaxies and the central part of spirals.

The number of galaxies they found, given the volume of space at which they looked, matches the density expected from today's population of ellipticals and spirals. In addition, images taken with the Hubble Space Telescope, including the extraordinarily detailed Hubble Deep Field (SN: 1/20/96, p. 36), reveal the shape of six of the distant galaxies. The images show that all six resemble compact balls—just the right shape to evolve into an elliptical galaxy or the central, spherical component of a spiral, Steidel explains.

"We think we're seeing the formation of [stars in] the oldest parts of galaxies," says Steidel. "[T]he space density, star formation rates, morphologies and physical sizes, masses, and early epoch of the galaxy population that we have isolated . . . all point to the conclusion that we are seeing directly, for the first time, the spheroidal component of present-day luminous galaxies," note Steidel and his coauthors.

McMahon agrees. "This means that when we study these objects, we are learning about how typical galaxies, like our Milky Way, have formed," he says.

The technique employed to find these galaxies, McMahon adds, is almost as intriguing as the team's results.

Astronomers hunting for primeval galaxies typically set their sights on a particular beacon—a wavelength of light known as Lyman-alpha. It is thought to be the single strongest emission from newly forming stars; hydrogen atoms radiate this ultraviolet light when an electron falls from the first excited state to the ground state. Researchers had assumed that this light would stick out like a sore thumb, broadcasting the fireworks of starbirth to telescopes several billion light-years distant.

But with the exception of a few isolated findings (see sidebar), numerous searchers have come up empty-handed. In retrospect, says Steidel, looking for Lyman-alpha provides at best a needle-in-the-haystack approach to detecting primeval galaxies.

He notes, for example, that even a small amount of dust in the young galaxy will quench the light from Lyman-alpha. That's because hydrogen atoms in the galaxy easily scatter Lyman-alpha photons. As a result, these photons can't leave the galaxy as readily as other particles of light and are more likely to encounter even trace amounts of dust.

Steidel cites another limitation. To pick out Lyman-alpha emission from the general background of galactic light, astronomers must use a filter that per-

Two Lucky Finds

In comparing portraits of galaxies taken through different color filters, Charles C. Steidel of the California Institute of Technology in Pasadena, Calif., and his colleagues have found a way to systematically identify distant galaxies in their first blush of starbirth. But in other cases, luck played a larger role. Completely by accident, Howard K.C. Yee of the University of Toronto happened on a single galaxy that he classifies as primeval. So did Stanislav G. Djorgovski of Caltech.

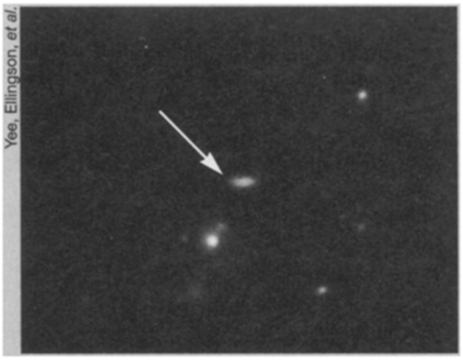
A year ago, Yee, Erica Ellingson of the University of Colorado at Boulder, and their colleagues had their hands full analyzing thin dark lines—the absorption spectra—of some 2,500 galaxies obtained with the Canada-France-Hawaii Telescope on Hawaii's Mauna Kea. The spectra were part of a survey to measure the velocity of galaxies that congregate in clusters. One galaxy had Yee and Ellingson puzzled. Its spectra didn't match that of any resident of a cluster. In addition, the object was unusually bright.

Yee showed the oddball spectra to a visitor, Jill Bechtold of the University of Arizona in Tucson. Familiar with the fingerprints of faraway objects, Bechtold quickly identified the spectra as those of a galaxy nearly as distant as the galaxies found by Steidel's team. At a redshift of 2.7, this galaxy lies about 12.5 billion light-years from Earth, so far away that the light it emits must traverse nearly the entire breadth of the universe to reach Earth. The radiation detected by a telescope today thus provides a snapshot of what the galaxy looked like when the universe was about 20 percent of its current age.

The luminous appearance of the galaxy—about 100 times brighter than any of the primeval galaxies found by Steidel and his colleagues—suggests that it is making stars at a furious rate, churning out the equivalent of 1,000 new suns every year. Infrared and visible-light spectra reveal that massive young stars, which die out rapidly, produce the bulk of the galaxy's light. This indicates, says Yee, that the galaxy probably began its first burst of star formation no more than 30 million years earlier.

"This object appears to fit every definition of a protogalaxy," he and his colleagues will report in the May ASTRONOMICAL JOURNAL.

Yee notes that observations planned with the Hubble Space Telescope should



Yee, Ellingson, et al.

At a redshift of 2.7, an unusually bright galaxy (arrow) imaged with the Canada-France-Hawaii Telescope may be primeval.

settle the debate over whether the galaxy is truly as luminous as it appears or whether some of the brightness stems from a cosmic mirage known as gravitational lensing. In lensing, the gravitational field of a massive foreground object bends and amplifies light from the galaxy, making it seem brighter than it really is. If this were the case, the galaxy would still reside at the same great distance from Earth but wouldn't be making as many new stars as it appears to be.

During the past 2 decades, astronomers have used the bright light of quasars, the powerhouses that lie at the centers of some galaxies, to explore the distant reaches of the universe. On their way to Earth, these brilliant beacons pass through a vast array of gas clouds and galaxies, each of which absorbs some of the quasar's light.

A decade ago, researchers discovered that some of the absorption lines are much stronger than others. Each line indicates the presence of a group of objects, known as damped Lyman-alpha absorption systems. These systems collectively contain enough gas to form all the spiral galaxies, and perhaps the elliptical galaxies, present in the cosmos today (SN: 9/17/94, p. 188).

While looking for primeval galaxies last September with the W.M. Keck Telescope on Mauna Kea, Djorgovksi and his colleagues stumbled upon an intriguing object: a distant galaxy, with a redshift of 3.15, that qualifies as a damped Lyman-alpha system. The galaxy lies directly in the path of light emitted by the quasar 2233+131. Their image of the galaxy, the astronomers report, ranks as the first clear-cut portrait of a damped Lyman-alpha object.

"There have been some preliminary reports that people have seen emission from damped Lyman-alpha objects, but these have not survived follow-up observations," says Djorgovski. "Up until now, we have never had a direct detection of a galaxy responsible for damped Lyman-alpha absorption."

Several properties of the galaxy, he adds, suggest that it is in the early stages of formation. The evidence strongly supports the notion that damped Lyman-alpha systems represent a population of protogalaxies in the early universe, Djorgovski says. He and his collaborators, Michael A. Pahre of Caltech, Bechtold, and Richard Elston of the Cerro Tololo Inter-American Observatory in La Serena, Chile, reported their work last month at a meeting of the American Astronomical Society in San Antonio.

Intriguingly, the object also happens to be one of the galaxies found by Steidel's team that meet the color criterion for a primeval galaxy. — *R. Cowen*

mits the passage of only a very narrow range of wavelengths. The expansion of the universe shifts all light, including Lyman-alpha, to redder wavelengths. The greater the galaxy's distance from Earth, the larger the redshift. To look for galaxies that reside at particular distances, astronomers pick filters designed to detect specific redshifted Lyman-alpha emissions.

This technique severely restricts the range of distances that observers can search at any one time, Steidel points out.

In 1992, Steidel and Donald Hamilton of the Max Planck Institute for Astronomy in Heidelberg, Germany, described a novel method for picking out distant galaxies from the zoo of celestial bodies in a telescope image. They noted that galaxies that reside far away should show up at about the same level of brightness at red and green wavelengths but vanish in the ultraviolet. That's because hydrogen gas absorbs ultraviolet light, and the most distant galaxies have the largest amount of hydrogen between them and Earth.

To spot these "ultraviolet dropouts," the astronomers would have to compare images of galaxies taken in a variety of colors, ranging from the red to the near ultraviolet. Steidel and his collaborators gathered such multiwavelength portraits at three observatories: the William Herschel Telescope in the Canary Islands, Spain, the Cerro Tololo Inter-American Observatory in La Serena, Chile, and Palomar Observatory near Escondido, Calif. In each set of images, a significant number of the faintest, smallest galaxies—the objects most likely to be distant—did indeed disappear in the ultraviolet.

The team collected lots of candidates, but other researchers remained skeptical. "We found these objects and had no way of proving to anyone that they were [at the distance] where we said they were—other than these arguments about color," Steidel recalls. "We were at a dead end."

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To prove their case, Steidel and his collaborators needed to measure the actual distances to the dropout galaxies.

Last October, the astronomers got their chance. Atop an extinct volcano in Hawaii, they pointed the world's largest optical telescope—the W.M. Keck Telescope on Mauna Kea—at some of their candidates. The spectra revealed that 17 of these galaxies have redshifts between 3 and 3.4, indicating that the bodies reside about 13 billion light-years from Earth.

"There was a lot of relief and a lot of excitement," Steidel recalls. "This was really the leg we needed to stand on to push this technique further along."

In applying the multicolor search method, he adds, "we are trying to get a global picture. We're not interested in finding an unusual object in order to say that we've found the most distant galaxy known. Instead, we want to know what the typical galaxy population is like, how far galaxy formation has come along at a certain snapshot [in time.] And we're finding [these galaxies] in a systematic way, rather than by pure luck."

Last month, Steidel and his colleagues headed back to Hawaii, just days after two of his collaborators, Dickinson and Giavalisco, helped unveil the Hubble Deep Field image at a meeting of the American Astronomical Society in San Antonio. The team zeroed in on six galaxies, imaged in the Deep Field and another Hubble picture, that vanished in the ultraviolet. Using Keck to measure redshifts, the team found that all six galaxies are indeed distant, Steidel told SCIENCE NEWS.

Like the other 17 objects observed in October, these galaxies have a bluish tinge compared with older galaxies, indicating that they are still forming their first generation of stars. So far, says Steidel, use of this color criterion has proved a winning strategy: 90 percent of the galaxies that vanish in the ultraviolet reside at large distances.

Because his team has spied so many galaxies at this remote epoch, Steidel concludes that galaxy formation was already well under way 13 billion years ago. Evidence of even earlier galaxy formation also comes from the existence of the powerful light beacons called quasars, with redshifts as great as 5. The atypical galaxies that house quasars must have formed even before the more ordinary galaxies that Steidel's team has found.

But when did the average, run-of-the-mill galaxy assemble? That's the question astronomers are now poised to answer, says Alan Dressler of the Carnegie Observatories. Armed with the new findings on primeval galaxies, "we're ready to bust into the early universe and find out how galaxies formed," he notes.

Steidel and his colleagues have already taken the first step. In a cursory examination of the Hubble Deep Field, he and Dickinson independently applied the same ultraviolet dropout technique. This time, however, they sought galaxies from even greater distances and more remote reaches of cosmic time. Such objects, which would reside farther than 13.5 billion light-years from Earth, would have a redshift greater than 4.

The astronomers saw few galaxies that fill the bill.

"Basically, you should be able to see the same kind of [distant galaxies], were they to exist, at a redshift greater than 4," Steidel comments. "The fact is that we don't."

Dickinson cautions that the color criterion for finding distant galaxies is harder to apply at higher redshifts but admits that the preliminary findings suggest a startling possibility. If the galaxies aren't visible, perhaps they hadn't yet come into being.

"I think that means it's very likely that the galaxies we've been seeing had formed somewhere between redshift 4 and redshift 3.5," Steidel says.

Astronomers may finally have peered far enough back in time to come face to face with a blank slate—the point at which most galaxies had yet to assemble. □

Astronomy

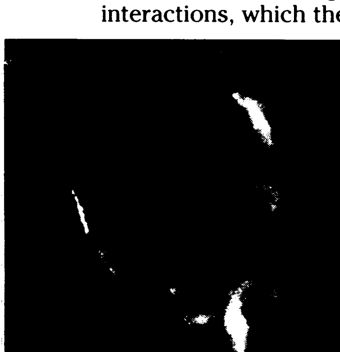
Galactic harassment

As astronomers have peered deeper into space and further back in time, they've noticed a curious trend. Clusters of galaxies that date to several billion years ago contain a high percentage of spiral galaxies with lots of blue, young stars. In contrast, clusters today mainly harbor the football-shaped galaxies known as ellipticals and contain redder, older stars.

To explain this phenomenon, some researchers have suggested that galaxies in clusters collide like bumper cars, triggering starbirth and ultimately transforming spiral galaxies into ellipticals. Others have suggested that the gravitational tug exerted when one galaxy slowly passes another may account for the structural changes.

New computer simulations suggest a third explanation. A rarer interaction, in which galaxies remain far apart and pass each other at high speed, may best explain the changes in clusters, assert Ben Moore of the University of Washington in Seattle and his colleagues in the Feb. 15 NATURE. Although such interactions, which the team calls "galactic harassment," may occur only once every billion years, simulations indicate that the cumulative effect can indeed trigger star formation and transform a small spiral galaxy into an authentic elliptical.

Robert D. Joseph of the University of Hawaii in Honolulu challenges the simulations, which treat the harassing galaxies as points instead of extended objects. He says that at present, the model is too simplistic to explain convincingly the observed changes in clusters.



University of Washington

Simulation of a spiral galaxy as it orbits through a dense galactic cluster. Other galaxies in the cluster have stripped material from the spiral, creating the two long tails.

Narrowing the gap between cosmic ages

Everyone knows you can't be older than your mother. Yet that's the paradox facing cosmologists as they try to determine the age of the universe. On the one hand, astronomers have estimated that globular clusters, the oldest groupings of stars in the universe, have a minimum age of 14 billion years. On the other hand, several determinations of the Hubble constant, which measures the cosmic rate of expansion, indicate that the universe is only 8 to 12 billion years old.

A new analysis of the ages of the 17 oldest clusters in our galaxy lessens the discrepancy. Brian Chaboyer of the Canadian Institute for Theoretical Astrophysics in Toronto and his colleagues fed recent observational data and predictions into more than 4 million computer models of stellar evolution. The team tested how uncertainties in the estimated composition of stars and the rate at which they burn hydrogen would affect the calculated age of clusters.

In the Feb. 16 SCIENCE, Chaboyer's team reports that globular clusters have a minimum age of 12 billion years. The new lower limit, at least 2 billion years younger than previous estimates, overlaps—just barely—with some Hubble Space Telescope measurements of the age of the universe. "We're at a point now that a few billion years [less] does start to make a difference," notes Chaboyer. He adds, however, that a discrepancy remains because "the odds are 20 to 1 that globular clusters are older than 12 billion years."