Grappling with Galaxy Formation

Connecting the dots between galaxies near and far

By RON COWEN

One little, two little, three little galaxies. Four little, five little, six little galaxies . . . .

Astronomers peering at some of the earliest, most distant gatherings of stars in the universe are trying to figure out exactly what these dim objects were and how they relate to the billions of galaxies that fill the sky today. Some of these bodies are so remote that the light they emitted several billion years ago is only now reaching Earth. Telescope images therefore provide snapshots of what these galaxies looked like when they were very young.

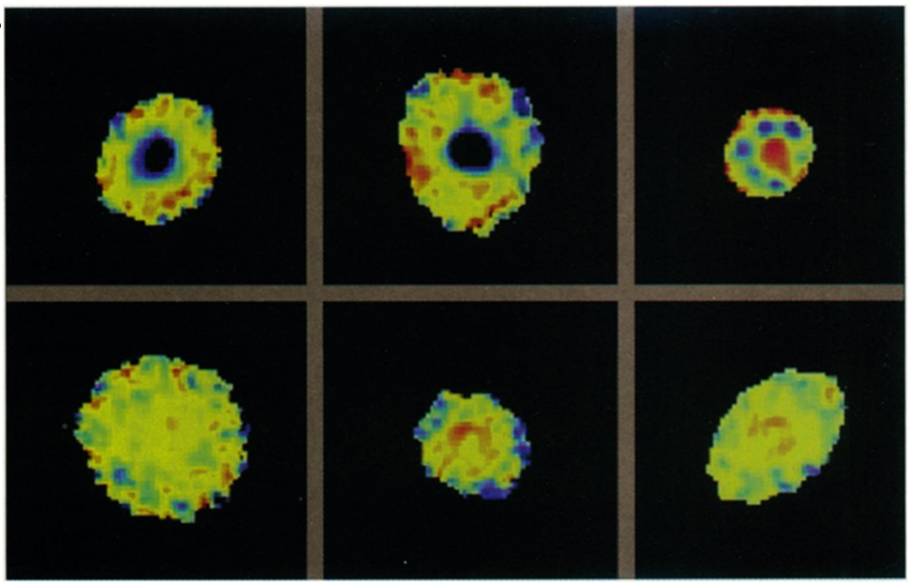
Just 4 years ago, researchers knew of perhaps 70 of these baby galaxies, which date from a time when the universe was no more than 3 billion years old. Since 1996, that number has jumped to more than 850 (SN: 5/2/98, p. 280).

The study of distant galaxies, however, is no longer just a numbers game. Astronomers have begun to closely scrutinize distant galaxies in infrared light, a range of wavelengths that promises to reveal the mass of these faraway bodies. As they determine which are heavy and which are light, researchers may be able to choose among competing theories of galaxy assembly—and find out whether the universe will end in a Big Crunch or expand forever.

Scientists are also now collecting sharper images in visible light, enabling them to discern subtle color variations within individual galaxies and gather new clues about galaxy formation.

"We're trying to piece together the story of how the big, regular galaxies that we see around us today formed," says Richard S. Ellis of the University of Cambridge in England.

"It's a new era in the study of distant galaxies," says theorist Matthias Steinmetz of the University of Arizona in Tucson.



Abraham *et al.*/Univ. of Cambridge

Maps show the variation in internal colors among elliptical galaxies in the Hubble Deep Field. According to traditional theory, the stars in an elliptical galaxy should be old and well mixed, giving each galaxy a uniform color. The two leftmost galaxies in the top row, however, have blue centers, indicating the presence of young stars there. The third galaxy in that row shows evidence of young stars in its periphery. About two-thirds of the field galaxies show little or no color variation, like those in the bottom row.

Two sets of exquisitely sharp images recorded by the Hubble Space Telescope are making a special contribution to the study of galaxy formation. In late 1995, Hubble stared at a small patch of sky in the northern celestial hemisphere for 2 weeks, and in 1998 it did the same in the southern hemisphere. Observations of the Hubble Deep Field North and South, as the patches of sky are now called, have produced the sharpest images of galaxies ever made.

Many astronomers have used these color portraits to pick out the galaxies likely to lie farthest from Earth and therefore be the youngest. One successful strategy is to search for galaxies that glow brightly at red wavelengths but are invisible in the near ultraviolet (SN: 2/24/96, p. 120).

Ellis, Roberto Abraham of the University of Cambridge, and their colleagues are studying the Hubble images in a different way. Rather than examining the overall hue of a galaxy, they are scrutinizing the variations of color within it. Although the most remote galaxies in the Hubble fields are too faint to clearly show a color variation, the astronomers have discerned differences in color within galaxies that lie as far as halfway to the edge of the visible universe.

"For a couple of years now, we've been thinking that the Hubble data has not been fully explored," says Ellis. "People have really just been studying the overall properties of the galaxies—getting their shapes—but they haven't been actually using the colors of the individual subcomponents within each galaxy."

Mark Dickinson of the Space Telescope Science Institute in Baltimore notes, "You see [distant] galaxies that have blue arms or blue knots and red centers—just as you see color variations in nearby galaxies."

Observed in detail, most galaxies resemble a Seurat painting, with each picture element, or pixel, a differently colored dot. Gradations in color from one pixel to another can suggest which parts of a galaxy formed first and which came last.

Massive, short-lived stars tend to emit most of their light at shorter, bluer wavelengths. Lightweight, long-lived stars glow more brightly at longer, redder wavelengths. Thus, a reddish tinge typically indicates a galactic region that contains stars that formed earlier than those in bluer regions.

By fitting the color of each pixel to models for age and star-formation history, "we try to work out how different components of the galaxy form," Abraham notes. "Most people now view galaxy formation as a process, not an event, and the key notion is that different parts of a galaxy probably form at different times," he says. When astronomers assign a single color to a galaxy as a whole, they "effectively assign a single formation history to the [entire] galaxy," he says.

Many remote galaxies, observed as they appeared when the cosmos was perhaps 25 percent of its current age, look like nothing more than compact blobs. These could be the building blocks of the more mature galaxies that lie nearer Earth.

Modern-day galaxies come in three types: spirals with swirling, starlit arms; football-shape ellipticals; and irregular galaxies, which have no organized structure. This set of galaxy types is known as the Hubble sequence.

"The real challenge for those of us studying the origin of galaxies is to try to understand the steps by which the Hubble sequence came into being," says Ellis.

"I'm glad to see someone is finally trying to do this in a very systematic way," Dickinson says, commenting on the Cambridge team's work. He plans to collaborate with those scientists, providing them with near-infrared observations of Hubble Deep Field North that he took last year.

Dickinson notes, however, that even in the Hubble images, the color variations show up clearly only in the largest galaxies, limiting the analysis to a small subset of the galaxies detected.

A popular theory holds that elliptical galaxies arise when two spirals crash into each other. In this model, the collision destroys the spiral arms of the two merging galaxies to form a football-shape body. Such mergers would produce short-lived, blue stars.

Abraham, Ellis, and their coworkers have found evidence supporting this model. Nearby elliptical galaxies tend to be uniformly red. However, ellipticals in the two Hubble fields, which lie farther from Earth and thus date from an earlier time in the universe, show a wider palette of internal colors. This mix of colors strongly hints that ellipticals once contained a substantial number of the transient blue stars likely to have formed in a merger.

"That's probably not a stunning surprise at this point, given what we know about galaxy evolution, but it's nice to see it directly," comments Dickinson. Ellis and his colleagues presented the findings in August at the Royal Astronomical Society's National Astronomy Meeting in St. Peters Port, England.

The team also investigated the colors of spiral galaxies. There they found a puzzle. The traditional theory holds that spiral galaxies formed from the inside out, with the bulging central region taking shape first and the outer parts forming later.

If bulges really are the senior citizens among galaxy components, then they should contain long-lived stars and look about as red in the recent past as they do now. Ellis and his colleagues found, however, that the bulges of older galaxies are decidedly bluer and have a wider range of colors than expected—even among galaxies just a few billion years younger than those around us today.

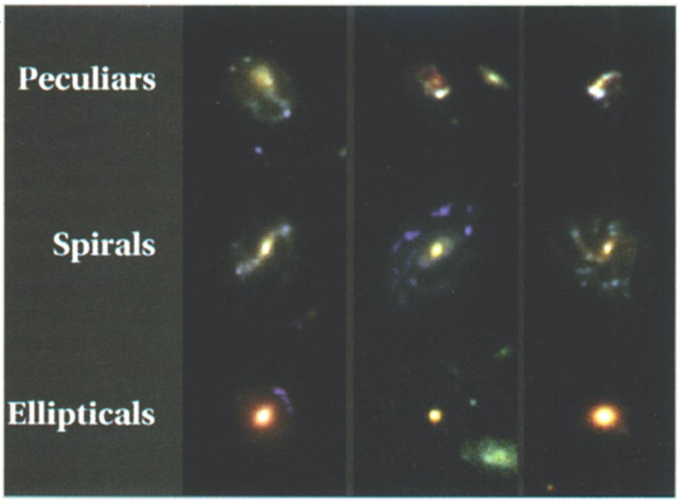
The most radical explanation for the observations is that galaxies simply don't form from the inside out. In such a model, spiral galaxies are born without a bulge. Their swirling disks of stars and gas become unstable, however, and form a rectangular structure at their center. This barlike pattern in turn evolves into a bulge.

Equally likely, however, is that the bulges really are the oldest parts of spiral galaxies, but they somehow become rejuvenated. Their fountain of youth could be gas falling onto the core of a galaxy, triggering a second wave of starbirth within the bulge. This new generation of stars would cause the bulge to look bluer.

Still, the astronomers don't know exactly why an influx of gas should occur. Finding relatively blue bulges, says Ellis, is "an indication of the huge amount of detail that we're getting from these images, and it's going to be important to follow up with ground-based telescopes."

Several of the follow-up studies that Ellis has in mind, and that other teams of astronomers have already begun, require infrared detectors. These instruments provide the only way to measure the distance and mass of remote galaxies.

The need to examine infrared signals harks back to the notion of redshift. As the universe expands, galaxies move farther apart and the light they emit appears shifted to longer, or redder, wavelengths. The more distant the galaxy, the greater its recession velocity, and the bigger the shift. So in telescopes on Earth, the vast population of stars that glow in visible light in a faraway galaxy shows up in the infrared.



Abraham et al./NASA

Distant galaxies that appear in the Hubble Deep Field. Peculiar galaxies, which resemble compact blobs, are rare in nearby reaches of the cosmos but are common in the distant universe. Spirals and ellipticals are more common in the nearby universe.

The motion of these stars provides the best measure of a galaxy's mass. Researchers are eager to weigh distant galaxies and determine the rate at which these faraway objects grow heavier over time because such data can distinguish between models of galaxy formation.

The leading model presupposes that the universe is filled with an unseen, slowly moving substance called cold dark matter. As this matter began to gather into clumps, its gravity attracted ordinary, visible material. These blobs of gas, which eventually formed stars, settled around the densest concentrations of the dark matter. In this scenario, little blobs begat big blobs and little galaxies begat big galaxies. Therefore, if the theory is correct, the baby galaxies of the universe shouldn't have much heft.

Weighing a galaxy, however, is a tricky business, notes Sandra M. Faber of the University of California, Santa Cruz. Appearances can be deceiving. A galaxy may look bright because it's big and massive, containing lots of stars, or it could be relatively puny but undergoing an intense wave of starbirth.

By measuring the velocity of gas and stars swirling inside a galaxy, researchers attempt to get a handle on its mass. The higher the velocity, the greater the galaxy's gravitational tug on its own material, and the heavier its mass.

To determine velocity, astronomers analyze how the galaxy's gas and stars emit and absorb light at particular wavelengths. If the orbiting material has a high velocity, the light it emits or absorbs will appear as a broad peak or valley in a spectrum, rather than a sharp spike.

The light-gathering ability of several giant telescopes, including the twin Keck instruments atop Hawaii's Mauna Kea, are crucial for taking spectra of faint, faraway galaxies. "My personal goal is to use these telescopes to study distant galaxies, in particular to study their masses," says Faber.

Using the low-resolution spectrograph on the Keck telescopes, Nicole P. Vogt of the University of Cambridge, Faber, and their colleagues took spectra of some 600 galaxies. These bodies are not among the most distant objects in the universe but reside halfway to the edge of the observable universe.

About one-third of the galaxies that the team studied turned out to be small, compact objects that are unusually bright. Moreover, they don't follow a well-known relationship between the rotation speed and brightness of galaxies much closer to Earth.

"That's exactly what you'd expect," Faber says, if galaxies during that time were colliding and setting galaxies aflame with new stars.

Probing further back in time, other astronomers have managed to get a rough measure of the various speeds at which gas swirls around inside five more remote galaxies. Using the United Kingdom Infrared Telescope on Mauna Kea, Max Pettini of the University of Cambridge, Charles C. Steidel of the California Institute of Technology in Pasadena, Dickinson, and their colleagues found that the spread of velocities within four of the five galaxies was relatively small, as indicated by their narrow emission lines.

That's a hint, but not proof, that the four galaxies were not very massive, Dickinson says.

R.R. Jones/UC Santa Cruz

The DEIMOS spectrograph, shown here with optics researcher David Hilyard, will be installed at the Keck observatory next year. Astronomers hope that by 2003, the instrument will measure the exact distances to some 50,000 galaxies that lie about halfway to the edge of the observable universe.

This preliminary finding dovetails with the idea that galaxies began small and became the building blocks for elliptical galaxies and the bulges of spiral galaxies seen today. The poor quality of the data and the small number of galaxies studied so far, however, doesn't allow a firm conclusion.

Although telescopes provide pictures of galaxies as they looked long ago, "you don't get to watch one galaxy evolve from one time to another," Dickinson notes. So, "the hardest part of any of this . . . is to know how to connect what you see at one time to what you see at another. If you want to connect the dots, you need samples of galaxies that span very broad ranges" of cosmic time, he says.

At present, astronomers are faced with a 3-billion-year gap in cosmic history. They have detected few galaxies that date between 8 billion and 11 billion years ago because these far away objects require high-quality infrared spectrographs that have not been available.

"There seems to be something interesting going on [in that epoch]," says Steinmetz. "The galaxy population that we observe today probably formed in that period."

A new, near-infrared spectrograph recently installed on Keck I should make it easier to fill in the gap, as well as to measure the mass of galaxies. Ultimately, says Dickinson, if astronomers can weigh several thousand distant galaxies, they might be able to decide whether the universe has enough mass to ultimately collapse or whether it will expand forever, as several recent observations have indicated (SN: 12/19&26/98, p. 392).

In a universe that expands forever, clusters of dark matter would have formed soon after the Big Bang, and the first galaxies would have more mass than they would in a cosmos destined for collapse.

Kurt L. Adelberger of Caltech, along with Steidel, Dickinson, and their collaborators, has begun to map the distribution of baby galaxies over large patches of sky. By so doing, they hope to trace the underlying distribution of dark matter and shed further light on the architecture of the universe. The degree to which the galaxies cluster and the size of the structures they form may reveal the fundamental character of the universe.

A spectrograph called DEIMOS (Deep Imaging Multiobject Spectrograph) that Faber and her colleagues have built for the Keck telescopes is scheduled to be installed late next year. By 2003, Faber expects that the instrument will have determined the position and mass of 50,000 galaxies that lie halfway to the edge of the observable universe. Comparing this detailed map with the pattern of much nearer galaxies, the team hopes to elucidate exactly how the distribution of galaxies reveals dark matter.

"There's the potential for making all kinds of sweeping comparisons," says Dickinson, especially between galaxies seen at different cosmic times. "We've put a lot of effort into figuring out how to find distant galaxies and what we can measure from them. . . . Now, we have to try to understand how to tie it all together, and that takes more than just going out to the telescope and counting things." □