Galaxy Formation Theory Meets Its Match

From gas clumps to galactic clusters

By RON COWEN

Second in a two-part series

"Mystery of galaxy formation may be solved." That provocative headline from an April press release drew chuckles from audiences at two recent cosmology meetings.

Yet the headline may not be entirely off the mark. Analyses of the deepest images ever made of the universe, recorded by the Hubble Space Telescope 18 months ago, suggest that theorists are homing in on how clumps of gas in the early cosmos evolved into the starlit elliptical and spiral galaxies seen today.

The current generation of galaxy formation theories assumes that the vast majority of mass in the universe is made up of exotic, invisible particles known as cold dark matter (SN: 6/7/97, p. 354). The models, more than a decade old, make ad hoc assumptions about such complex processes as star formation and have often come under fire. Nonetheless, some of the key theoretical predictions about the formation of galaxies and the peak of star birth have begun to be borne out by observations.

"At the coarse level, the observations are in accord with theory," notes Hubble astronomer Richard S. Ellis of the University of Cambridge in England. "In broad brush, this is a victory for cold dark matter," adds theorist George P. Efstathiou of the University of Oxford in England.

For scientists trying to comprehend how structure grows in the universe, cold dark matter has it all over ordinary matter. This exotic material responds only to gravity, so its evolution as the universe expands is relatively simple to model. Ordinary gas, in contrast, falls under the influence of nuclear reactions, ionizing radiation, magnetic fields, and the like, making its behavior far more challenging to simulate.

As Simon D.M. White, director of the Max Planck Institute for Astrophysics in Garching, Germany, puts it, "we can calculate the evolution of dark matter, but we can't see it." In contrast, White notes, the stuff that can be seen is far trickier to understand.

The two types of matter do have an intimate link. As localized concentrations of cold dark matter come together under their own gravity, they also draw in ordinary gas. Over time, the gas cools, enabling it to condense toward the center of a disk, or halo, of dark matter and make stars—a baby galaxy.

As more material falls in, or as two dark matter halos merge, the galaxy grows larger and larger. In such models, cold dark matter provides the cosmic gravity that builds galaxies and it does so from the bottom up, making small objects that then aggregate into larger ones.

This process happens slowly, according to computer simulations performed by several groups over the past 5 to 10 years. The simulations indicate that galaxies form fairly late in the history of the cosmos and that star birth doesn't peak until the universe is about half its current age.

"For many years, everyone thought [late galaxy formation] was a crazy idea," recalls White. The prediction that galaxies assembled rather late in the history of the universe was "a nail in the coffin" of the theory of cold dark matter, says Michael S. Turner of the University of Chicago and the Fermi National Accelerator Laboratory in Batavia, Ill.

The Hubble Deep Field, new images of a small patch of the heavens, have forced researchers to pry out that nail. The myriad galaxies in the images, young and old, irregular and highly structured, have put astronomers face to face with the cosmic past (SN: 1/20/96, p. 36).

For Ellis, the variety and number of galaxies aren't the most striking features of the pictures. Instead, he marvels at what he doesn't see.

Rather than being jam-packed with galaxies, the images show a vast amount of blank sky.

"We think we have actually got to the end of the era when galaxies were forming their stars," Ellis commented last month at a conference on the Hubble Deep Field at the Space Telescope Science Institute (STScI) in Baltimore. "We're looking back far enough to see through the period when galaxies were forming, out to the other side."

Moreover, an assortment of images of less remote galaxies recorded by several ground-based telescopes supports the notion that astronomers are seeing to the edge of galaxy formation. Astronomers calculate that star birth peaked when the cosmos was only half its current age (SN: 4/26/97, p. 262). As models of cold dark matter suggest, the cosmos appears to be a late bloomer.

Estimates of the distance from Earth to many of the faintest galaxies in the Hubble Deep Field suggest that they are unusually diminutive. Follow-up observations using the W.M. Keck Telescope on Mauna Kea confirm the remoteness of these compact galaxies and indicate that some of them date from a time when the universe was one-third to one-fourth its current age (SN: 2/24/96, p. 120).

Several researchers interpret these small, starlit objects as galactic fragments that later merged to form a single large galaxy, as theory predicts. Last year, Rogier A. Windhorst of Arizona State University in Tempe and his colleagues reported that they had found about 18 so-called subgalactic clumps in the Hubble Deep Field (SN: 9/7/96, p. 149). At least eight, and perhaps more, lie equally distant from Earth.

The small relative velocities of the clumps and their proximity to each other indicate that many of them "have no choice but to merge" later in the history of the universe, he says.

"People had searched for primordial galaxies for 20 years, and almost nobody had ever found one. This study simply shows that the Holy Grail is out there, but it's out there in 100 pieces. These clumps hadn't yet had a chance to collect themselves into one large galaxy, but they will over the next few billion years.

"I think this is one of the best direct confirmations of cold dark matter," declares Windhorst.

"I'm not claiming a precise prediction," says Turner, "but [the theory of cold dark matter] says that galaxies should have formed rather recently, and that's what we're seeing."

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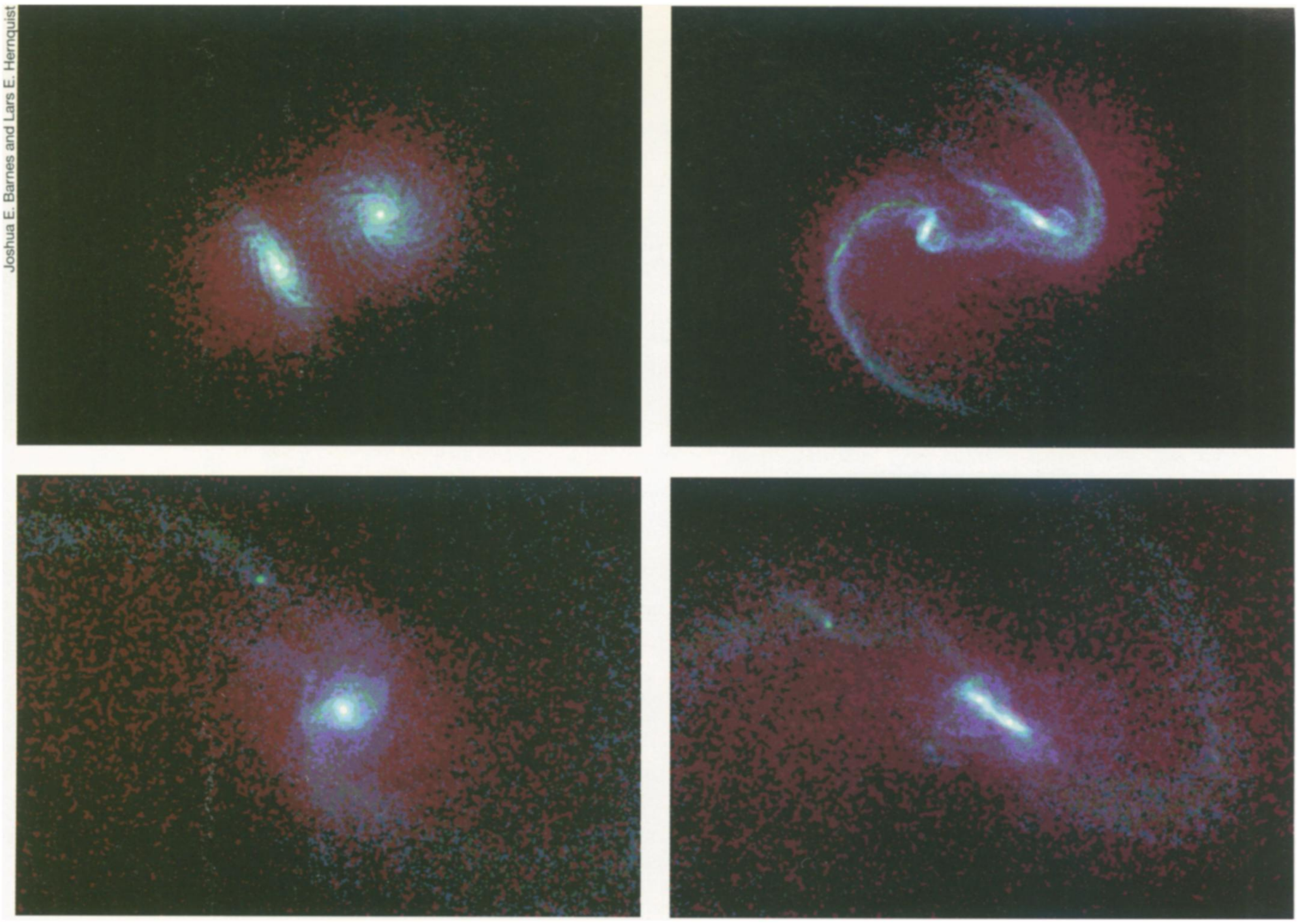

From spiral to elliptical: In this computer simulation (clockwise from upper left), two spiral galaxies (blue), each residing at the center of its own dark matter halo (red), approach each other and merge. The merger scrambles the orderly, flattened orbits of stars and gas in each spiral, generating a single elliptical galaxy.

Although the case is less clear-cut, the Hubble Deep Field also seems to lend credence to detailed models of galaxy formation developed independently by White and Guinevere Kauffmann of the Max Planck Institute and by Carlos S. Frenk and Shaun Cole of the University of Durham in England and their colleagues. Their simulations show that the first galaxies to form are spiral. That's because each halo of dark matter tends to have some rotation, which it imparts to the gas falling toward its center. As this spinning gas cools and contracts, it flattens into a disk.

In this scenario, elliptical galaxies are secondary, arising only after the first batch of spirals has appeared. If two dark matter halos chance to collide, the embryonic galaxies at their centers may coalesce. This merger scrambles the ordered rotation of the two spirals, and they combine into a single elliptical galaxy. The collision may also generate a sudden rash of star birth, consuming all the gas in the galaxy. Its gas supply exhausted, the elliptical galaxy can no longer make stars. Its population of stars grows older and redder as the galaxy ages. The red color of elliptical galaxies today generally suggests that their days of star formation have long since ceased.

An elliptical galaxy may turn back into a spiral one. Gas at the fringes of the galaxy could slowly coalesce around the core, allowing star formation to resume. Alternatively, a merger with another galaxy may introduce new gas around the elliptical galaxy. Either way, the elliptical would then end up as the elderly core of a new star-forming spiral. In this way, notes White, spiral and elliptical galaxies are constantly being created and destroyed, and there is no one magic epoch when galaxies formed.

The model suggests that the universe in the distant past contained far fewer large elliptical galaxies than it does today. Although an analysis of the Hubble Deep Field remains ambiguous on that point, Hubble astronomer Mark E. Dickinson of STScI and Johns Hopkins University in Baltimore says he finds hints of such a deficit.

Not everyone accepts the model of galaxy formation proposed by White and by Frenk. Michael Rowan-Robinson of Imperial College in London cautions that the early universe may have witnessed a vast amount of star birth, the evidence of which lies hidden behind a veil of dust. Hubble's newly installed Near Infrared Camera and Multi-object Spectrograph, a high-resolution infrared detector, could lift that veil—if its wide-field camera gets back into focus (SN: 5/3/97, p. 272).

Cosmologist Jim Peebles of Princeton University points out another potential problem with the model. For some 20 years, astronomers have detected dense clouds of hydrogen gas in the early universe. These clouds, he notes, may represent large, fully grown galaxies, a violation of the deliberate, step-by-step assembly required by cold dark matter. On the other hand, says S. Michael Fall of STScI, the abundances of heavy elements—material produced by stars—in these clouds are consistent with star formation occurring relatively late in the universe.

For Ellis, recent advances in modeling are not nearly enough. "The theory is still empirical; it's telling us what we're seeing. The job then is to physically explain why [galaxy formation] happens at that time and how different types of galaxies came into being."

Or as White puts it, "The data suggest that we've already seen galaxy formation. All that remains for us is to actually understand it." □