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Studies of Light and Shadow

Spotlighting dark matter and galaxy formation

Ron Cowen

New surveys of the sky are examining the two facets of galaxy formation. One focuses on the glitter. The other examines the gloom. A census of both the light and the dark parts of the cosmos is essential for understanding how today's universe came to be, the scientists say.

One of the new surveys looks at the panorama of galaxy shapes, masses, colors, and sizes that existed when the cosmos was about half its current age—a critical time when galaxies began to take the form they're in today. The other survey also sizes up galaxies but uses some gravitational sleight of hand to expose the dark side—the vast concentrations of dark matter that provide the framework for all the visible stars and gas in the universe. Dark matter, though unseen, makes up more than 90 percent of the mass of the universe, theorists say.

Together, the new surveys paint a more detailed portrait of galaxies and their origin than astronomers have ever had.

Astronomers assembled this three-dimensional map of the cosmos' invisible dark matter by analyzing data from the largest survey of galaxies ever conducted with the Hubble Space Telescope. A separate, ground-based survey traces the growth of galaxies since the universe was half its current age.
Scoville *et al.*/NASA

Dark landscape

The Hubble Space Telescope's Cosmic Evolution Survey (COSMOS) is the largest galaxy study the telescope has ever conducted. It covers an area nine times the size of the full moon on the sky. That's big enough not only to map the distribution of several hundred thousand galaxies, but also to unveil the arrangement of dark matter in unprecedented detail.

"It's a milestone achievement to see where the dark matter lies," says COSMOS astronomer Richard Ellis of the California Institute of Technology (Caltech) in Pasadena. Without this invisible stuff, he says, the universe as we know it wouldn't exist. According to the leading model for the formation of cosmic structure, dark matter coalesced earlier in the universe's history than ordinary, visible matter did. It's the tug of dark matter that pulled stars and gases into galaxies.

As the cosmos evolved, dark matter formed an irregular scaffold across the cosmos. Galaxies continue to concentrate in the densest regions of this network, forming the tapestry of galaxy clusters and superclusters seen today. Dark matter also maintains the shape of those clusters against the diluting effect of cosmic expansion, which would otherwise wash out cosmic structures.

Dark matter betrays its presence through its gravitational effect on visible matter. As first predicted by Albert Einstein in the 1930s, any large concentration of mass—visible or not—acts as a gravitational lens, bending the light coming to Earth from galaxies that lie directly behind that concentrated mass. The effect distorts the galaxies' observed shapes.

By measuring the shapes of half a million distant galaxies recorded with the sharp eye of Hubble's Advanced Camera for Surveys, Caltech astronomer Richard Massey and his collaborators inferred the distribution of matter that resides directly in front of those galaxies, as seen from Earth. The researchers describe their work in the Jan. 18 *Nature*. They also presented their findings in January at a meeting of the American Astronomical Society in Seattle.

Astronomers don't know the original, undistorted shape of any particular galaxy, notes Massey. But by analyzing the images of hundreds of thousands of galaxies, he and his colleagues found departures from the expected pattern of galactic shapes and, from those, estimated the distortions imprinted by dark matter.

New dimension

To add a critical third dimension to their work, the COSMOS researchers used the large Subaru telescope on Hawaii's Mauna Kea to record the colors of the galaxies observed by Hubble. The colors indicate approximate distance because the expansion of the universe shifts the light emitted by the most remote galaxies to the reddest wavelengths. The more distant the galaxy, the longer its light must travel to reach Earth, and the farther back in time observers see the galaxy.

Treating the survey as if it were an archaeological dig, the team divided the observable galaxies into slices from three different cosmic epochs. Gravity-generated distortions in images of the galaxies from each time slice then enabled the researchers to map the distribution of dark matter as it appeared 3.5 billion, 5 billion, and 6.5 billion years ago. The earliest map represents the cosmos at nearly half its current age. The maps demonstrate how dark matter weaves a cosmic web, with filaments growing in size and density as the universe ages, Ellis says.

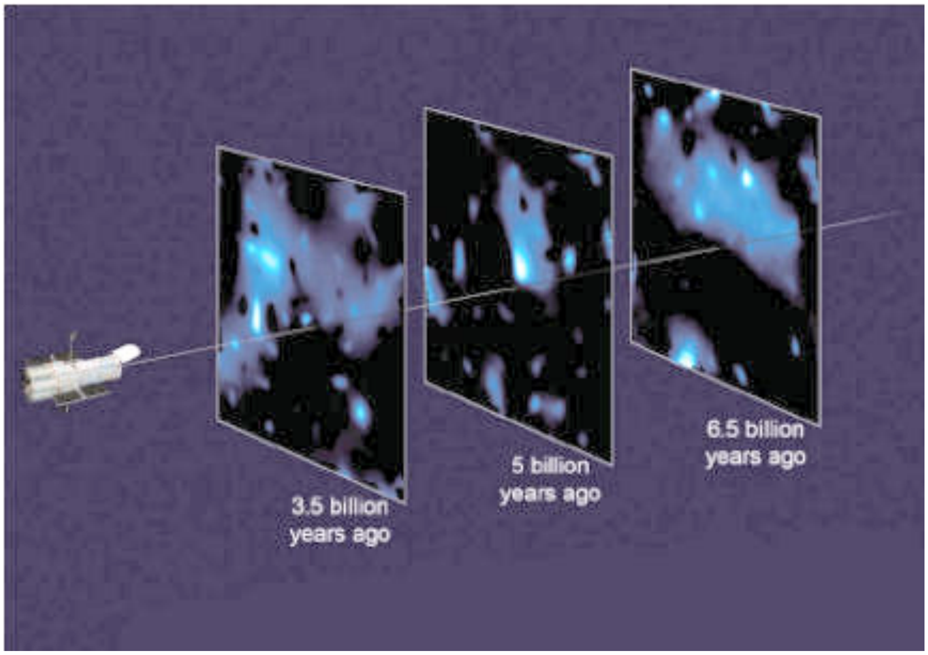
"It's very reassuring" that the dark matter structure revealed by COSMOS matches models that theorists have touted for more than 2 decades, notes Ellis. Mapping dark matter using the gravitational-lens technique dates back to the 1980s, but the distribution "has never been seen very clearly" or on such a large scale, he adds.

The Hubble study covers a smaller area of sky than searches for dark matter with ground-based telescopes have, but the new observations drill deeper into space and include a higher density of galaxies, notes gravitational-lensing pioneer J. Anthony Tyson of the University of California, Davis.

"This is a great step forward, as observations from space avoid the distortion and time variation that Earth's atmosphere imposes on the astronomical signal," notes theorist Eric Linder of the Lawrence Berkeley (Calif.) National Laboratory in a commentary accompanying the Jan. 18 *Nature* report on the COSMOS data. "The new maps have a much higher resolution than the best ground-based observations."

Dark and light

The COSMOS map has also enabled Ellis, Massey, and their colleagues to examine the evolution of galaxies. The researchers are seeing how well the galaxies "were painted on the dark matter," says Ellis.



DARK CLUMPS. The Hubble Space Telescope's COSMOS survey revealed these images of dark matter as distributed (left to right) at 3.5 billion, 5 billion, and 6.5 billion years ago. As the dark matter coalesced into clumps, the densest areas formed the framework for clusters of galaxies.
Massey *et al.*, NASA, ESA

In general, galaxies cluster around the densest concentrations of dark matter, in accord with theory, notes COSMOS Caltech astronomer Nick Scoville. Regions that shine brightly at X-ray wavelengths, an indicator of highly concentrated gas in a strong gravitational field, almost always overlap with the highest densities of dark matter. Nonetheless, notes Scoville, there are some puzzling discrepancies.

In some places, the galaxies clump where there is no underlying dark matter, and some dark matter coalesces where no corresponding bright material lies. "For the dark matter skeleton of mass in the universe, flesh sometimes occurs without supporting bones, and bones without surrounding flesh," notes Linder.

It's too soon to tell whether the discrepancies merely point to the limited sensitivity of Hubble's detectors and the team's image-processing technique or whether they represent true anomalies, says Scoville. Differences would be expected if proposed dark matter particles were to interact with matter only though gravity. In contrast, visible matter can be pushed around by other forces, including the pressure of light. The clumping might also elucidate the nature of dark matter, since different types of dark matter particles would clump in different ways.

Obtaining more information on the clumping of dark matter would require a much broader study of the heavens. Tyson and his colleagues have proposed a survey across the entire sky using a ground-based telescope to be built atop Cerro Pachon in Chile.

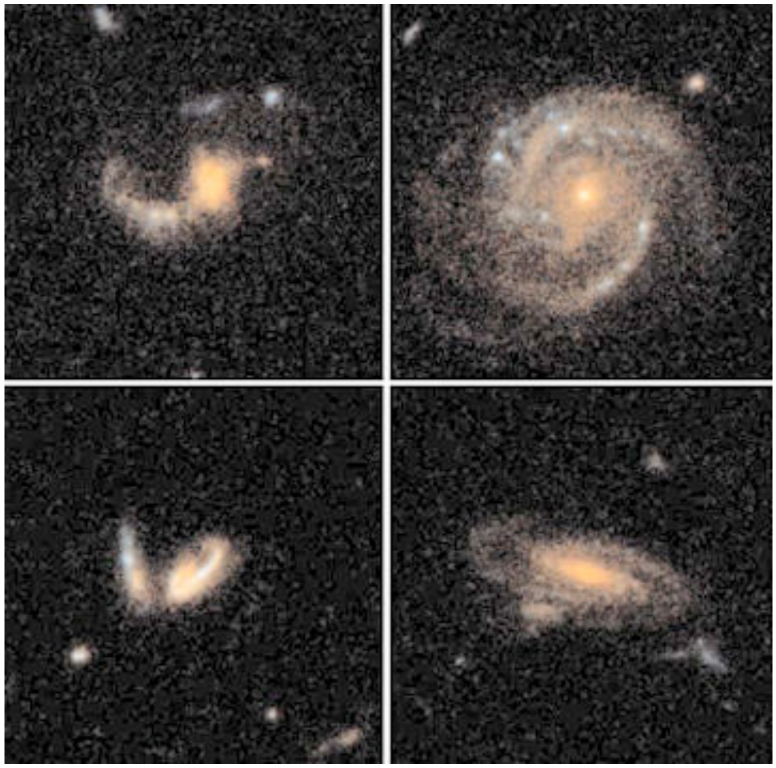
The COSMOS survey provides new evidence that the young universe contained many more small, closely packed galaxies than it does today. That observation supports the "bottom-up" model of galaxy formation, which holds that many large galaxies such as the Milky Way are the products of the merger of dwarf galaxies.

COSMOS also corroborates previous findings that galaxies now forming large numbers of stars tend to be lower in mass and situated in lower-density regions of the dark matter framework than are galaxies that formed most of their stars in the past.

Theorists call this shift—from big to little—in star-formation activity downsizing. They argue that the massive galaxies associated with the densest concentration of dark matter formed and evolved faster than small galaxies in less-populated regions, where gravity takes longer to condense enough matter to ignite star formation. Scoville and his colleagues report their findings supporting the downsizing scenario in an upcoming *Astrophysical Journal*.

The bright side

Another large survey, called AEGIS (for All-wavelength Extended Groth Strip International Survey), is also shedding light on galaxy formation. The study is an extension of one begun in 1994, when Princeton University astronomer Edward J. Groth used Hubble to record a small field of galaxies.



GOING THE DISTANCE. These galaxies, studied in the AEGIS survey, appear as they were about 6.5 billion years ago.
Noeske, J. Lotz, DEEP2 Team, U.C. Berkeley, U.C. Santa Cruz, NASA

AEGIS has now directly measured the distances to more than 10,000 galaxies dating to when the universe was about half its current age. A team led by Sandy Faber of the University of California, Santa Cruz and Marc Davis of the University of California, Berkeley measured those distances using a spectrograph on the Keck 2 telescope atop Mauna Kea. The device simultaneously takes the spectra of 150 galaxies.

A host of other ground-based telescopes, as well as Hubble and the Chandra X-ray Observatory in space, have added to the survey. The array has registered emissions ranging from the shortest, most-energetic X rays to the longest radio waves coming from galaxies. AEGIS' observations trace the rate of star formation over the last half of cosmic history and gauge the mass of the galaxies in which stars reside.

The survey finds that heavy galaxies formed their stars relatively early in cosmic history, while many less-massive galaxies are late bloomers that are still making stars steadily.

"To understand the properties of galaxies like our Milky Way, it is crucial to know when back in time they made how many of their stars," says AEGIS researcher Kai Noeske of the University of California, Santa Cruz.

Quietly making stars

Collisions between galaxies fan the flame of star formation by stirring up gases and dust, which then condense into stars. Previous studies show that collisions played a key role in triggering sudden bursts of star birth during the early history of the universe.

But to the surprise of many astronomers, collisions don't appear to have played dominant roles in making stars during the past several billion years. The AEGIS team reports this finding in an upcoming *Astrophysical Journal*

Letters devoted to the survey's results.

Rather than producing stars in bursts, galaxies within a few billion light-years of Earth steadily convert gas into stars until their gas supplies dwindle. Moreover, the rate of star formation in galaxies is tightly related to the total mass of stars they possess. The lowest-mass galaxies produce stars at a slow rate.

Faber, Davis, and their team came to those unexpected conclusions after using the Keck 2 spectrograph to measure the mass, star-formation rate, and number of stars already formed for some 3,500 galaxies. The study revealed that galaxies of similar weight tend to have about the same star-formation rate. That correlation is strongest for the lowest-mass galaxies.

"This is not what you would expect if strong starbursts were frequent—some galaxies would be star bursting, some would be quiescent, and star-formation rates would be all over the place," says Noeske. "We see that the average level of this range of star formation declines with time, in a gradual manner."

The survey indicates that "galaxies of a given mass march in a loose lockstep," says Noeske. "Star formation in galaxies follows a quite simple pattern," he asserts, "and simple patterns often mean that there are only few basic physical mechanisms at work. ...We can now find out what these mechanisms are by measuring how star formation behaves with time and mass of the galaxy, and compare that behavior to models."

Astronomers plan to combine data from surveys such as COSMOS and AEGIS, piecing together the light and the dark views of the universe, to glean the full story of how galaxies evolved.

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