Cosmic Structure: Matter on the Largest Scales

Nick Scoville

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Cosmic Structure: Matter on the Largest Scales

Two major questions of modern astrophysics relate to matter on the largest scales. First, how did nature’s largest discrete objects—galaxies and clusters of galaxies—form from the nearly uniform matter left over after the Big Bang? Secondly, once formed, how did they evolve into their counterparts that we see in the nearby universe today? The fact that these ambitious questions are even addressable is because of the finite speed of light. Because it takes time for light to travel across space, things appear as they were when the light began its trip to the telescope. Today, astronomers use Hubble to view galaxies as far as 12.7 billion light-years away, seeing them as they were less than 1 billion years after the Big Bang. At that time, the universe was only 6% of its present size and age, yet the universal arrangement of matter was well underway. The role of the Cosmological Evolution Survey (COSMOS) is to use the telescope as a “time machine” to visit the past in order to test our expectations about the history of cosmic structure.

For an astronomer, “matter” includes any material that responds to gravity. Based on a large body of evidence, astronomers believe there are two distinct types of matter in the universe, “ordinary matter” and “dark matter.” We see ordinary matter all around us as it emits, reflects, and absorbs light. Atoms, molecules, and ions are ordinary matter—stars, planets, and even people are ‘condensations’ of this ordinary matter. By contrast, dark matter does not interact directly with light, except by its gravity, which bends the space through which light travels. Because dark matter cannot lose energy by emitting light, it forms no bonds as in the atoms or molecules of ordinary matter, and cannot condense into dense objects like stars and planets. The dark matter remains more rarified, but pervasive throughout the universe, and the gravitational attraction it exerts on the ordinary matter is only substantial on the very large cosmic scales of galaxies and galaxy clusters. Except for its gravitational tug, dark matter is the diffuse phantom of the universe.
One of the most remarkable achievements of 20th century astronomy was establishing the proportions of the types of matter in the universe. From the motions of galaxies bound in clusters, we know that stars can account for only about 1% of all matter. Intergalactic gas in clusters of galaxies—so hot it is visible only in x-rays—accounts for much more, about 15% of all matter. The remainder, 84% of all the gravitating mass in the universe, is dark matter. While the physical nature of dark matter is not yet known, its reality, principal characteristics, and gravitational dominance on cosmic scales are generally accepted (see accompanying article by Clowe).

**What are our expectations concerning the cosmic history of the structure of matter?**

Our earliest clue is the cosmic microwave background (CMB)—a primordial glow visible to radio telescopes—which covers the whole sky. This is the “skin” of the Big Bang, beyond which we cannot see. The moment of cosmic time, or epoch, of the CMB is when the universe was about 300,000 years old and it first became transparent to light. The CMB is highly uniform, varying in brightness by less than 1/1000th of 1% across the sky. Over the subsequent hundreds of millions of years—up to the time of the earliest galaxies imaged by *Hubble*—we expect to find that these density enhancements grew in magnitude as dominant dark matter fell freely under gravity, collapsing into low-density clumps and filaments. With no friction, dark matter would collapse only so far, and no farther, stopped by its inability to shed energy in any type of light, such as x-rays, radio waves, or visible light.

Meanwhile, we expect that the gravity of the dominant dark matter also acted to collect ordinary matter within this emerging framework. Because the ordinary matter does experience friction and can shed energy in various types of light, we expect it continued to contract more than the dark matter, into ever-smaller condensations—into clouds of gas, parts of which further collapsed to form the first generation of stars. Assemblages of stars became protogalaxies, which collided and merged. Groups of galaxies formed protoclusters (see article by Miley). Ultimately, most gas gathered in the space between the galaxies within clusters, where we see it emitting x-rays.

COSMOS tests these expectations by conducting an inventory of matter through cosmic time, discovering the relation between ordinary matter and dark matter, and observing the evolution of galaxies and clusters.
The COSMOS observations

The COSMOS data set is a montage of 581 deep images in the constellation Sextans, obtained by Hubble’s Advanced Camera for Surveys (ACS). It is the largest montage produced by Hubble to date. In 2003 and 2004, 10% of Hubble’s observing time—1,000 hours, 6 weeks in all—was devoted to obtaining this collection of images.

Within the COSMOS field, the research team cataloged over 2 million galaxies, creating the largest sample ever studied in the early universe. The team gathered additional data from NASA’s Chandra X-ray Observatory and Spitzer Infrared Observatory, the European Space Agency’s XMM/Newton Telescope, and an armada of the largest ground-based telescopes. The team analyzed and melded this vast and various information set into an unprecedented scientific portrait of a great cosmic volume.

The weak lensing distortions, due to dark matter concentrations along the line of sight, are illustrated in a simulation. On the left, spherical background galaxies are shown as they would appear undistorted. On the right, concentrations of dark matter have been superposed in the foreground to distort the space through which the light from the distant galaxies travels to us, thus bending the image of each galaxy in a patterned fashion over small areas of the sky.
**Mis en place—everything in its place**

The COSMOS picture is two dimensional. Galaxies may appear close together, but most are widely separated along the line of sight. We need a third dimension of distance to learn which associations are true and which are line-of-sight coincidences. In addition, we see these galaxies at different ages, so we need another dimension—time—to know how galaxies and their associations evolved over cosmic time. The team used photometric redshifts to assign each galaxy in the catalog its correct location in distance and time (see sidebar).

The photometric data (measurements of brightness and color) of galaxies came from concerted observations at the largest ground-based observatories. The observing protocol used 34 filter bands, covering the ultraviolet to the near infrared. In addition to producing redshifts (i.e., distance and time), the COSMOS team used the photometry to provide physical characterizations. That is, the color and brightness of a galaxy indicates the number, mass, and age of its stars, from which the total stellar mass and average stellar age of the galaxy can be estimated. Therefore, the photometric data yielded a three-dimensional inventory of stellar mass over the COSMOS field to a distance of 11.5 billion light-years, or redshift $z = 3$. 

Slices of the COSMOS field, illustrating the association of ordinary matter and dark matter over cosmic history.
Using the Chandra and XMM/Newton x-ray observatories, the team imaged the hot gas in the densest galaxy clusters to a distance of 8.8 billion light-years, or $z = 1.3$.

The dark matter concentrations along the line of sight distort and warp the space through which the light from more distant galaxies travels to us. This enabled the team to use the distortion patterns in the shapes of half-a-million distant galaxies to infer the distribution of foreground dark matter in the COSMOS field (see sidebar on weak lensing in article by Clowe). In this case, the information about the third dimension, the distance into the sky, was gained by exploiting a peculiarity of gravitational lensing—that the distortion is greatest for galaxies at twice the distance of the mass concentration that acts as the lens. By studying the distortion in subsets of galaxies within narrow ranges of distance, the team pieced together the variations of the dark matter distribution with redshift (distance and time).

The COSMOS survey confirms our basic expectations about the development of cosmic structure. A statistical comparison of the observed distributions of ordinary matter and dark matter shows that normal matter, largely in the form of galaxies, accumulates along the densest concentrations of dark matter. The data show that in both the dark matter and the galaxies, a loose network of filaments grew over time, intersecting in massive structures that coincide with the locations of clusters of galaxies. Both forms of matter have grown increasingly clumpy as gravity continues to concentrate them.

**Evolution of galaxies in relation to structure**

Hubble’s exquisite images enable astronomers to classify even the most distant galaxies according to shape. When they are grouped by cosmic age, the galaxies illustrate evolution—the process of their development through time. In the COSMOS field, the new knowledge about the large-scale distribution of matter enables astronomers to relate galactic evolution to cosmic environment.

In the densest regions of the early universe, the COSMOS filter photometry finds that galaxies already include old stars, implying that these galaxies were first to form, and that they accumulated the greatest mass. By contrast, the galaxies with ongoing star formation are located in less-populated regions and cosmic voids. After correcting for redshift, the general color of the earliest galaxies is blue, because of their extremely young stellar populations. Their appearance is irregular, as they are in the process of initial assembly.
At intermediate epochs, the majority of the elliptical galaxies have taken shape (most rapidly in the densest environments); their stellar populations appear red, indicating little ongoing star formation. At the same time, the spiral galaxies are still forming in the environments that are less dense. In the most recent epochs, the spiral and elliptical galaxies display their familiar shapes in the modern universe.

COSMOS has involved an international team of over 100 scientists in the United States, Japan, Germany, Switzerland, France, Italy, and Great Britain. It is a pleasure to acknowledge their great contributions to COSMOS. The public is invited to http://cosmos.astro.caltech.edu/ and COSMOS in Google Sky.
Selected galaxies seen in COSMOS images shown for a range of redshift $z$, cosmic age, and distance. In contrast to the nearby present-day galaxies, which exhibit the two most common shapes (spirals and ellipticals), the galaxies seen at successively higher redshift become smaller and more disordered. At the earlier epochs, larger fractions of the galaxies appear as multiple systems undergoing galactic collisions—an important process by which galaxies grow in mass and size. (The galaxies seen at successively higher redshifts are intrinsically smaller and less organized.)

<table>
<thead>
<tr>
<th>$z$</th>
<th>Cosmic Age (billion years)</th>
<th>Distance (billion light-years)</th>
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<tbody>
<tr>
<td>5.7</td>
<td>1.0</td>
<td>12.7</td>
</tr>
<tr>
<td>5.0</td>
<td>1.2</td>
<td>12.5</td>
</tr>
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<td>3.3</td>
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<tr>
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<td>5.9</td>
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</tr>
<tr>
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<td>8.7</td>
<td>5.0</td>
</tr>
<tr>
<td>0.1</td>
<td>12.4</td>
<td>1.3</td>
</tr>
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A small portion of the approximately 2 million galaxies imaged by Hubble in the COSMOS survey. At the largest scales, the galaxies in the universe appear to form a network of immense filaments separated by even larger voids. Evidence is mounting that galactic filaments accumulate along concentrations of dark matter.
Cosmological Redshift, Cosmic Time, and Distance

The history of cosmic structure has a context: the general expansion of the universe since the Big Bang (see article by Riess). This expansion causes the cosmological redshift, which is an easily measured effect on the spectrum of a galaxy, revealing its age and distance.

The spectrum of a galaxy is the variation of its brightness with the wavelength of light. It contains distinctive features caused by the normal, common atoms found in the atmospheres of its stars. Because the laws of physics are universal, the same types of atoms produce identical features whether the atoms are located in the most distant galaxy, or in a present-day laboratory on Earth. Nevertheless, when we compare the spectrum of a distant galaxy with a laboratory spectrum, we find the spectral features of the galaxy have shifted to longer wavelengths—that is, redshifted. During the time it took the light to travel from that far-away galaxy to the telescope, the universe expanded, which stretched all waves of light like letters printed on a balloon.
For astronomers, the symbol $z$ stands for the numerical value of the cosmological redshift, and the observed wavelength is $1 + z$ times the laboratory wavelength. At $z = 1$, every wavelength is doubled, and normally visible light in the wavelength range 400–650 nanometers (nm, billionth of a meter) would be shifted into the near infrared, 800–1300 nm. For the furthest galaxy studied by Hubble, at $z = 6.7$, the fundamental spectral line of hydrogen—the Lyman-$\alpha$ line at 121 nm, in the far ultraviolet—is observed in the far red at 932 nm, beyond the range of the human eye.

Two particular features, which are distinctive steps in the spectrum, are most useful for estimating the redshifts of faint, distant galaxies. Called the “Lyman and Balmer breaks”—the steps are due to the most energetic internal transitions in the hydrogen atom. The Lyman and Balmer breaks are useful because astronomers can easily estimate their location in the spectrum—which determines the value of the redshift, $z$—by measuring the brightness of a galaxy through a series of color filters. Astronomers call measurements of brightness “photometry,” and this way of estimating $z$ the “photometric redshift.”

Using a cosmological model, the value of $z$ translates into three important characteristics of a galaxy: its cosmic age (billions of years after the Big Bang), the look-back time at which we see it (billions of years in the past), and the distance to it (billions of light-years).

Nick Scoville is the Principal Investigator of COSMOS and Moseley Professor of Astrophysics at Caltech in Pasadena, California. He was born in 1945, the son of Herbert (an arms control scientist) and Ann Curtiss Scoville (a sculptor). He obtained his B.A. (1967) and Ph.D. (1972) at Columbia University. His research includes radio, infrared, and optical observations, and theoretical astrophysics.