{ EXTRAGALACTIC ASTRONOMY }

As far as Hubble can see

Astronomer **Sangeeta Malhotra** provides an insider's look at the Hubble Ultra Deep Field.

Last year, astronomers at the Space Science Telescope Institute in Baltimore revealed the Hubble Space Telescope's Ultra Deep Field (HUDF), a million-second exposure that revealed the faintest objects ever seen.

To an astronomer, the term "deep" usually refers to the faintness of objects detected during an observation: A deeper observation detects fainter objects. But the word "deep" also has a more literal meaning. It implies knowledge of distances in the third dimension, as in "How deep is this lake?" Such information is not easily obtainable from astronomical images. Yet, thanks to a Hubble observing program called the Grism ACS Program for Extragalactic Science (GRAPES), my colleagues and I have been able to provide exactly that for the HUDF.

The first step in measuring distance is to get spectra — to split the light from stars, nebulae, and galaxies into discrete wavelengths, like sunlight separated into rainbow colors by a prism or a raindrop. When examined closely, the light often shows breaks or sharp lines. Due to the expansion of the universe, spectral lines shift farther toward the red the more distant a galaxy is, a phenomenon discovered by Edwin Hubble. Astronomers determine distance by comparing redshifts of the same spectral lines in nearby and distant galaxies. It's fitting, then, that we're able to measure the distances of some of the faintest and farthest galaxies using the telescope named for Hubble.

Why is the Hubble Space Telescope so sensitive? Even the largest ground-based telescopes suffer from image-blurring from small motions in Earth's atmosphere. From its orbital perch, Hubble takes sharper images and can resolve small, distant galaxies. Another less well-known advantage of Hubble's location is that our atmosphere glows at red and infrared wavelengths. Yet, distant galaxies are brightest in these wavelengths because intervening intergalactic matter absorbs the other colors.

Sounding the Ultra Deep Field

Two years ago, all of Hubble's strengths came together in a project to carry out spectroscopy of the Ultra Deep Field. Imaging the region using the Advanced Camera for Surveys (ACS) and the Near Infrared Camera and Multi-

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MORE THAN 10,000 galaxies inhabit the Hubble Ultra Deep Field. The space telescope's accumulated observations of this 3-arcminute-square patch in the constellation Fornax amounts to a million-second exposure. The image is centered at R.A. 3h32m40.0s, Dec. –27°48'. This cosmic snapshot is at the very limit of Hubble's vision. More distant galaxies, glowing at long infrared wavelengths, are beyond the reach of the telescope's present instruments.

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STEVEN BECKWITH

Object Spectrometer (NICMOS) took about a month of telescope time spread between September 2003 and January 2004. As part of the GRAPES project, my team performed spectroscopy on the HUDF target region between October 2002 and January 2003, using about 10 percent of the time that went into imaging.

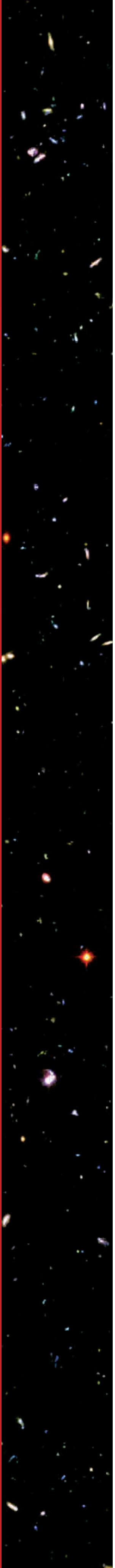
We quickly discovered that GRAPES is not just an extragalactic survey, for the HUDF distance scale starts within our own galaxy. The closest object we have identified, an M-type dwarf star we designated Ultra Deep Field (UDF) 366, lies 2,000 light-years away, still in our galaxy's disk.

Most of the stars we detected are low-mass M dwarfs, which are both faint and numerous. We can't use redshifts to determine distances to these stars. Instead, we examine spectral features to help us identify their type and luminosity. Then, we figure distance by comparing the brightness we expect to what we actually observe. It's a tricky business, employing many indirect arguments.

> Just 40 hours of Hubble observations have taken us back 12.6 billion years.

Next in the HUDF distance scale come small, blue galaxies actively forming stars and bearing a resemblance to nearby dwarf irregular galaxies. The ACS grism (a cross between a diffraction grating and a prism, used for separating light into its component colors) reveals prominent emission lines caused by gas heated and ionized by active star formation. The median distance of these galaxies is 6 billion light-years, so we see them when the universe was half its present age. This was the peak era of star formation. Since then, galaxies have slackened their pace.

At similar distances, we also see massive elliptical galaxies. Sometime in the previous billion years, their star formation halted, so their stellar population skews old. Looking back another 3 billion years and more, the abundance of these old systems was a surprise. They formed quickly in the universe's first couple of billion years and then



HUDF in-depth

OBJECTS WITHIN THE HUBBLE ULTRA DEEP FIELD range from stars in our own neighborhood to the most distant galaxy with a directly measured redshift (6.7). Astronomers express distances in the far universe using redshift because it's the most easily determined distance indicator. The preferred alternative is to express extreme distances in terms of the universe's age. IMAGES COURTESY NASA/ESA/STScI/STEVEN BECKWITH AND SANGEETA MALHOTRA

The nearest star in HUDF is known as UDF 366, an M-type dwarf star just 2,000 light-years away.

The farthest star resolved is UDF 2457, another M dwarf. It lies 59,000 light-years away.

UDF 1344 is a star-forming galaxy at redshift 0.0369 (504 million light-years away).

UDF 8316 (center) is an elliptical galaxy at redshift 0.62. Its light took 5.8 billion years to reach us.

UDF 7556, a spiral at redshift 0.89 (6.1 billion years after the Big Bang), is making a lot of stars.

UDF 521 sparkles with newborn stars at redshift 1 — 5.7 billion years after the Big Bang.

This majestic spiral (UDF 423) whirls at redshift 1, when the universe was 43 percent its present age.

We view UDF 1446 at redshift 2.47, as it was when the universe was 2.6 billion years old.

UDF 2881 is a Lyman-break galaxy at redshift 4.6, or 1.3 billion years after the Big Bang.

UDF 5225 is a galaxy with a tail at redshift 5.2, or about 1.1 billion years after the Big Bang.

UDF 2225 is the brightest galaxy at redshift 5.8, when the cosmos was 940 million years old.

UDF 30591 (red dot) is a Lyman-break galaxy at redshift 6.7 — the farthest directly measured.

stopped making new stars. We hope investigating these galaxies will lead to an insight into what prompts the onset of star formation in a galaxy — and what ultimately stops it.

Farscape

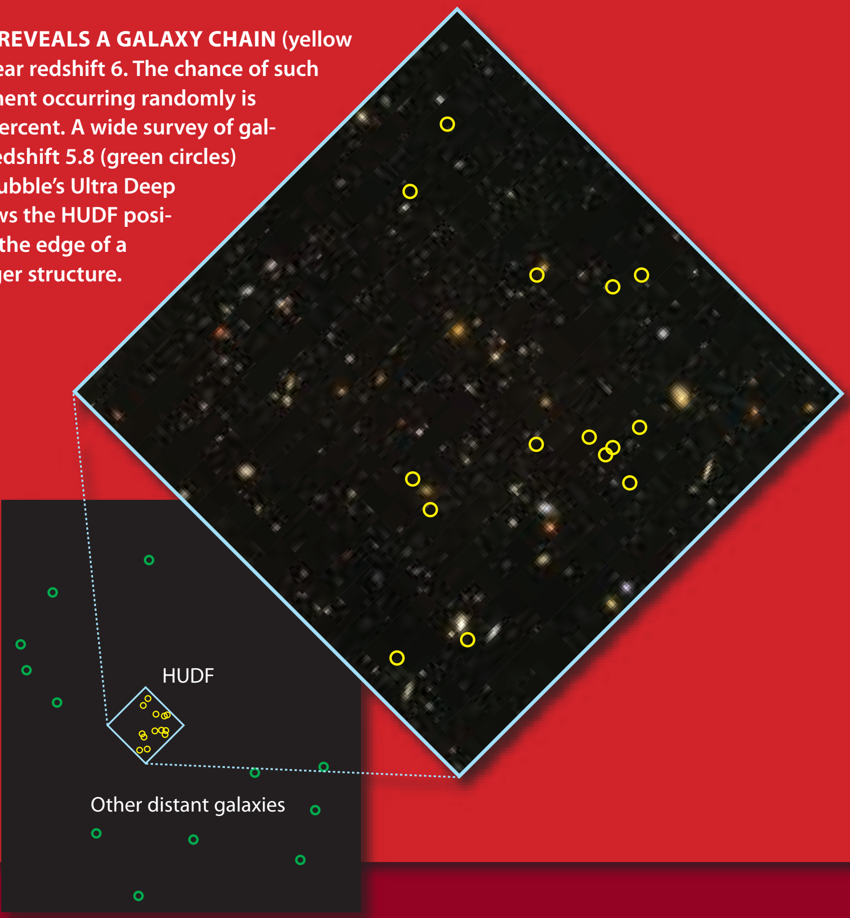
Beyond redshifts of 4 — corresponding to times earlier than about 1.5 billion years after the Big Bang — we can measure the distances of all galaxies thanks to a dramatic drop-off in the ultraviolet spectrum of hydrogen known as the "Lyman break." At such extreme distances, this spectral feature redshifts into the wavelength range ACS can detect. We see about 50 Lyman-break galaxies between redshifts of 4 and 7. And because the HUDF goes deep, we know these are the typical galaxies at those redshifts.

Looking at the colors of these galaxies tells us their stars are younger than those we see in galaxies at intermediate distances. The distant galaxies are ragged and irregular. This is partly because we're seeing them in ultraviolet light, and partly because the galaxies are still forming. Untangling the two effects will be valuable.

Because their spectra give us accurate distances, we can see that these galaxies are distributed in clusters all the way out to the highest redshift visible. For example, one cluster, or "wall," of galaxies lies at a distance of 6 billion light-years (redshift 0.67). Old, elliptical galaxies dominate these dense, high-redshift regions just as they do the local universe.

Galaxy chains

At about redshift 6, we see another primitive cluster of galaxies. They are among the most distant galaxies, with redshifts as high as 6.7. (In fact, the location for HUDF was selected to include a relatively bright galaxy identified by a previous survey at redshift 5.8.) About two-thirds of the galaxies we find at this redshift occupy a third of the volume, and statistics tell us such a concentration is about 4 times greater than expected by chance. Moreover, the galaxies lie on one side of the Ultra Deep Field, clustering not only along the line of sight, but in the plane of the sky as well.



HUBBLE REVEALS A GALAXY CHAIN (yellow circles) near redshift 6. The chance of such an alignment occurring randomly is about 5 percent. A wide survey of galaxies at redshift 5.8 (green circles) around Hubble's Ultra Deep Field shows the HUDF positioned at the edge of a much larger structure.

ASTRONOMY: ROEN KELLY, AFTER S. MALHOTRA

To see how far this cluster extends, we took wide-field images of the region using Cerro Tololo Inter-American Observatory telescopes near La Serena, Chile. At redshift 5.8, which is accessible from the ground, we see a wall of galaxies spanning at least 20 million light-years — with the HUDF situated right at the edge.

One of the motives for the deepest imaging of this patch of sky was to take a census of galaxies at redshift 6. The light we see left these galaxies within the Big Bang's first billion years. But astronomers remain split on whether these are the first galaxies.

We can find some answers by looking at the diffuse gas surrounding galaxies, rather than at the galaxies themselves. We see the gas has been heated and ionized by energetic ultraviolet light, and there is some evidence that the amount of ionized gas falls off at redshift 6. This could be when galaxies first began forming stars, lighting up the universe for the first time since the Big Bang, ending the so-called Dark Ages.

A census of these galaxies would reveal whether they're the source of the ultraviolet light that ionized intergalactic gas. One group of researchers concluded the HUDF contains only a third of the galaxies needed. Another team claims that, once we take into account faint galaxies that might have been missed, there are enough to do the job. Where these galaxies cluster together, they produce enough ultraviolet light to ionize the surrounding gas. So, in the end, finding enough galaxies to ionize intergalactic gas may depend simply on where astronomers look.

So, how deep is the Hubble Ultra Deep Field? In terms of brightness, it is 1/10 of a million — that is, its brightest object outshines its faintest by 100,000 times.

In terms of distance, HUDF ranges 1/10 of a billion, meaning its nearest and farthest objects are separated by about 100 million times.

And in terms of time, HUDF has given us a glimpse of the universe nearly 800 million years after the Big Bang. Just 40 hours of Hubble observations have taken us back 12.6 billion years. For NASA's budget, that's a lot of Big Bang for the buck. A

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