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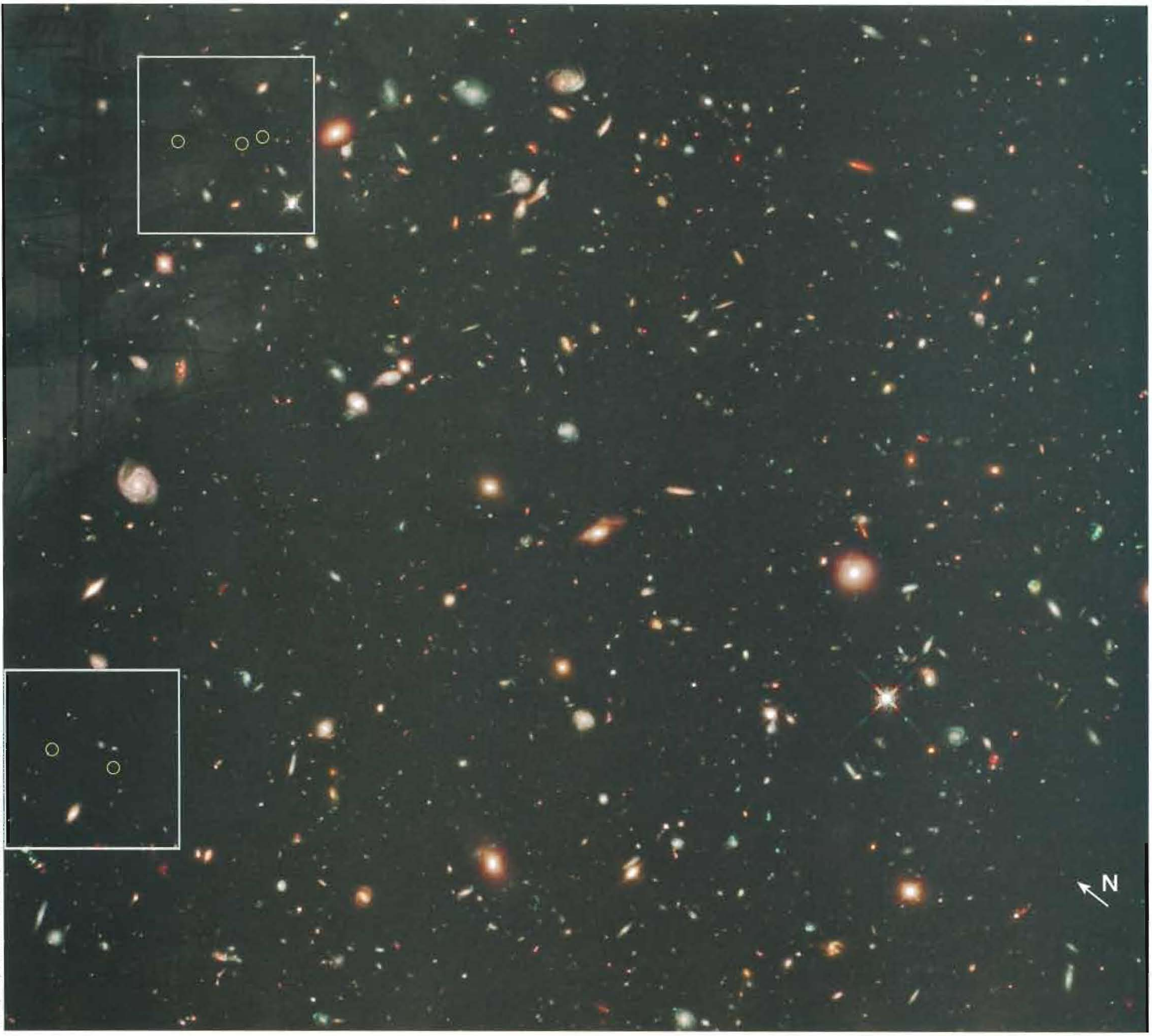
Seeing the Universe Take Shape

Finding the First

JONATHAN P. GARDNER

Hubble has imaged the most distant galaxies yet,

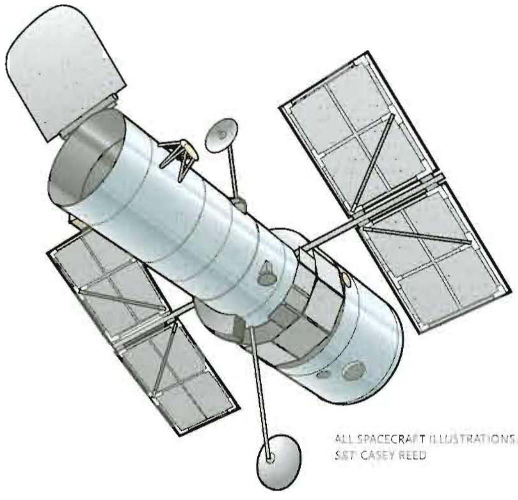
AUTHOR PHOTO: NASA / BILL HRYBYK



NASA / ESA / GARTH ILLINGWORTH / RYCHARD BOUWENS, ET AL.

Galaxies

but to see the first galaxies, astronomers need to go even deeper.



ALL SPACECRAFT ILLUSTRATIONS: S&T: CASEY REED

In May 2009, astronauts installed two new cameras in the Hubble Space Telescope, making Hubble more powerful than ever. The new Wide-Field Camera 3 (WFC3) increases Hubble's sensitivity and field of view at near-infrared wavelengths, improving its ability to search for distant galaxies by as much as a factor of 20.

It didn't take long for WFC3 to make its mark. Garth Illingworth, Rychard Bouwens (both at the University of California, Santa Cruz), and their colleagues recently used WFC3 to find 5 galaxies, circled in the image to the left, that are more distant than any seen before, pushing our knowledge of galaxy evolution back to just 600 million years after the Big Bang (a redshift of about 8.5).

These early galaxies are about the same distance as gamma-ray burst 090423, which recently established the record for most-distant known object (*S&T*: September 2009, page 26). But we're interested in more than just breaking records. We want to understand how galaxies formed, and how they built themselves up into the giant congregations that we see today.

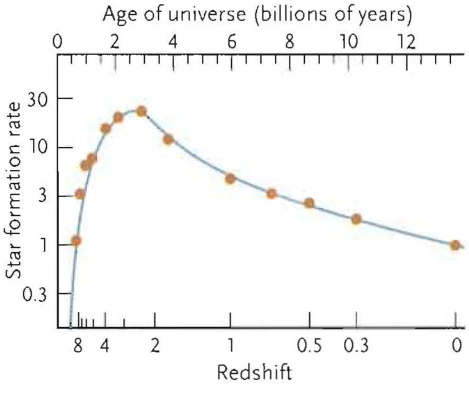
Astronomers study distant galaxies by taking long exposures in relatively empty fields. In 2004 astronomers pointed the Hubble Space Telescope at a small field in the southern constellation Fornax for more than 500 hours of exposure time. The resulting Hubble Ultra-Deep Field could see the faintest and most distant galaxies that the telescope is capable of viewing in visible light. The more recent WFC3 observations were made over the course of about 48 hours in the same field, and they extend the wavelength coverage into the near-infrared.

From the Ultra-Deep Field and other galaxy surveys, astronomers have built up a history of star formation. The peak occurred about 10 billion years ago, about a fourth of the universe's current age, when galaxies were churning out stars at about 15 times the rate today. As we go further back in time to when the very first stars and galaxies formed, the average star-formation rate should drop to zero. But the new WFC3 observations reveal a star-formation rate that remains comparable to that of galaxies today. Despite Hubble's impressive technical accomplishment, we have to go even deeper to observe how the universe's first galaxies formed.

There are two problems: the first galaxies are too faint for Hubble or any existing telescope, and cosmic expansion has redshifted their visible light even beyond Hubble's new near-infrared capability. To detect them,

GOING ULTRA-DEEP *Left:* By using Hubble to stare at a single field, astronomers bore a "tunnel" through space and time to see galaxies in the early universe. The latest Hubble Ultra-Deep Field, which shows the same patch of sky as an earlier Ultra-Deep Field, includes data taken by the new WFC3 camera. By going further into the infrared, this image reveals 5 galaxies around redshift 8.5.

STAR-FORMATION HISTORY *Right:* A variety of surveys have enabled astronomers to plot the rise and fall of star formation dating back to redshift 8. Given the fact that mature stars existed at redshift 8, the first stars and galaxies must have formed even earlier, during a mysterious epoch that the James Webb Space Telescope is being built to explore.



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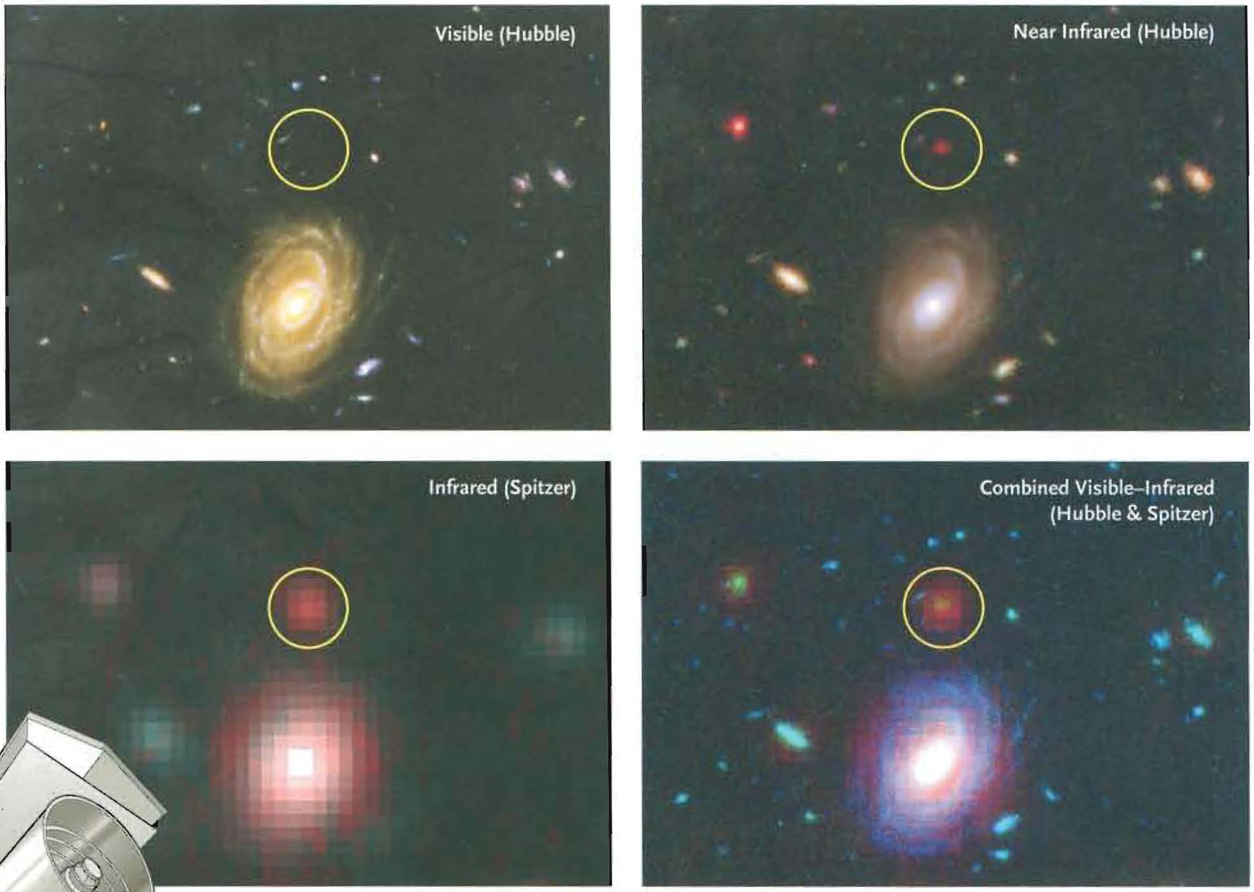


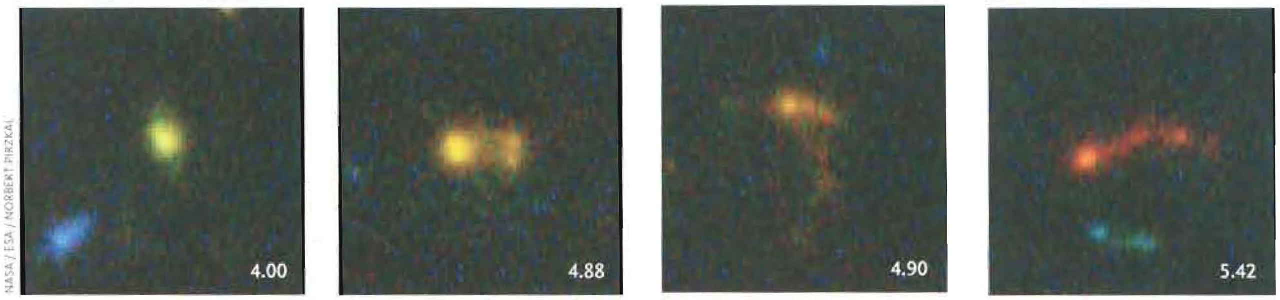
NASA / ESA / JPL-CALTECH / BAHRAM MOBASHER

DISTANT GALAXY The Hubble and Spitzer space telescopes teamed up to detect one of the most distant galaxies ever seen (circled), at a redshift of about 6.5. The relatively massive galaxy becomes increasingly brighter in near-infrared and infrared wavelengths, an indication that its stellar population is surprisingly mature for a galaxy that existed only 850 million years after the Big Bang. This discovery suggests that the galaxy and many of its stars formed hundreds of millions of years earlier.

NASA is building the James Webb Space Telescope for launch around 2014. Webb will have a 6.5-meter primary mirror, much bigger than Hubble's 2.4-meter primary, and Webb will be optimized for infrared observations to see the highly redshifted first galaxies.

Building Galaxies

After the Big Bang, the universe was filled with hydrogen and helium, expanding and cooling and responding to the gravity of growing clumps of dark matter. Theory says that large stars formed first, when the universe was about 100 million years old, a redshift of 30 (*S&T:* May 2006, page 30). These stars quickly exploded as supernovae, whose winds blew all the gas out of the relatively small dark-matter clumps, disrupting any chance that nearby stars would form. At about 250 million years (redshift 16), clouds of gas began to collapse to form stars very rapidly, in a wide range of sizes. The first galaxies were born.



NASA / ESA / NORBERT PIRZKAL

The early galaxies seen in the Hubble Ultra-Deep Field were small by today's standards, not much bigger than globular clusters. They look like a mess: compact, blobby aggregations that resemble train wrecks. Their masses are difficult to measure, but they are all clearly smaller than our Milky Way. But these galaxies evolved into the regular galaxies that make up the Hubble Sequence.

Galaxies build up through hierarchical merging. Relatively nearby galaxies appear to be interacting gravitationally, producing tidal tails, rings, and other structures that indicate recent collisions. When two large spiral galaxies collide in supercomputer simulations that trace the gravitational interactions of hundreds of millions of stars, they go through stages that look like observed merging galaxies (*S&T*: October 2006, page 30). The final result of these simulations is an elliptical galaxy.

Spiral and elliptical galaxies are built up over cosmic history, as larger and larger galaxies merge. Spirals become ellipticals in major mergers; ellipticals merge in the centers of galaxy clusters to become central dominant galaxies, such as M87 in the Virgo Cluster. By this process, the very small galaxies that first formed in the early universe built up into the giant congregations we see today. For example, hundreds of small galaxies merged to form galaxies such as our Milky Way. The earliest galaxies are not only faint because they are very distant; they are also ultra-faint because of their diminutive size.

ROBERT GENDLER

COLLIDING GALAXIES The famous colliding galaxies of the Antennae (NGC 4038 and 4039) allow astronomers to study the same merger processes in the relatively local universe that occurred much more frequently in the early universe. Note the extended tidal tails from gravitational interactions. The two galaxies might eventually merge into a giant elliptical galaxy.

Techniques for Going Deep

Computer models give us good ideas for how galaxy mergers occurred, but we'd like to see how this process occurred in the early universe. One way to accomplish this task is to use a technique predicted by Einstein's general theory of relativity. The dark matter in a cluster of galaxies can act as a gravitational lens, focusing the light from background objects and boosting their observed brightness by a factor of 10 or more. Astronomers have used this technique to find a few faint and very distant galaxies, but the magnified area is small, so it's difficult to obtain a statistical sample.

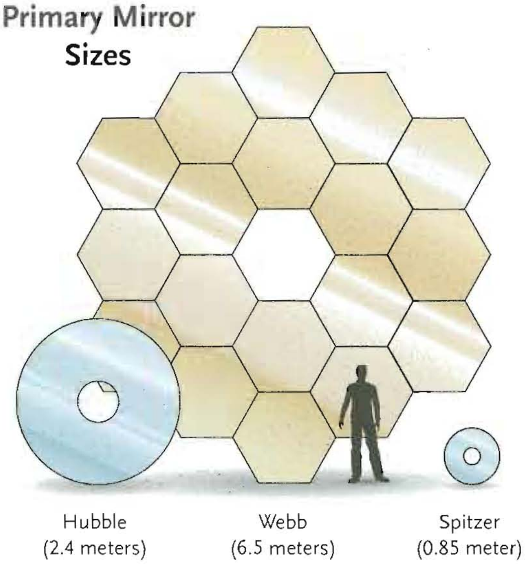
The Hubble Ultra-Deep Field was taken through 4 wide visible-light filters, with the recent WFC3 addition taken through 3 near-infrared filters. For the most distant galaxies, cosmic expansion has redshifted their ultraviolet output into the near-infrared. Intergalactic gas absorbs light emitted at even shorter ultraviolet wavelengths, so even-higher-redshift galaxies successively drop out of the images. By observing how galaxies disappear in these deep images, astronomers can measure the galaxies' redshifts. But at the highest redshifts, when the emitted ultraviolet light is redshifted beyond the near-infrared part of the spectrum, Hubble can't see the galaxies at all, not even when using a gravitational lens.

Infrared light is heat radiation, so a telescope must be very cold to see it at all. Otherwise, doing infrared astronomy with a warm telescope is like doing visible-light astronomy with a telescope full of light bulbs; the telescope itself outshines what you're trying to observe.

Heaters keep Hubble at room temperature, about 25°C,

TRAIN WRECKS These faint, fuzzy blobs in the Hubble Ultra-Deep Field might not seem like much, but they're the building blocks of today's galaxies. Each blob is 1/100 to 1/1,000 the size of our Milky Way, but blazes with the light of millions of young stars. The tadpole-like tails in three of the galaxies indicate that they're merging with neighboring galaxies. The numbers refer to each galaxy's redshift.

For more on the James Webb Space Telescope, visit www.jwst.nasa.gov.



in order to maintain its stability as it goes in and out of sunlight in low-Earth orbit. Although the telescope has some near-infrared capability, its temperature limits its sensitivity at the longest wavelengths. In 2003 NASA launched the Spitzer Space Telescope, an infrared-sensitive telescope that uses liquid helium to stay colder than –262°C, or only 11°C above absolute zero. Spitzer provides the infrared sensitivity that Hubble lacks. When astronomers pointed Spitzer at the Ultra-Deep Field, they were surprised to discover that some of the most distant galaxies were shining brightly in the infrared.

When galaxies first form stars, the largest stars dominate their light. These stars, 30 to 50 solar masses, are very hot and put out most of their radiation in the ultraviolet. But burning brightly has its price, and the most massive stars are also the shortest lived. After just a few million years, they run out of hydrogen fuel and explode as supernovae. Smaller stars, like our Sun, come to dominate the light output of the galaxy. These smaller stars are cooler and put out most of their energy as visible or near-infrared light, with much less ultraviolet.

For the distant galaxies in the Ultra-Deep Field, their emitted ultraviolet light is redshifted to the edge of the visible-light band, and their emitted visible light is redshifted into the infrared. The Spitzer detections showed that these galaxies were not forming their first generation of stars, but contained a substantial population of older stars, possibly as much as 400 or 500 million years old. Some of these galaxies must have formed when the universe was much less than 1 billion years old, and their ultraviolet light was redshifted well into the infrared, beyond Hubble's reach.

Although Spitzer was cold enough to detect infrared light, its primary mirror is just 85 centimeters. This small size limits Spitzer's sensitivity to faint galaxies in two ways. First, it's simply not collecting enough light to see galaxies fainter than those in the Ultra-Deep Field. Second, the telescope's resolution depends on the ratio of the wavelength divided by the aperture. With longer wavelengths and a smaller mirror, the faintest galaxies in Spitzer images overlap one another.

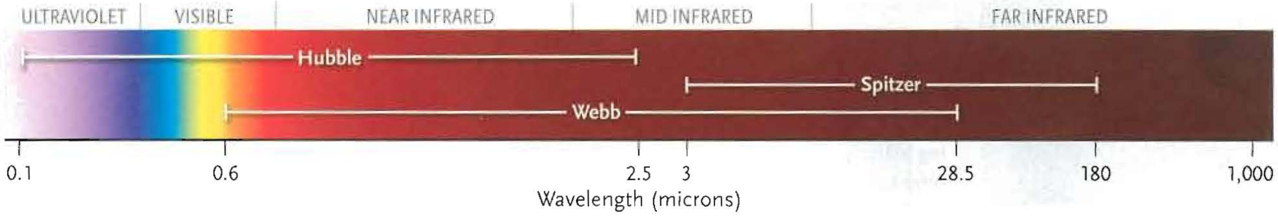
The James Webb Space Telescope

The James Webb Space Telescope will be colder than Hubble and larger than Spitzer. Sitting behind a giant sunshield, Webb will radiate its heat into deep space and passively cool to beyond –225°C. Its large mirror and cold temperature translates into the infrared sensitivity needed to detect the first galaxies that formed 250 to 400 million years after the Big Bang.

There are major technological hurdles in building Webb. As Hubble goes in and out of sunlight, heaters keep the telescope at a constant temperature. NASA launched Spitzer into a solar drift-away orbit, orbiting the Sun behind Earth and drifting 10 million miles from Earth each year. By moving away from us, Spitzer can use a shield to prevent sunlight from heating the telescope.

Webb will also hide behind a sunshield, one as big as a tennis court! NASA will launch Webb into a special orbit around the second Lagrangian point in the Earth–Sun system, called L_2, about 1 million miles from Earth. Being more distant from the Sun than Earth, the observatory would normally take longer than one year to orbit the Sun, and slowly drift away, like Spitzer. But at L_2, Earth's gravity will pull on Webb just enough to keep it in synch, so the Sun, Earth, and the L_2 point are always in a line. Webb's sunshield will not only protect the telescope from the Sun's heat, but also from scattered light from the sunlit portions of the Earth and Moon. The telescope will always be overhead at midnight each night.

The largest launch rockets are 5 meters wide, so

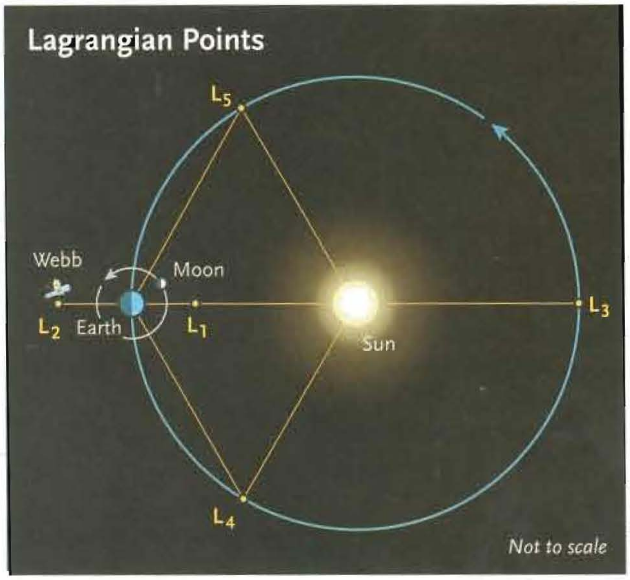


S&T: CASEY REED (3)

another technological development is needed to enable Webb to deploy its 6.5-meter primary mirror in space. The mirror consists of 18 segments, each with an independently controllable position. The mirror will stand on its edge in the rocket and the three segments on each side will be folded back like the leaves of a tabletop. The sunshield is folded around the mirror. After launch, the solar panels will unfurl to supply the observatory with power. The communications antenna will point toward Earth, and a deployed isolation tower will separate the telescope from the spacecraft. The sunshield will then unfold, and its five layers will separate.

The sunshield has five layers for two reasons. First, heat can escape between the layers. Second, if it's punctured by a micrometeorite, the holes will be unlikely to line up in such a way that sunlight will scatter onto the primary mirror. Finally, the secondary mirror will be supported on a three-legged spider, and the leaves of the primary mirror will be folded out. Once everything has been deployed, the telescope will be pointed at a bright star, and the 18 petals of the primary mirror will be brought to a common focus.

All this new technology comes at a price. The total life-cycle cost of Webb will be about $5 billion for NASA, plus additional contributions from Europe and Canada. Late 1990s estimates ranged from $500 million to $1 billion for construction costs only, which did not include technology development, design work, or post-launch operations. But even the cost of the construction phase has more than doubled. Much of this increase is due to the rigorous testing program that will virtually ensure that Webb will work when it reaches its proper orbit. The current cost of Webb is comparable to the cost of Hubble's construction, once corrected for inflation and changes in accounting procedures. Following an independent review, the Webb



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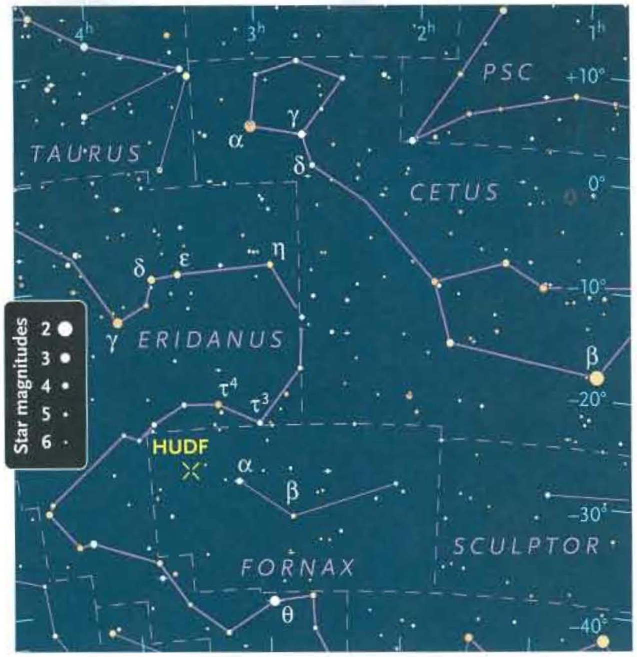
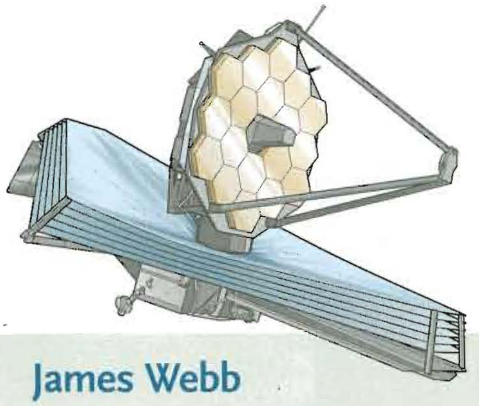
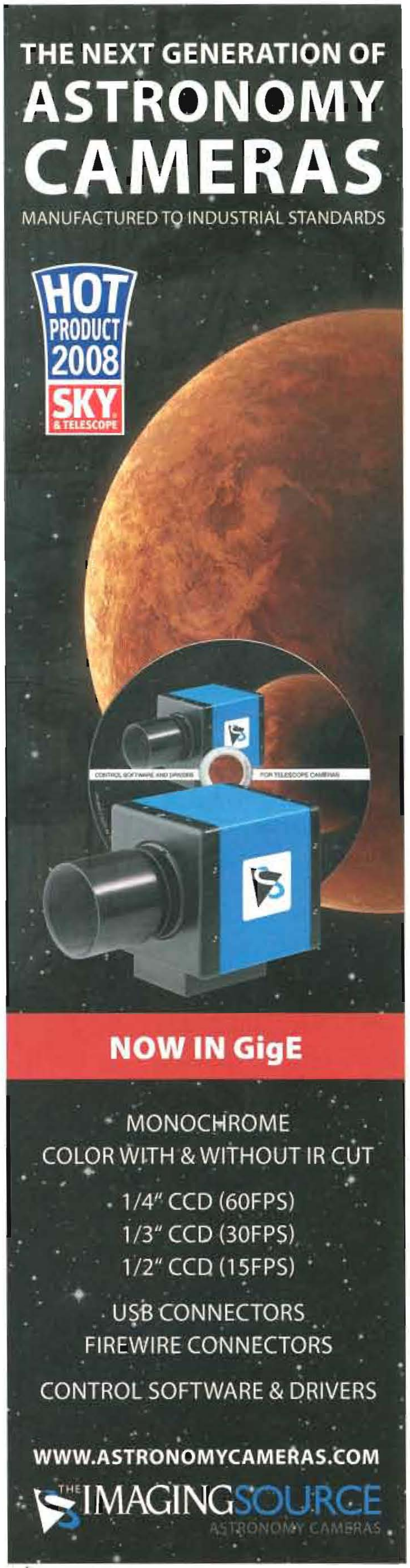


DEEP AND DARK The Hubble Ultra-Deep Field lies in the dim constellation Fornax, tucked into a dark loop of Eridanus. The field is centered on right ascension $3^h\ 32^m\ 40.0^s$, declination –27° 48′ 00″. Only 3 arcminutes on a side, it spans as much sky as a grain of sand held at arm's length. The yellow cross marks the spot; the actual field at this scale is microscopic.



James Webb

The James Webb Space Telescope is named for NASA's second administrator. James Webb's term (1961–1968) spanned the presidencies of John F. Kennedy and Lyndon Johnson, a period of rapid growth for NASA that witnessed the successful completion of the Mercury and Gemini manned spaceflight programs, and the early years of Apollo. Many successful space-science missions were also developed or flown during Webb's tenure.



project recently transitioned to its formal "implementation" phase, and NASA certified the budget and schedule to Congress.

A General-Purpose Observatory

The James Webb Space Telescope will be the successor to Hubble and Spitzer. Like Hubble, it represents a major international collaboration, with contributions from the European and Canadian space agencies. Although initially designed to detect the first galaxies, it will be a general-purpose observatory able to address nearly every aspect of astronomy.

Stars and planets form in dense clouds of gas and dust in a complex interaction between gravity, angular momentum, gas pressure, and magnetic fields. Dust blocks much of the ultraviolet and visible light from escaping the cloud, and stellar cradles such as M16 appear as beautiful but opaque nebulae. Infrared light penetrates the dust to reveal the forming stars. At a later stage, the star forms a protoplanetary disk; the star heats the disk so that it glows in the infrared. By providing high-resolution, high-sensitivity images in the infrared, Webb will be a powerful tool for investigating the formation of stars and their planetary systems.

Like Hubble and Spitzer, Webb will be used by thousands of astronomers from around the world, and it will deliver beautiful pictures. And just as we saw with Webb's predecessors, its most important discoveries are likely to be things we haven't even thought of yet. ✦

Jonathan P. Gardner is Chief of the Observational Cosmology Laboratory at NASA's Goddard Space Flight Center.

High Redshift = Large Distance

Redshift is a measure of how much an object's light is shifted toward the red end of the spectrum. Redshifts for objects within our galaxy are generally due to motion away from Earth. But redshifts for distant galaxies result from cosmic expansion, with the higher the redshift, the farther the galaxy.

We see distant galaxies as they existed long ago, and the expanding universe has grown in size since then. So astronomers often refer to distances to extragalactic objects in terms of redshift rather than light-years. Astronomers sometimes use lookback time, or time elapsed since the Big Bang, which took place about 13.7 billion years ago.

NASA Space Telescopes Compared

	HUBBLE	SPITZER	JAMES WEBB
Orbit	Low-Earth Orbit	Heliocentric Earth-Trailing	Sun–Earth L_2
Length	13.3 meters	4 meters	22 meters
Mass	11,110 kilograms	865 kilograms	6,530 kilograms
Mirror temperature	300 kelvins	5.5 kelvins*	35 to 55 kelvins
Launch date	1990	2003	2014 (scheduled)
Launch vehicle	Space Shuttle *Discovery*	Delta II	Ariane V
Focal length	57.6 meters	10.2 meters	131.4 meters
No. of instruments	5**	3*	4
Angular resolution	0.043 arcsec at 0.5 microns (μ)	1.6 arcsec at 6.5 μ	0.063 arcsec at 2.0 μ

* Since the depletion of coolant on May 19, 2009, the Spitzer primary mirror has warmed up to about 30 kelvins, and only 1 instrument is working. ** Hubble currently has 5 science intruments, plus the Fine Guidance Sensor, which is sometimes used for astrometric science. Hubble has had 12 total instruments over its liftime, including those that have been replaced in the servicing missions.