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Webb's discovery of dozens of galaxies in the epoch close to the Big Bang has astronomers revisiting long-held theories about the early universe. PAGE 24

Cosmic jolt

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Cosmic jolt

The James Webb Space Telescope has found dozens of previously unknown galaxies, including some that appear to be far bigger than expected for their age. Now scientists are questioning their theories about the early universe. Karen Kwon spoke to astronomers at the forefront of these discoveries.

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With its commissioning nearing completion last June, the James Webb Space Telescope moved its reaction wheels to position its giant mirror to spend two days observing Pandora's Cluster, known to astronomers as Abell 2744, a giant collection of galaxies discovered in the 1950s by the legendary astronomer George Abell. Light emitted billions of years ago from Abell 2744 bounced off Webb's primary mirror and up to a secondary mirror that focused it down through an opening in the primary mirror and into NIRCam, short for Near Infrared Camera. This light left the cluster billions of years ago in visible and ultraviolet wavelengths, but because objects in the universe have been flying away from one another as the universe expands at an accelerating rate, the wavelengths reaching Webb from Abell 2744 were weakened and lengthened into the infrared spectrum. Inside NIRCam, these soft waves passed through lenses and were separated into longer- and shorter-wavelength elements. The longer-wavelength light then traveled through a filter to reach a playing card-sized square detector made of infrared-sensitive metal alloy, while the shorter-wavelength light reached a two-by-two array of the same detectors.

Given this complexity, it's perhaps not hard to see why Webb took 25 years and $8.8 billion for the international coalition led by NASA and prime contractor Northrop Grumman to build and send to space. Not long after the Abell 2744 observations, astronomer Tommaso Treu of the University of California, Los Angeles and about 30 colleagues from around the world gathered on Zoom to see the fruits of this complex process: the first in a series of images from Webb that have upended what astronomers have long theorized about the early universe as a dusty place that grew some early stars, which in turn triggered a long, slow process of galaxy formation.

Treu and company chose Abell 2744 in the belief that the collective mass of its several hundred galaxies would curve space-time in a gravitational lensing effect that would magnify light from the never-before-seen celestial features beyond the cluster and further back in time. Believing this would amount to a unique window into the early universe, they

▲ Technicians install the Near Infrared Camera onto the James Webb Space Telescope's science instrument module at NASA's Goddard Space Flight Center in 2014. The images taken by NIRCam during science observations are downloaded as bits and translated into color by visual developers at the Space Telescope Science Institute in Maryland.

submitted a proposal and were given some of the first scientific observation time with Webb.

On the Zoom call, a so-called quick-look image from Webb loaded up in front of Treu and his colleagues.

"It was very emotional," recalls Treu, the principal investigator for Webb's observation of Abell 2744 in the Grism Lens-Amplified Survey from Space project. The name is a remnant from their previous observations of Abell 2744 with the Hubble Space Telescope, whose grated prism lenses divided the wavelengths.

With the Webb images in hand, the astronomers got to work identifying features that could be galaxies by running images through computer programs they built. Out of the six that looked most distant, one designated as GHZ2 was viewed as it existed 367 million years after the Big Bang, meaning an estimated 97.3% of the way back to the theorized birth of the universe. The galaxy broke the record for the most distant galaxy, and therefore the closest to the Big Bang, ever observed.

This record, however, turned out to be the first of many dominoes to fall. A succession of even more distant galaxies were found via Webb in the ensuing months. Astronomers led by Brant Robertson of the University of California, Santa Cruz discovered four galaxies. One was viewed as it existed an estimated 320 million years after the Big Bang, and the other 347 million years. The first they named JADES-GS-z13-0 and the second JADES-GS-z12-0 — JADES standing for JWST Advanced Deep Extragalactic Survey. Such galaxies are old in one sense but young if one considers them baby pictures that were taken between 97.5% and 97.7% of the way back to the Big Bang, which astronomers believe occurred 13.8 billion years ago.

The number of galaxies was also startling. Haojing Yan of the University of Missouri presented at the annual American Astronomical Society meeting in January that his team found 87 galaxies that were imaged by Webb as they existed between 200 million and 400 million years after the Big Bang.

And then there was the shocking size and brightness of some of the galaxies. "It's our understanding that it should take at least a billion years, probably a couple billion years, in order for things that are that massive to form," says Erica Nelson, an astronomer at the University of Colorado Boulder, referring to six galaxies that she and other astronomers discovered. Webb imaged those as they existed between 500 million and 700 million years after the Big Bang. Their findings were published in the paper, "A population of red candidate massive galaxies ~600 Myr after the Big Bang," in the journal Nature in February.

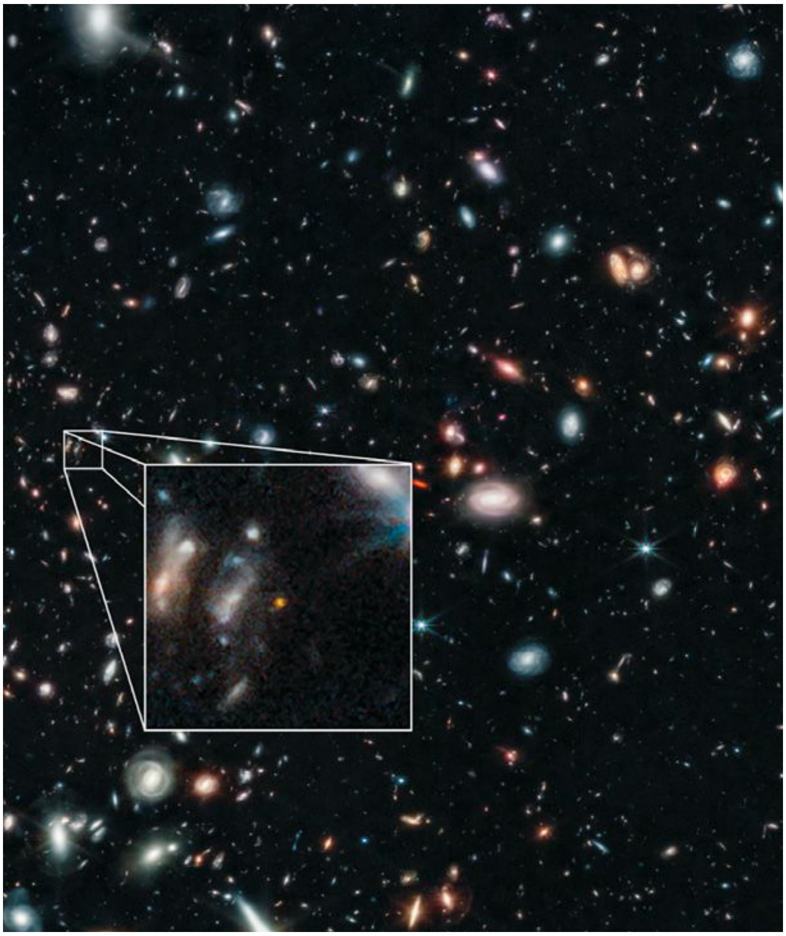
Could this mean that the universe started earlier than scientists currently believe? Not according to Treu, who characterizes the evidence supporting the theorized age of the universe as "very solid." Scientists use the universe's rate of expansion to calculate backward to the Big Bang, when the expansion started. Included in these calculations are the current density and composition of the universe, gleaned from astronomers' observations of cosmic microwave background, the leftover radiation from the Big Bang. The improved sensitivity of today's ground and space telescopes gives scientists great confidence in these calculations. Upending this standard cosmological model would require new and "extraordinary" evidence, Treu says.

What about challenging or disproving the theory that the universe began when a speck of compressed matter exploded?

"It is pretty clear that nothing we've seen challenges the Big Bang theory," says Nobel Laureate John Mather, the senior project scientist for Webb. But the findings are certainly challenging scientists' theories of the period after the Big Bang, such as how abundant dust was in the early universe and how soon after the Big Bang stars and galaxies started forming.

Determining distances

The most distant photo ever taken on Earth was produced in 2016 when Pic Gaspard, a peak in the French Alps, was photographed from Pic de Finestrelles, located 443 kilometers away on the border of France

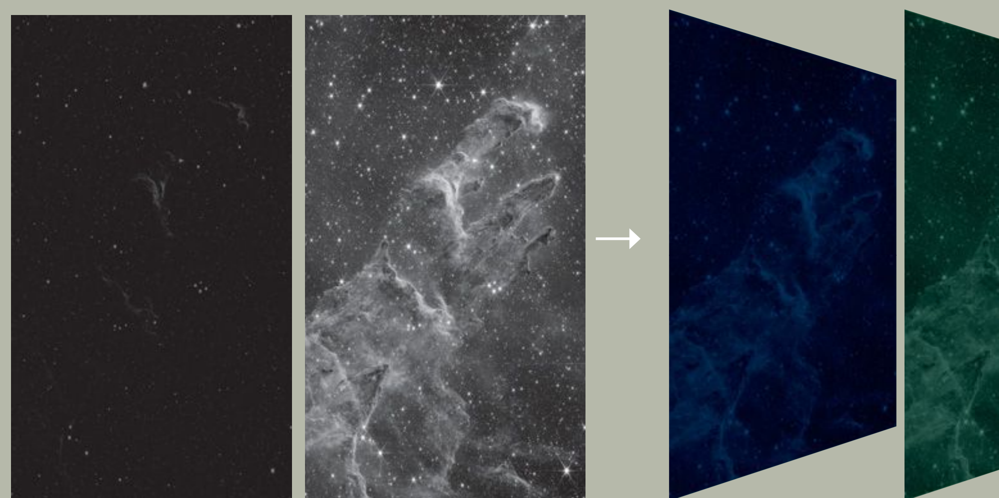


▲ The small orange dot in this inset box is the galaxy that Tommaso Treu's team discovered last year when the James Webb Space Telescope's detectors collected photons from beyond the Abell 2744 galaxy cluster. Named GHZ2, this new galaxy was the first of a slew discovered in several months that astronomers estimate formed at least 97% of the way back to the Big Bang.

NASA, ESA, CSA, Tommaso Treu

A new view of the "Pillars of Creation"

The eye-catching pictures from the James Webb Space Telescope don't arrive at astronomers' computer screens in those magnificent colors. They are composites that begin as black and white images, first with some faint dots and then with features illuminated. Imaging specialists at the Space Telescope Science Institute in Baltimore then spend dozens of hours translating those into hues in the blue, green and red light channels that our eyes can see.



▲ After the specialists turn the raw images into black and white photos via image processing software, each image is assigned a color. The specific color is determined by the filter on Webb's Near Infrared Camera — with blue assigned to the filters that detect the shortest wavelengths, and red assigned to the longest.

and Spain, according to the Guinness World Records.

So how do you image something that's at least a billion billion times — that's not a typo — farther away?

The answer goes back to the expanding universe. Light waves emitted from a galaxy decompress into infrared wavelengths as they travel toward us, and these wavelengths are the same as heat radiated from a source. If the redshifted wavelengths are very weak compared to their surroundings, you need to keep your instruments very cold to sense them.

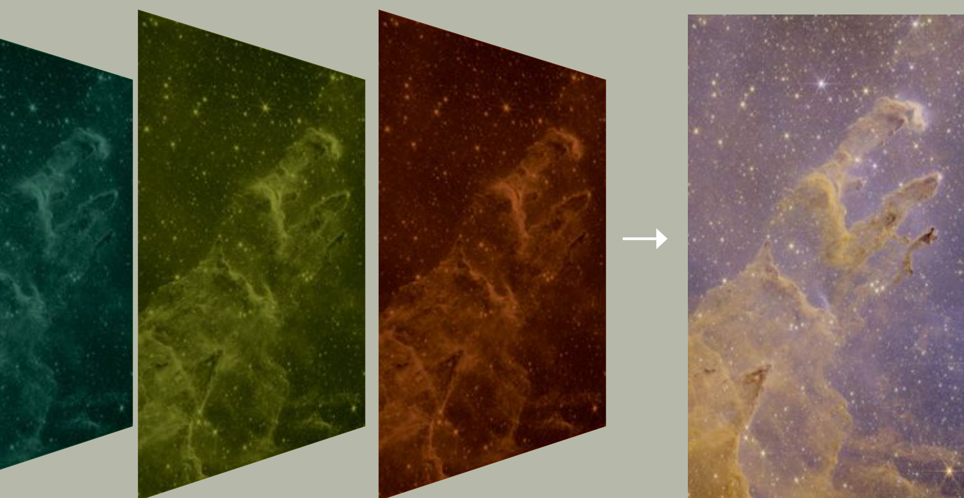
That's why Hubble possesses only limited infrared capabilities after a 1997 maintenance mission that added a near-infrared instrument.

"Hubble is actually a warm telescope," says Marcia Rieke, an astronomer at the University of Arizona and the principal investigator for Webb's NIRCam. Hubble's mirror temperature is 21 degrees Celsius (70 degrees Fahrenheit), making it less ideal for observing distant galaxies.

Enter Webb, whose operating temperatures at their coldest are close to absolute zero. That's even lower than those achieved by NASA's Spitzer Space Telescope, which was deactivated in 2020 and left in a trailing Earth orbit. This coldness is achieved partly by orbiting the sun-Earth second Lagrange point 1.5 million kilometers from Earth, a location where gravitational forces and the orbital motions of celestial bodies remain in balance as Earth revolves around the sun. Webb can orbit there by expending little fuel, but the big advantage for infrared astronomy is that the shadow of Earth provides a cooling effect that is combined with positioning Webb's mirrors and instruments behind a tennis court-sized sunshield to block the remaining light. This strategy keeps the temperature of the instruments below 50 kelvins, or minus 370 degrees F. The 0.74-meter-diameter secondary mirror and 6.5-meter primary mirror both stay slightly warmer at 53 K (minus 364 F). That's the cold side of Webb. On the other side of the sunshield, the warm side, are the reaction wheels, propulsion jets and computer.

All this is to say that Webb's coolness and sensitivity make it the best tool astronomers have had for seeking out faraway galaxies.

With the help of these features, NIRCam took images of Abell 2744 between June 28 and 29 of last year. By radiating heat off into space with a passive cooling system, NIRCam's temperature is kept well below 50 K — in fact, 39 K (minus 389 F). This assures NIRCam's detection range is from 0.6 to 5 microns. Also, its 10 mercury-cadmium-telluride detector



▲ The color images are then layered to create an initial composite. In the final step, features are made more discernible, for example by increasing the contrast of the dusty pillars to distinguish them from the background. Also, stars are sometimes brightened to distinguish them from the background, but their shapes and sizes are not edited.

Graphic by Thor Design; reporting by Cat Hofacker
Source: Space Telescope Science Institute

arrays are larger and more sensitive than previous space telescopes' detectors, says Rieke.

But the above features alone cannot help astronomers determine how far away a galaxy is. For that, they rely on NIRCam's filters, circular optical components about 10 centimeters in diameter arrayed on a wheel. For observing Abell 2744, the GLASS team used seven filters, each allowing only the light within a small wavelength range to come through. NIRCam observed the galaxy cluster through these filters in succession: First, one whose transmittance window is between 0.795 and 1.005 microns, then a "redder" filter that allows higher wavelengths between 1.331 and 1.668 microns, and finally the reddest one, with a window between 3.881 and 4.982 microns.

The goal of all this was to find the Lyman break, a threshold in collections of wavelength observations where invisible features suddenly become visible in the infrared. Plot the Lyman break on a cosmic timeline and compare it to where the break would have happened without the redshift, and you can estimate the age of a cosmic feature. As the filter wheel turned, switching filters from "bluer" ones to a "redder" ones, distant galaxies suddenly appeared in areas that previously showed nothing bright, and at a specific wavelength threshold. By plotting the intensity of the filtered images as a function of wavelength and connecting the dots via a computer model, the astronomers had found the Lyman break.

These newfound galaxies do not appear before the Lyman break because photons with wavelengths lower than 0.121567 microns are absorbed by the neutral hydrogen atoms that are abundant in the universe. But because of the cosmic redshift, a distant galaxy's Lyman break is usually higher than 0.121567 microns.

This photometry method is one way to find the distance to a galaxy, but it's not the most precise method. For more accurate measurements, spectroscopy — dispersing light to find the intensity of each wavelength component — is needed.

Treu puts it this way: "From photometry, we say Los Angeles is in the United States. And from spectroscopy, we say UCLA is pretty close to the beach."

Webb's Near Infrared Spectrograph, or NIRSpec, operates at a similar temperature and wavelength range as NIRCam. But while NIRCam, being a camera, can take a picture of a large swath of the sky, NIRSpec cannot. What it can do, with its multi-slit assembly, is focus on up to 200 objects at once. Before the light arrives at its detectors, NIRSpec splits it into different wavelengths, similar to how a prism turns white light

into a rainbow. And NIRSpec's ability to break down a galaxy's light is 25 to 250 times more sensitive than using NIRCam, depending on which NIRSpec setup is chosen. With NIRSpec, the amplitudes of specific wavelengths corresponding to various elements, such as hydrogen, are turned into spectral lines that tell astronomers the degree of a galaxy's redshift and, therefore, the distance of a galaxy.

A recent case illustrates NIRSpec's ability to pinpoint exact distance. When the galaxy CEERS-93316 was discovered about a month after GHZ2, it appeared to have been born even closer to the Big Bang, given the estimate that it was spotted as it existed 236 million years after the Big Bang. However, when the galaxy was observed with NIRSpec, spectroscopy revealed that the galaxy was being viewed as it appeared 1.2 billion years after the beginning of the universe. Proficiently producing stars, CEERS-93316 appears to be particularly dusty, which made it resemble a highly redshifted galaxy.

In their initial proposal sent five years ago, Treu

Northrop Grumman technicians began final assembly of the James Webb Space Telescope in 2019 by lowering the mirrors and science module onto the spacecraft element. The dark protrusion in the center is where photons gathered by Webb's gold primary mirrors enters to reach the science instruments, which include the Near Infrared Camera, or NIRCam, that takes the majority of Webb's images.

NASA/Chris Gunn

FACT

The relationship between time and distance when it comes to galaxies is not as simple as it might sound. Let's take GHZ2, a galaxy discovered via the Abell 2744 cluster that astronomers have known of since the 1950s. The light that left that galaxy traveled for 13.6 billion light years to get to Webb. Yet GHZ2 is now 33.2 billion light years away from Webb. How could this be? Because the universe expanded while the light was traveling.

and his team requested observation time with NIRSpec. But because the Space Telescope Science Institute (STScI) in Baltimore determines the time slots for the highly coveted telescope, it is unclear when they will be able to verify GHZ2's age with the high-tech spectrograph.

That said, Treu is pretty confident in his team's results. For one, the photometrically determined distances of most galaxies matches with NIRSpec's findings, with only rare exceptions. And secondly, Treu has since used the Atacama Large Millimeter/submillimeter Array radio telescope located in Chile to do spectroscopy of GHZ2 — and its result agreed with the NIRCam findings. But still, Treu says he hopes he will get to use NIRSpec soon.

Rethinking galaxy formation

Confidence is growing among astronomers that what they are seeing are not old stars whose long-wavelength signals could be mistaken for early galaxies.

"I think the overabundance of bright galaxies is real," Treu says. "There's no doubt about it."

Among the galaxies that need confirming are those spotted by Nelson of the University of Colorado Boulder and her colleagues. The six galaxies they found appear to be as large as the Milky Way, which astronomers estimate took 13 billion years to reach its current size.

Scientists had theorized that after the Big Bang, only a few kinds of atoms existed, mainly hydrogen and helium. Over the first 400 million years, the first stars formed and grew thousands of times as large as our sun in a manner that's different from how stars form today. These hot, bright stars burned for a few million years and then exploded, creating dust and other molecules that provided the ingredients for the stars and galaxies that formed over the next hundreds of millions of years.

Astronomers are now revisiting this timeline.

"We knew we didn't know," Mather says. "We had to guess. It was a wrong guess."

So the search for early, distant galaxies continues. Plenty of questions remain: How did the first stars explode? Did the next ones grow right away afterward? How did galaxies grow?

And while astronomers continue to sift through the Webb images delivered so far, STScI is poised to announce the next round of proposals selected for observation time later this month.

Who knows what mysteries of the early universe these observations will unlock? ★