PNAS INNER WORKINGS

The James Webb Space Telescope prompts a rethink of how galaxies form

Adam Mann, Science Writer

The topmost four of these five galaxies (known together as Stephan's Quintet) are quite near Earth in cosmic terms, ranging from 40 million light-years away to 290 million light-years. Their close proximity, shown in unprecedented detail with a JWST image released in July 2022, allows astronomers to more easily witness the merging of and interactions between galaxies. An array of images from JWST is spurring new questions about galaxy evolution. Image credit: NASA, European Space Agency (ESA), Canadian Space Agency (CSA), and the Space Telescope Science Institute (STScI).

Katherine Whitaker was on a video call with colleagues last summer when NASA released the first pictures from the ultra-powerful James Webb Space Telescope (JWST). Among the many awe-inspiring images was one of a sliver of sky surrounding the galaxy cluster SMACS 0723: It was brimming with some of the oldest and most distant galaxies ever recorded. "We would zoom in and be like, 'Oh wow,' and 'What the heck is that?'" recalls Whitaker, an astronomer at the University of Massachusetts Amherst. "It was joy—pure joy."

That thrill was merely a taste of what was to come. In just its first year of scientific operations, the $10-billion infrared telescope has delivered stunning views of the nascent universe, finding large numbers of surprisingly bright galaxies that existed at a time when the cosmos was in its infancy. With its 6.5-meter mirror, JWST was designed to investigate this early era, which was mostly out of reach for its predecessor, the 2.4-meter Hubble space telescope (HST). Observations thus far have astonished researchers and left them trying to digest exactly what they're seeing.

According to the standard model of cosmology, after the fiery Big Bang 13.8 billion years ago, the universe cooled, and energy turned into matter that eventually

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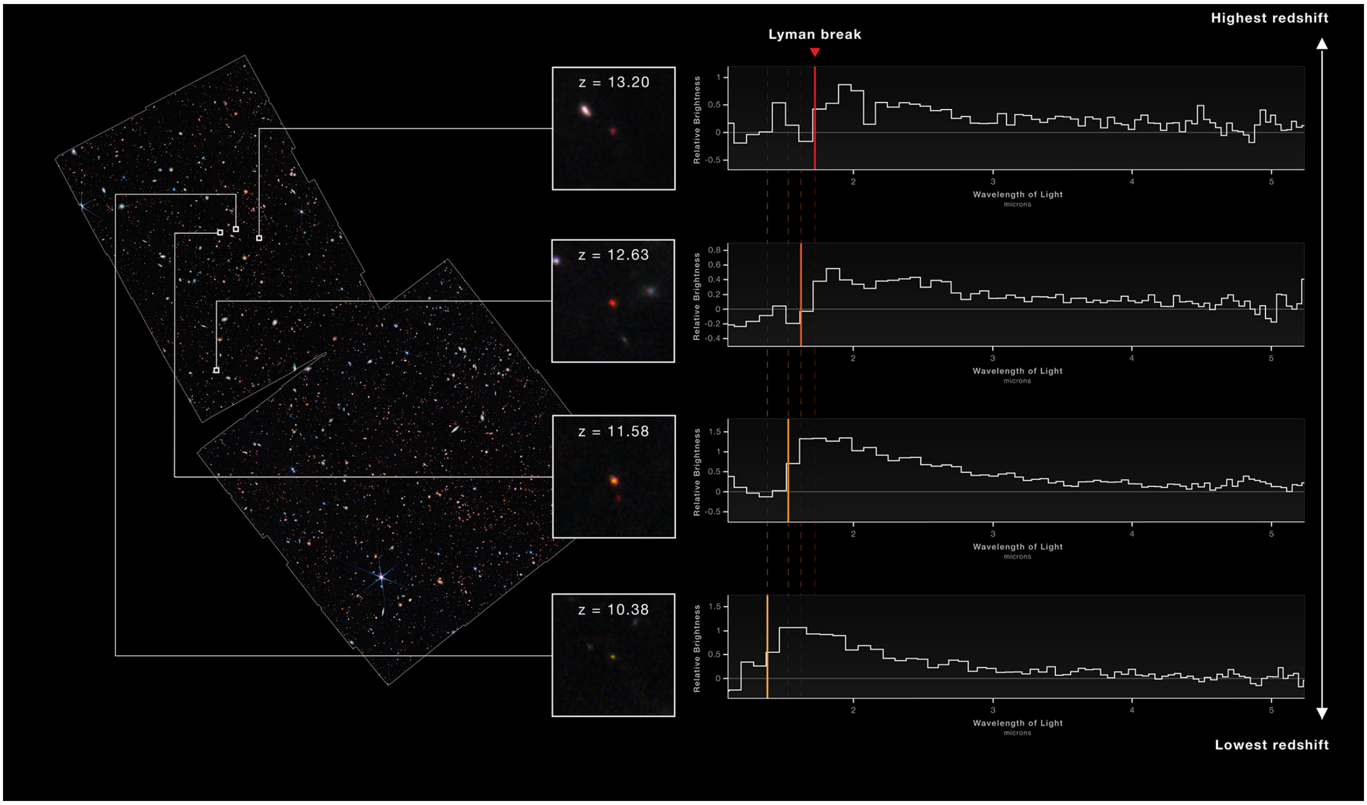

By separating a beam of light out into its constituent colors, astronomers can learn a lot about the universe. JWST uses this process, known as spectroscopy, to determine the distance to different objects, as the expansion of space steadily shifts wavelengths toward the redder portion of the electromagnetic spectrum. Here, the light from four extremely distant galaxies reveals that they date back to less than 400 million years after the Big Bang, when the universe was only about 2% its current age. Image credit: NASA, ESA, CSA, M. Zamani (ESA/Webb), Leah Hustak (STScI).

coalesced during the first few hundred million years, forming the first generation of stars and galaxies. Astronomers thought they had a decent understanding of this process.

But JWST's initial results may suggest that stars and galaxies were forming far faster than anyone expected. The telescope had done nothing less, read the headlines, than "break the universe" and upend models of cosmic history. Subsequent data have ruled out some of the more dramatic findings, and new simulations can accommodate at least a few of the strange observations. But some bright, massive, and early galaxies continue to confound theorists, suggesting that our understanding could shift in the coming years. "No data at the moment has broken the universe," says Priyamvada Natarajan, a theoretical astrophysicist at Yale University in New Haven, Connecticut. "But I think there are interesting potential tensions emerging on different scales."

Resolving these tensions will require researchers to revisit their fundamental assumptions about galactic evolution. That could mean bringing new ideas to the forefront—while leaving others in the cosmic dustbin.

Hubble Hands Over

In May 2009, astronauts installed one of Hubble's final and most important instruments. Known as the Wide Field Camera 3 (WFC3), it vastly improved the telescope's ability to see in the infrared. As the universe expands, traveling light gets stretched out to longer wavelengths, or the redder portions of the electromagnetic spectrum, so the oldest entities can't be seen in the shorter ultraviolet or visible wavelengths. WFC3 allowed Hubble to capture the light from several record-breaking objects, including the galaxy GN-z11, which existed when our universe was only 3% of its current age, or a mere 400 million years old (1).

Yet, Hubble never found much from this early epoch. Were the few visible big, bright galaxies due to limitations in the observatory's instruments? Or were astronomers witnessing the very beginnings of galaxy formation? Once JWST launched in December 2021, scientists swiftly dismissed the latter possibility. Two teams spotted the galaxy GLASS-z12, about 50 million years older than GN-z11 (2). Other JWST observations showed staggering numbers of galaxies potentially existing as early as 180 million years after the Big Bang. "There's a lot of galaxies that are bright enough for us to detect [with JWST]," says Jeyhan Kartaltepe, an astrophysicist at the Rochester Institute of Technology in New York. "We knew there would be some, but people were surprised at how many there are and how easy they were to find."

These galaxies are also potentially more massive than cosmologists expected. The scorching conditions in the first few hundred thousand years after the Big Bang meant that matter couldn't settle down and condense into entities such as stars and galaxies. As the universe expanded and cooled, standard cosmological theory holds that particles of dark matter, mysterious stuff that outweighs normal matter six to one, clumped under the force of gravity and formed massive halos. These then gravitationally attracted regular matter, which slowly accumulated in the halos and produced the stars and galaxies we see today. Most models estimate that a galaxy the size of our Milky Way wouldn't form until roughly 1 billion to 2 billion years after the Big Bang.

Yet, in that first JWST image of the SMACS 0723 cluster, astrophysicist Erica June Nelson of the University of Colorado Boulder noticed "these big honking red disks" that appeared to be extremely massive galaxies rapidly forming stars. These dusty red elongated galaxies, six of them, all seem to have existed within the first 500 million to 700 million years of cosmic history. Based on the objects' brightness, Nelson's team calculated that they might each weigh at least 10 billion times the sun's mass (3). One, in particular, was a colossus containing perhaps 100 billion suns, on par with our own galaxy, and could have two nearby companions, suggesting that it was part of a galactic group. "Their quoted properties are so massive that it's really hard to see how you can form those and keep our current models of cosmology completely intact," says Michael Boylan-Kolchin, a theoretical astrophysicist at the University of Texas at Austin.

Galactic Disagreements

Not everyone is convinced that these objects are quite so hefty or so distant. A group of astronomers from the United States and France pointed out that the galaxies' properties suggest that they could be mostly filled with young, low-mass stars, which would make them about 1,000 times less massive than originally calculated (4). Nelson and her colleagues spent a good deal of time investigating this possibility in their own work, eventually dismissing it as requiring too many unlikely premises to be right. Another paper from the Cosmic Evolution Early Release Science (CEERS) Program, one of the major JWST survey teams, estimated that the largest galaxy is actually located much closer to us, at an era more than 1 billion years after the Big Bang (5). By applying a different set of assumptions to the same data, they posit that a fraction of its overall light could be coming from a supermassive black hole feeding on material in its center, meaning that it has fewer stars and roughly 10 times lower mass overall, an interpretation that Nelson agrees is probably correct.

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>
> **—Stephen Wilkins**

Such discrepancies point to the difficulty of early JWST science. Most of the telescope's initial results have been based on imaging data, in which a galaxy's distance and mass are inferred based on its brightness and color. This method is useful, but beholden to certain assumptions. To nail down an object's properties, as well as its time and place in cosmic history, astronomers typically rely on the more painstaking process of spectroscopy, in which light is separated into its constituent colors containing telltale chemical signatures. Cosmic expansion steadily shifts these signatures en masse toward longer wavelengths, providing an accurate measure of the distance light has traveled.

In one instance, imaging data from JWST placed a galaxy dubbed CEERS-93316 at 240 million years after the Big Bang—making it one of the most distant objects ever recorded (6). But about a year later, spectroscopic measurements from the telescope showed that it was far closer, existing at a less record-breaking epoch 1.2 billion years after the Big Bang (7).

In other cases, spectroscopy backed up initial estimates. Four distant galaxies spotted early on in the JWST Advanced Deep Extragalactic Survey (JADES) were shown to be at their originally identified extreme distances. That includes JADES-GS-z13-0, the current champion, which existed roughly 320 million years after the Big Bang (8). When the telescope's next observation cycle begins in July, its spectrograph will deliver data on a large number of such objects, including Nelson and her colleagues' potentially massive and faraway galaxies.

Still, the many galaxies that JWST has found are already enticing theorists to reconsider some of their basic ideas. Cosmological models predict the number of dark matter halos of different sizes that should be present at different epochs of the universe's history. "If we say galaxies only live inside these lumps of dark matter, there aren't quite enough dark matter lumps to host the galaxies that have been reported," says Alice Shapley, an astronomer at the University of California, Los Angeles. As a result, computer simulations that produce too few dark matter halos and galaxies have fallen by the wayside. Additional data might force further modifications.

"People still have wiggle room"—surrounding the exact numbers, masses, and formation times of galaxies—"but this wiggle room is getting squeezed," says astronomer Haojing Yan of the University of Missouri in Columbia.

Dark Goings-On

Most in the field acknowledge that their understanding of galaxy formation will likely have to shift to account for the JWST observations. But will it be a minor adjustment or a more radical alteration? Among the simpler possibilities is that the earliest stars and galaxies came together more efficiently than researchers currently believe. It could be that the primordial universe was much denser and more compact than researchers think, perhaps allowing gas and dust to collapse especially quickly into stars. "Maybe in the very earliest systems, it's all kind of going gangbusters and there's nothing to stop it," Boylan-Kolchin says. This would allow for the creation of larger numbers of galaxies that are heavier much earlier in cosmic history than existing theories suggest. But the efficiency of galaxy formation would likely have to be much higher than current models assume.

A more exotic explanation tweaks conceptions of dark energy, which is generally believed to be causing the observed accelerated expansion of the universe. Physicists consider the density of dark energy to have been a constant since the Big Bang, but discrepant measurements of the cosmos' expansion might require a rethink of the nature of dark energy. Studies of the nearby universe suggest a faster expansion rate than the rate extrapolated from observations of the infant universe. Several models that have been around since before JWST launched, called "early dark energy," posit that more dark energy existed roughly 50,000 years after the Big Bang, Boylan-Kolchin says. Such models, which help resolve the expansion rate discrepancy, also happen to predict that galaxies grew faster and more abundantly in the early universe, which could explain the JWST sightings.

But there's an obvious problem: The standard model of cosmology, with its constant dark energy density, has been extremely successful in explaining the evolution of the large-scale structure of the universe, comprising the observed web of galaxies, galactic clusters, and clusters of clusters. Any changes to that model will need to retain such positive aspects while addressing the new observations.

Most researchers are taking a wait-and-see approach before abandoning longstanding ideas in favor of some new view of the cosmos. "Over the next 6 months, we'll get some really nice pictures, both literally and figuratively," says astronomer Stephen Wilkins of the University of Sussex in the United Kingdom. "Hopefully, we'll tighten our constraints and be able to tell which models are correct and which ones are wrong."

Regardless, the new eye on the sky has energized and pushed astronomers to question bedrock assumptions. "You have a few times in your career where you're like, 'Okay, this is a watershed moment,'" Shapley says. "We're in one of those moments right now."

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