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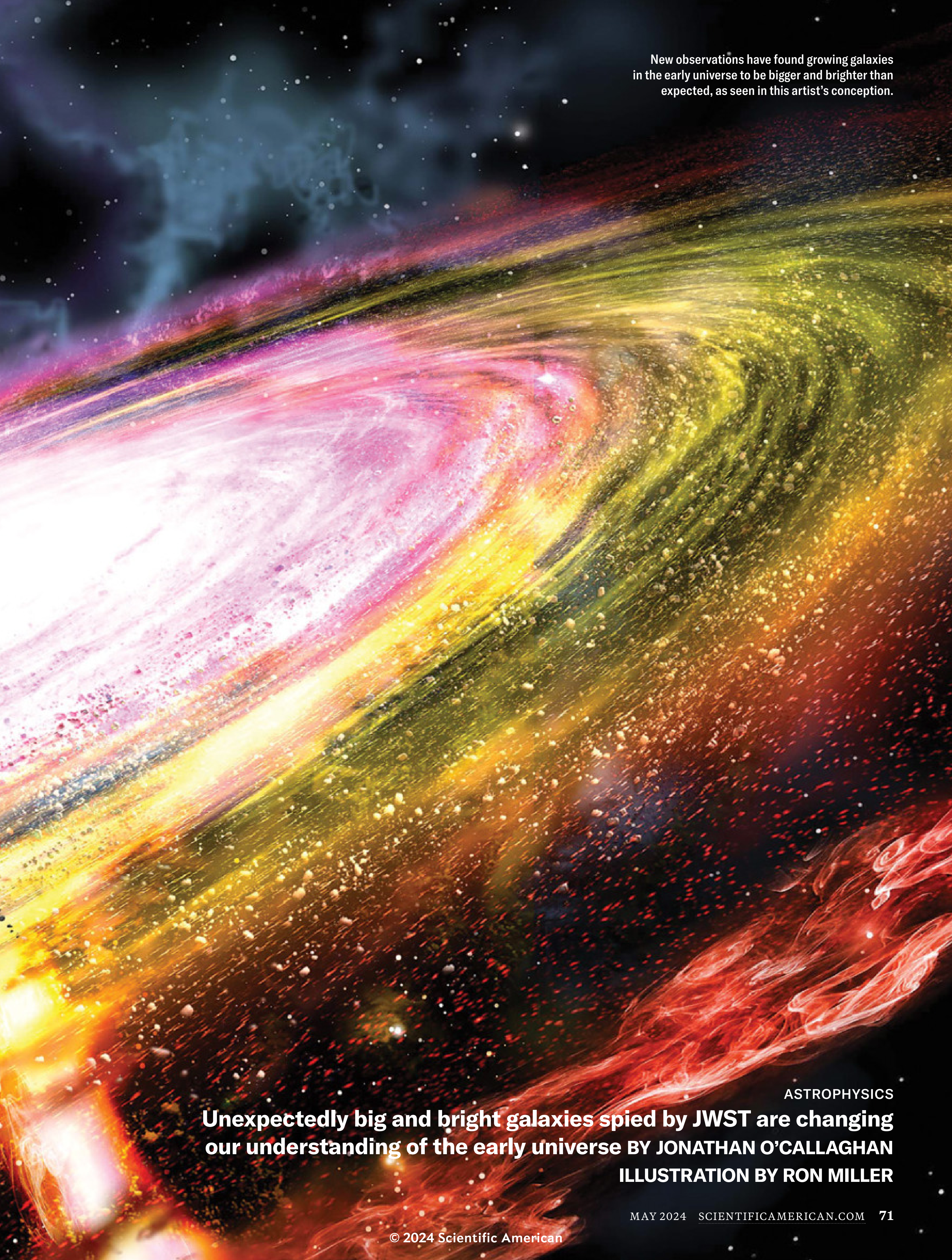
Uncanny Galaxies



New observations have found growing galaxies in the early universe to be bigger and brighter than expected, as seen in this artist's conception.

ASTROPHYSICS

Unexpectedly big and bright galaxies spied by JWST are changing our understanding of the early universe

BY JONATHAN O'CALLAGHAN

ILLUSTRATION BY RON MILLER

EVER SINCE IT OPENED its giant infrared eye on the cosmos after its December 2021 launch, the James Webb Space Telescope (JWST) has been finding an overabundance of bright galaxies that stretch back to the very early universe. Their brightness—a proxy for their number of stars and hence their mass—is deeply puzzling because galaxies shouldn't have had enough time to become so bulky in such early cosmic epochs. Imagine visiting a foreign land and finding that many of the toddlers there weigh as much as teenagers. You might have questions, too: Are the children so large because of something in the water, or might it instead be that your grasp of human growth is fundamentally flawed? Theorists who pondered JWST's big, bright early galaxies felt much the same: Was something fundamental amiss in our understanding of cosmology? Namely, was our knowledge of the expansion of the universe after the big bang simply wrong?

The answer, it appears, need not be quite so dramatic. Several studies investigating some of these early galaxies now point toward an astrophysical explanation for the unexpected girth—such as earlier-forming black holes or bursts of star formation—rather than some physics-shattering result. "Most people would put their money on the astrophysical explanation right now," says Mike Boylan-Kolchin, a cosmologist at the University of Texas at Austin. "I'd count myself in that category as well."

Before JWST's debut, its predecessor, the Hubble Space Telescope, held the record for the earliest galaxy ever found. We can see that object, called GN-z11, as it was about 13.4 billion years ago, around 400 million years after the big bang. Once JWST turned its gaze on the universe, however, it repeatedly smashed Hubble's record. Scientists are now studying galaxies stretching back to at least 320 million years after the big bang. And later this year fresh data releases from ongoing JWST galaxy surveys should push this record back even further.

The oldest galaxies JWST found were brighter and more active than expected, with star-formation rates comparable to the one-star-per-year rate of the Milky Way today. But they were squeezed into much more compact regions around one one-thousandth the size of our galaxy. And as JWST peered deep into the early universe, it also examined a more recent swath of cosmic history, up to about 750 million years after the big bang. The older galaxies it found there were still quite young and strange: they were about one-thirtieth the size of the Milky Way (much *bigger* than expected) and had star-formation rates that must have been 1,000 times higher than our galaxy's. Scientists called these relatively older systems ultramassive galaxies and kept scratching their heads: neither set of galaxies could be wholly explained by current models.

In the journal *Physical Review Letters,* Nashwan Sabti of Johns Hopkins University and his colleagues recently proposed an explanation for JWST's ultramassive galaxies. They used existing data from Hubble to examine hundreds of galaxies in ultraviolet light in the same epoch of the universe as these galaxies, about 450 million to 750 million years after the big bang. Unlike JWST, which observes primarily in infrared, Hubble is sensitive to the UV end

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of the electromagnetic spectrum, where young massive stars blaze brightest. Hubble's UV observations allowed the researchers to better gauge the rates of star formation in the mysterious ultramassive galaxies. "So we have the star-formation rate—the change in stellar mass over time—versus the stellar mass itself from JWST," Sabti says.

> "We showed Hubble doesn't give you much wiggle room to play around with cosmology. That means the source [of ultramassive galaxies] is very likely astrophysics."
> —Nashwan Sabti *Johns Hopkins University*

By comparing those two pieces of information, Sabti and his colleagues found that the galaxies could be explained within the confines of our cosmological model of the universe, the Lambda Cold Dark Matter (Lambda-CDM) model. It best replicates the observed patterns and properties of galaxies and other large cosmic structures. No esoteric physics were required. In fact, any such tweaks would put the Hubble observations at odds with JWST; the galaxies were growing exactly as expected in accordance with Lambda-CDM's predictions. "We showed that Hubble really doesn't give you much wiggle room to play around with cosmology," Sabti says. "That means the source [of the ultramassive galaxies] is very likely astrophysics."

Boylan-Kolchin says the paper makes a "great point" in comparing Hubble and JWST data from this period of the universe. He isn't completely convinced just yet, however. "I don't think the case is airtight that it has to be an astrophysical explanation," he says. "The loophole is that you're not necessarily observing the same galaxies with JWST and Hubble. Galaxies can be luminous [in infrared] for JWST but invisible for Hubble. If the most massive ones happen to be in that [infrared] regime, then maybe Hubble wouldn't be seeing them."

Sabti's paper is not the only recent work that points toward an astrophysical explanation for JWST's peculiar galaxies, however. Earlier this year in the *Astrophysical Journal Letters,* Joseph Silk of Johns Hopkins and Sorbonne University in Paris and his colleagues looked at the earliest galaxies seen by JWST, which predate GN-z11. The researchers wrote that there might be a way to grow the galaxies more quickly in the universe if black holes formed earlier than the galaxies, within the first 50 million years after the big bang. That could explain why star-formation rates in the early universe were so high: the black holes could have powered the galaxies earlier than expected and crushed clouds of dust and gas into stars more quickly. The mechanism involves reasonably well-understood astrophysical processes called feedback and outflow.

"There are far more black holes than we expected" in JWST's observations, Silk says, "and the galaxies they're in are very compact," barely 300 light-years across, compared with the Milky Way's diameter of 100,000 light-years. "This means the feedback is greatly enhanced," Silk says. "Our basic hypothesis is that the black holes really formed before most of the stars, and their vigorous outflows then created lots of stars. As time went on, this died away and led to the more conventional star formation that we have [today]. We think this is just a very special phenomenon that occurred early on and can explain the mysteries that we're seeing with JWST."

Fabio Pacucci of the Center for Astrophysics | Harvard & Smithsonian and his colleagues have studied the role black holes might have played at a later time in galaxies' evolution. In a galaxy like our own in the modern universe, the mass of stars outweighs the mass of the galaxy's central supermassive black hole—a feature that is ubiquitous among large galaxies—by a ratio of 1,000 to 1.

Using JWST to examine galaxies from 750 million to 1.5 billion years after the big bang, Pacucci found that some of them in this window may have a black hole whose mass matches their stellar mass—or perhaps even exceeds it. That points to a model of black hole growth in the early universe in which black holes grew from the direct collapse of clouds of dust and gas in the first 100 million years of the cosmos rather than from stars. This proposal is consistent with that of Silk and his colleagues and thus may bolster the astrophysical explanation of the rapid early growth of galaxies.

FROM OUR ARCHIVES
JWST Finds Strange Harmony in Early Galaxies and Black Holes. Fabio Pacucci; ScientificAmerican.com, September 21, 2023.
Scientific American.com/archive

If that idea is correct, upcoming gravitational-wave observatories—such as the Laser Interferometer Space Antenna (LISA) space observatory, which was recently approved by the European Space Agency and is set for launch in 2035—might find these "heavy seed" black holes. "If these heavy seeds happened, then we would see a lot of mergers" with LISA, Pacucci says. "It's possible this will ease the problem of excessive mass."

There are ways to explain JWST's galaxies without black holes, too. Guochao Sun of Northwestern University and his colleagues have suggested that some galaxies in the universe might have gone through periods of "bursty" star formation. An abundance of supernovae could have temporarily led to a feedback process over 10 million years or so that increased star formation to rates "10 to 100 times" higher than those of more sedate galaxies, Sun says.

That could have caused the brightness of some galaxies in the early universe to "jump up and down very drastically," leading to a skewed sample of more visible bright galaxies. "You don't need to form stars at a very high efficiency," Sun adds. It may be that JWST's mysteriously bright early galaxies merely represent the upper end of dramatic fluctuations in star formation, with dimmer, more prosaic galaxies being more numerous but, so far, unseen.

Astrophysics, for the time being, reigns supreme. There is much at stake, however. "The fact that cosmology could be at play here means it's really worth following it up until it's excluded," Boylan-Kolchin says. Black holes and star formation are promising explanations, but scientists will be watching for fresh JWST results to see which, if any, of the new models hold firm. ●