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A New Era for Astronomy

How the James Webb Space Telescope is transforming our view of the universe

A NEW ERA FOR ASTRONOMY

How the James Webb Space Telescope is transforming our view of the universe

Close your eyes and imagine "space," and there's a good chance your mind will pull up a picture taken by Hubble. The space telescope became a household name in the 1990s as the images it captured appeared on TV and in magazines, newspapers and movies. Over the decades it created a shared visual lexicon of outer space and seeded multiple generations' imaginations with visions of glowing nebulae, haunting planets and faraway galaxies. More than 30 years after launch, Hubble is still going strong. But now its successor promises to outdo it.

The first photos from the James Webb Space Telescope (JWST) went out to the world on July 12, 2022, and they are stunners. The clarity and level of detail are unprecedented. Seeing the telescope's new views of some familiar objects—from the oft-photographed Carina Nebula to the planet Neptune—feels like putting on new glasses with a stronger prescription. Only the first batches of JWST photos have been released so far, but each image has created a stir, suggesting that in the coming years the telescope's pictures will infiltrate the public subconscious just as thoroughly as Hubble's.

The triumph is especially sweet given what it took for JWST to get here. Scientists started planning it more than three decades ago, and the effort to build the observatory fell so far behind schedule and so far over budget that many feared it would never be launched at all. When the telescope finally lifted off on December 25, 2021, with an ultimate price tag of nearly $10 billion, astronomers felt a rush of relief. In the subsequent six months JWST proved to be working even better than planned, and astronomers really began to enjoy themselves.

Now scientists are ecstatic. In the three months after the initial results from the telescope were released, scientists submitted some 200 papers interpreting them to the preprint server arXiv. A deluge is sure to follow—the telescope's initial observing time is already spoken for by the lucky researchers whose proposals won out in a highly competitive peer-reviewed selection process.

In the following pages, we've collected some of the cosmic portraits JWST has given us so far. On page 42, we show how scientists create finished images from the telescope's raw data. On page 28, journalist Jonathan O'Callaghan explains how some of those photos have already thrown the field of cosmology into crisis. And on page 39, astrophysicist Fabio Pacucci describes how Hubble and JWST have changed science by taking pictures of "empty" space.

Soon the first image we call to mind when we think about space may well be one of JWST's. How long it will run and what its ultimate legacy will be are still open questions. But it's certainly off to a shining start. —*Clara Moskowitz, Senior Editor*

THE TARANTULA NEBULA is a nursery of dust and gas where new stars are being born. Hot young stars sparkle in blue at the center of this image from JWST's NIRCam, and rusty ripples at the outskirts represent cooler gas where future stars will form.

NASA, ESA, CSA, STScI and Webb ERO Production Team

BREAKING COSMOLOGY

JWST's first images include unimaginably distant galaxies that challenge theories of how quickly these structures can form

By Jonathan O'Callaghan

GALAXIES from the depths of cosmic time appear in a small crop from "deep field" observations taken by the James Webb Space Telescope (JWST). The most distant objects in such images may reveal surprising new details about the early universe.

Jonathan O'Callaghan is a freelance journalist covering commercial spaceflight, space exploration and astrophysics.

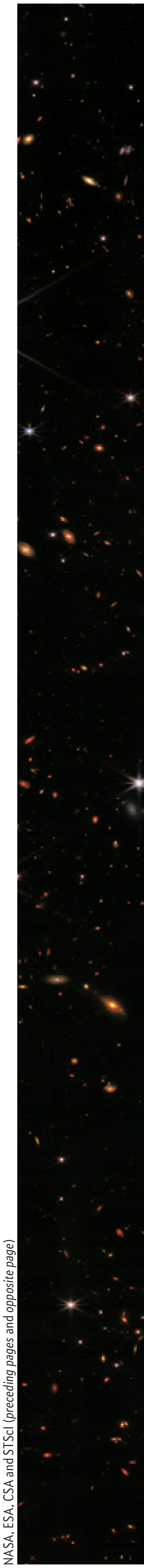
ROHAN NAIDU WAS AT HOME WITH HIS GIRLFRIEND WHEN HE FOUND THE GALAXY that nearly broke cosmology. As his algorithm dug through early images from the James Webb Space Telescope (JWST) late one night this past July, Naidu shot to attention. It had sifted out an object that Naidu recognized was inexplicably massive and dated back to just 300 million years after the big bang, making it older than any galaxy ever seen before. "I called my girlfriend over right away," Naidu says. "I told her, 'This might be the most distant starlight we've ever seen.'" After exchanging excited messages with one of his collaborators "with lots of exclamation marks," Naidu got to work. Days later they published a paper on the candidate galaxy, which they dubbed "GLASS-z13." The Internet exploded. "It reverberated around the world," Naidu says.

The discovery of this galaxy, just weeks into JWST's full operations, was beyond astronomers' wildest dreams. JWST—the largest, most powerful observatory ever launched from Earth—was built to revolutionize our understanding of the universe. Stationed 1.5 million kilometers away from earthly interference and chilled close to absolute zero by its tennis court–sized sunshade, the telescope's giant segmented mirror and exquisitely sensitive instruments were designed to uncover details of cosmic dawn never before observed.

This is the scarcely probed era—no more than a few hundred million years after the big bang itself—in which the very first stars and galaxies coalesced. How exactly this process unfolded depends on exotic physics, ranging from the uncertain influences of dark matter and dark energy to the poorly understood feedbacks between starlight, gas and dust. By glimpsing galaxies from cosmic dawn with JWST, cosmologists can test their knowledge of all these underlying phenomena—either confirming the validity of their best consensus models or revealing gaps in understanding that could herald profound new discoveries.

Such observations were supposed to take time; initial projections estimated the first galaxies would be so small and faint that JWST would find at best a few intriguingly remote candidates in its pilot investigations. Things didn't quite go as planned. Instead, as soon as the telescope's scientists released its very first images of the distant universe, astronomers such as Naidu (at the Massachusetts Institute of Technology) started finding numerous galaxies within them that, in apparent age, size and luminosity, surpassed all predictions. The competition for discovery was fierce: with each new day, it seemed, claims of yet another record-breaking "earliest-known galaxy" emerged from one research group or another. "Everyone was freaking out," says Charlotte Mason, an astrophysicist at the University of Copenhagen. "We really weren't expecting this."

In the weeks and months following JWST's findings of surprisingly mature "early" galaxies, theorists and observers have been scrambling to explain them. Could the bevy of anomalously big and bright early galaxies be illusory, perhaps because of flaws in analysis of the telescope's initial observations? If genuine, could they somehow be



NASA, ESA, CSA and STScI (*preceding pages and opposite page*)

THE INTERACTING galaxies of Stephan's Quintet, as seen by JWST, approximately 290 million light-years away from Earth. Covering one fifth of the moon's diameter, this mosaic is constructed from almost 1,000 separate images and reveals never-before-seen details of this galaxy group.

NASA, ESA, CSA and STScI

explained by standard cosmological models? Or, just maybe, were they the first hints that the universe is more strange and complex than even our boldest theories had supposed?

At stake is nothing less than our very understanding of how the orderly universe we know emerged from primordial chaos. JWST's early revelations could rewrite the opening chapters of cosmic history, which concern not only distant epochs and faraway galaxies but also our own existence here in the familiar Milky Way. "You build these machines not to confirm the paradigm but to break it," says JWST scientist Mark McCaughrean, a senior adviser for science and exploration at the European Space Agency. "You just don't know how it will break."

DEEP LOOKS FOR COSMIC DAWN

ONE MIGHT SAY JWST'S observations of early galaxies have been billions of years in the making, but more modestly they trace back to the Space Telescope Science Institute (STScI) in 1985. At the time the Hubble Space Telescope was still five years away from launching on a space shuttle. But Garth Illingworth, then deputy director of the STScI, was surprised one day when his boss, then

director Riccardo Giacconi, who died in 2018, asked him to start thinking about what would come after Hubble much farther down the road. “I protested, saying we’ve got more than enough to do on Hubble,” Illingworth recalls. But Giacconi was insistent: “Trust me, it’ll take a long time,” he said. So, Illingworth and a handful of others got to work, drawing up concept ideas for what became known as the Next Generation Space Telescope (NGST), later renamed to JWST after a former NASA administrator.

Hubble would be transformational, but astronomers knew its capabilities would be limited by its observations in visible light. As light from a very distant galaxy travels across the cosmic abyss, it is stretched by the expansion of the universe—a broadening of wavelengths known as redshift. The higher the redshift value, the more stretching the light has experienced, and thus the more distant its source galaxy. Redshifts for early

AN IMAGE FROM JWST reveals hundreds of previously invisible newborn stars in the stellar nursery known as the Carina Nebula, a vast agglomeration of gas and dust some 7,600 light-years from Earth.

NASA, ESA, CSA and STScI

galaxies are so high that their emitted visible light has stretched into infrared by the time it arrives at our telescopes, which is why Hubble could not see them. The NGST, for comparison, would observe in infrared and would boast a very large (and very cold) starlight-gathering mirror, allowing it to peer much deeper into the universe. "Everybody realized that Webb would be the telescope for looking at early galaxies," Illingworth says. "That became the primary science goal."

The need for the telescope was highlighted in December 1995, when astronomers pointed Hubble at a seemingly empty patch of the sky for 10 consecutive days. Many experts predicted the extended observation would be a waste of resources, revealing at best a handful of dim galaxies, but instead the effort was richly rewarded. The resulting image, the Hubble Deep Field, showed the "empty" spot was filled with galaxies by the thousands, stretching back 12 billion years into the 13.8-billion-year history of our universe. "There were galaxies everywhere," says Illingworth, now an astrophysicist at the University of California, Santa Cruz. The Hubble Deep Field showed that the early universe was even more crowded and exciting than most anyone had expected, offering observational treasures to those who took the time and care to properly look. Yet, impressive as Hubble's Deep Field was, astronomers wanted more.

After more than two decades of labor at a cost of some $10 billion, JWST finally launched on Christmas Day 2021. The telescope reached its deep-space destination a month later, where it

would endure exhaustive testing to ensure its optimal performance. By July 2022 it was ready to begin its long-awaited first year of science observations, known as Cycle 1. Part of the telescope's early time was devoted to high-impact programs across a range of disciplines from which data would immediately be made public. Two of those, CEERS (the Cosmic Evolution Early Release Science Survey) and GLASS (the Grism Lens–Amplified Survey from Space), independently spent dozens of hours looking for galaxies in the early universe by staring at separate small portions of the sky. Not much was expected—perhaps a slightly more ornate version of the Hubble Deep Field but nothing more. Steven Finkelstein of the University of Texas at Austin, the lead on CEERS, says extremely distant galaxies were predicted to pop up only "after a few cycles of data" from multiple programs.

A SIDE-BY-SIDE COMPARISON shows JWST's remarkably detailed observations of the Southern Ring Nebula in near-infrared light (*left*) and mid-infrared light (*right*). Located more than 2,000 light-years from Earth, the nebula is composed of shells of gas and dust expelled from a dying star, which in each image can be seen near the nebula's core.

Instead, much to the surprise of astronomers, extremely distant galaxies came into view immediately. Hubble's record for the most distant known galaxy had been GN-z11, spotted in 2015 at a redshift of 11 thanks to a 2009 upgrade that enhanced the telescope's modest infrared capabilities. A redshift of 11 corresponds to a cosmic age of about 400 million years, a point at the brink of when galaxy formation was thought to begin. But from the very first GLASS data, two teams—one led by Naidu in that breathless late-night discovery—independently found GLASS-z13 at a redshift of 13, some 70 million years farther back in time.

In their quest for quick results, the researchers relied on redshift estimates derived from simple brightness-based measurements. These are easier to obtain but less precise than direct measurements of redshift, which require more dedicated observation time. Nevertheless, the simplified technique can be accurate, and here it suggested a galaxy that was unexpectedly bright and big, already bearing a mass of stars equivalent to a billion suns, just a few hundred times less than that of the Milky Way's stellar population, despite our own galaxy being billions of years more mature. "This was beyond our most optimistic expectations," says Tommaso Treu, an astronomer at the University of California, Los Angeles, and the lead on GLASS.

The record didn't last long. In the following days, dozens of galaxy candidates from CEERS and GLASS sprang into view with estimated redshifts as high as 20—just 180 million years after the big bang—some with disklike structures that were not expected to manifest so early in cosmic history. Another team, meanwhile, found evidence for galaxies the size of our Milky Way at a redshift of 10, less than 500 million years after the big bang.

Such behemoths emerging so rapidly defies expectations set by cosmologists' standard model of the universe's evolution. Called Lambda CDM (LCDM), this model incorporates scientists' best estimates for the properties of dark energy and dark matter, which collectively act to dominate the emergence of large-scale cosmic structures. ("Lambda" refers to dark energy, and "CDM" refers to dark matter that is relatively sluggish, or "cold.") "Even if you took everything that was available to form stars and snapped your fingers instantaneously, you still wouldn't be able to get that big that early," says Michael Boylan-Kolchin, a cosmologist at the University of Texas at Austin. "It would be a real revolution."

HOW TO BUILD A GALAXY

TO UNDERSTAND THE DILEMMA, a brief refresher is needed. In the first second after the big bang, our universe was an almost inconceivably hot and dense soup of primordial particles. Over the next three minutes, as the cosmos expanded and cooled, the nuclei of helium and other very light elements began to form. Fast-forward 400,000 years, and the universe was cold enough for the first atoms to appear. When the universe was about 100 million years old, theorists say, conditions were finally right for the emergence of the first stars. These giant fireballs of mostly hydrogen and helium were uncontaminated by heavier elements found in modern-day stars, so they possessed significantly different properties. Larger and brighter than today's stars, these first suns coalesced in protogalaxies—clusters of gas that clung to vast, invisible scaffolds of dark matter. Gravity guided the subsequent interactions between these protogalaxies, which eventually merged to form larger galaxies. This process of becoming, of the early universe's chaos giving way to the more orderly cosmos we know today, is thought to have taken about a billion years.

NASA, ESA, CSA, STScI and Webb ERO Production Team

THE CARTWHEEL GALAXY displays its characteristic dust-rich "spokes" and starry inner and outer rings in this near-infrared view from JWST. These features ripple like shock waves from the galaxy's center, the site of a high-speed collision with another galaxy some 400 million years ago.

JWST's discovery of bright galaxies in the early cosmos challenges this model. "We should see lots of these little protogalactic fragments that have not yet merged to make a big galaxy," says Stacy McGaugh, a cosmologist at Case Western Reserve University. "Instead, we're seeing a few things that are already big galaxies." Some of these galaxies may be impostors, much closer galaxies shrouded in dust that makes them look dimmer and farther away when brightness-based measurements are used. Follow-up observations of GLASS-z13 in August by the Atacama Large Millimeter Array (ALMA) in Chile, however, suggest that is not the case for this candidate, because ALMA did not see evidence for large amounts of dust. "I think we can exclude low-redshift interlopers," says Tom Bakx, an astronomer at Nagoya University in Japan, who led the observations. Yet the lack of dust means ALMA struggled to see the galaxy at all, showing how difficult it could be for telescopes to confirm observations made using JWST's advanced capabilities. "The good news is there's nothing detected," Naidu says. "The bad news is there's nothing detected." Only JWST, in this case, can follow up itself.

The most startling explanation is that the canonical LCDM cosmological model is wrong and requires revision. "These results are very surprising and hard to get in our standard model of cosmology," Boylan-Kolchin says. "And it's probably not a small change. We'd have to go back to the drawing board." One controversial idea is modified Newtonian dynamics (MOND), which posits that dark matter does not exist and that its effects can instead be explained by large-scale fluctuations in gravity. To date, JWST's observations could support such a theory. "MOND has had a lot of its predictions come true—this is another one of them," says McGaugh, who is one of the idea's leading proponents. Others remain unconvinced. "So far everything that we've tried to test MOND hasn't been able to really provide a satisfactory answer," says Jeyhan Kartaltepe, an astrophysicist at the Rochester Institute of Technology.

One simpler solution is that galaxies in the early universe could have little or no dust, making them appear brighter. This scenario could confound efforts to calculate the galaxies' true masses and could perhaps also explain ALMA's difficulty spotting GLASS-z13. "It could be that supernovae didn't have enough time to produce the dust, or maybe in the initial phases [of galaxy formation] the dust is expelled from galaxies," says Andrea Ferrara, an astronomer at the Scuola Normale Superiore in Italy, who has proposed such a possibility. Alternatively, Mason and her colleagues suggest that in its observations of the early universe JWST may so far be seeing only the very brightest young galaxies, as they should be the easiest to spot. "Maybe there's something happening in the early universe that means it's easier for some galaxies to form stars," she says.

David Spergel, a theoretical astrophysicist and current president of the Simons Foundation in New York City, agrees. "I think what we're seeing is that high-mass star formation is very efficient in the early universe," he says. "The gas pressures are higher. The temperatures are higher. That has an enormous impact on the environment for star formation." Magnetic fields might have arisen earlier in the universe than we thought, driving material to kick-start the birth of stars. "We might be seeing a signature of magnetic fields emerging very early in the universe's history," Spergel says.

A RUSH TO BREAK THE UNIVERSE

THE RAPID FLOW of scientific papers from JWST's initial observations is no fluke; when the first data started streaming down, astronomers were eagerly waiting. "People had been working on their pipelines for years," Boylan-Kolchin says. Instead of the traditional peer-review processes, which can take months, astronomers published on arXiv, a website where scientific papers can be uploaded after minimal review by moderators but well before formal peer review. This new form of peer review is unfolding in near real time on Twitter and other social media platforms. "It's science by arXiv," Naidu says. The resulting frenzy was intense—and surprising. "I expected a lot of activity," says Nancy Levenson, STScI's interim director. "But I underestimated the amount."

The result was that scientific results could be rapidly publicized and discussed, but some fear at a cost. "People were rushing things a little bit," says Klaus Pontoppidan, JWST's project scientist at STScI. "The gold standard is a refereed, peer-reviewed paper." Early calibration issues with JWST, for example, may have affected some results. Nathan Adams at the University of Manchester in England and his colleagues found there could be dramatic changes, with one galaxy at a redshift of 20.4 recalibrated to a redshift of just 0.7. "We need to calm down a little bit," Adams says. "It's a bit too early to say we've completely broken the universe."

Such issues are unlikely to eradicate all of JWST's high-redshift galaxies, however, given their sheer number. "It's more likely that the early universe is different from what we predicted," Finkelstein says. "The odds are small that we're all wrong." Astronomers are now racing to conduct follow-up observations with JWST. Levenson says she's currently reviewing about a dozen proposals from various groups asking for additional JWST observing time, most of which are seeking to scrutinize high-redshift galaxy candidates. "Considering the excitement and importance of these early discoveries, we thought it was appropriate to ask for a little bit of time to confirm them," says Treu, who put forward one of the proposals.

More upcoming programs are set to hunt for distant galaxies, such as COSMOS-Webb, led by Kartaltepe, which is expected to hugely increase the known population of early galaxies by observing a wider swath of sky for hundreds of hours. "We estimate there are thousands we'll be able to detect," she says. Future proposals might look for evidence of those first protogalaxies, perhaps using the explosive deaths of supersized first stars in especially luminous and energetic supernovae as markers for their existence. Some estimates suggest JWST could see as far as a redshift of 26, just 120 million years after the big bang, a cosmic blink of an eye. Much other work will be done to follow up the growing list of high-redshift candidates. "Even confirming a handful of these would be quite amazing," Naidu says. "It would demonstrate we're not getting fooled."

JWST has ushered in a new era of science, and despite the uncertainties, the rapid communication of new discoveries has invigorated astronomers. "It's been fantastic," Treu says. "It's really wonderful to see the community so engaged and excited." Now the question is, if we can truly believe what we are seeing, is it time to reappraise our understanding of the dawn of time? "We're peering into the unknown," Mason says. SA

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THE BOUNTY OF "EMPTY" SPACE

Deep-field images uncover more of the universe than we ever thought possible

By Fabio Pacucci

THIS PAST JULY ASTRONOMERS WORKING WITH THE JAMES WEBB SPACE TELESCOPE (JWST) released the deepest astronomical image ever obtained, leaving the world in awe. Against the background of a galaxy cluster named SMACS 0723, seen as it appeared 4.6 billion years ago, myriad galaxies of different shapes and sizes appear like bright gems in the darkness of the cosmos. Some of these lighthouses were already shining when the universe was just a few hundred million years old. To understand how we reached this remarkable achievement—how astronomers have sailed to galactic islands so remote from us in space and time, collecting photons whose journey started breathtakingly close to the big bang—it helps to know how deep-field observations came to be.

The origin of Webb's first deep field is best traced to the early 1990s, with the launch of JWST's predecessor, the Hubble Space Telescope. The concept of deep-field observations was still in its infancy back then. Hubble was primarily designed for targeted observations. Astronomers would point the telescope to a source at a specific spot in the sky and expose (or "integrate") as needed, depending on the source's brightness. But Hubble could also be used for deep-field imaging, which is the opposite: astronomers would point the telescope to a sky region devoid of any visible source and use a very long exposure time to observe as many faint sources of light as possible, thereby reaching "deep" into the cosmos. From its perch in low-Earth orbit, above our planet's starlight-scattering atmosphere, Hubble was the best platform for deep-field imaging astronomers had ever known.

Not everyone thought the approach would prove revolutionary. In a famous article published in *Science* in 1990, John Bahcall of the Institute for Advanced Study in Princeton, N.J., and his colleagues argued that a deep-field image from Hubble would not reveal significantly more galaxies than ground telescopes. Bahcall, a giant in astrophysics, was widely known for his work on the problem of solar neutrinos and his calculations of the distribution of stars around a massive black hole. He contributed fundamentally to the development of the Hubble Space Telescope from its original concept in the 1970s to its launch. Bahcall thought Hubble deep-field images could be used to study the sizes and shapes of faint galaxies and to take a census of quasars (a rather old-fashioned word for accreting supermassive black holes), but he didn't believe they would reveal new populations of galaxies. Such tepid expectations tamped down any urgency to try deep-field imaging with Hubble.

The first attempt occurred around the winter holidays of 1995, after a much needed optics repair. The telescope spent 10 days of exposure time pointed at the Ursa Major constellation, staring at a tiny patch of the sky just one-thirteenth the moon's angular diameter. Weeks later, when astronomers saw the resulting image—known as the Deep Field North—they immediately realized it was a Christmas gift for the ages. Because the Milky Way's stars are sparse in the target region, Hubble was able to probe the cosmic abyss as if through a peephole. The telescope saw almost 3,000 faint galaxies of different shapes and sizes—many more than expected, some of them as far as 12 billion light-years away. Hubble was not only exploring space. It was also probing time, gathering starlight that had been emitted eons ago, during earlier epochs of the universe. The image quickly became iconic.

Hubble's deep fields captured more than 10,000 galaxies in one of astronomy's first "big data" challenges.

A crucial question arose: Was the galaxy-rich region revealed by the Deep Field North the norm throughout the universe, or did astronomers just happen to point the telescope toward a Pantagruelian crowding of galaxies? In 1998 Hubble obtained the Deep Field South. The exposure was similar, but the telescope pointed toward the southern celestial hemisphere, as far as possible from the first spot. This new image confirmed that the universe contained many more galaxies than previously thought, especially at vast distances. In addition to their scientific and inspirational value, these and other Hubble deep-field surveys were a technical triumph, capturing more than 10,000 galaxies in one of astronomy's first "big data" challenges.

Deep-field imaging is not restricted to the visible realm of the spectrum. At the turn of the millennium, the Chandra X-ray observatory, a revolutionary NASA mission launched in July 1999 and still active today, captured the first high-energy deep field. The Chandra Deep Field South was obtained by integrating for about one million seconds over a piece of the sky that was devoid of hydrogen clouds and dust from the Milky Way. The Chandra Deep Field South uncovered the extreme universe, revealing hundreds of black holes, some very remote. The image wasn't as visually spectacular as the Hubble photographs, but it was dense with science. Chandra later imaged the same field for a total exposure of about seven million seconds, capturing one of the deepest fields ever obtained in x-ray. In 2003 a new image called Chandra Deep Field North was released, containing data from more than 500 x-ray sources.

In 2006 scientists released the Hubble Ultra Deep Field, which was taken using an instrument called the Advanced Camera for Surveys that was added to the telescope during a servicing mission in 2002. This historic shot contained thousands of galaxies, some that we now know were shining when the universe was less than one billion years old. The Ultra Deep Field showed the history of galaxy formation in unprecedented detail. Distant galaxies conclusively appeared to be smaller and more irregular in shape than closer ones, providing substantial evidence to support galaxy evolution theories.

The technology used for Ultra Deep Field provides essentially the deepest image that can be obtained in optical wavelengths. If a galaxy is too far away, its optical light is shifted outside the visible range and into the infrared regime; this is a consequence of the cosmological redshift, in which the expansion of the universe stretches out the wavelengths of light traveling through enormous expanses of intergalactic space. It would take an infrared camera to look farther in space and time. With the addition of a new near-infrared camera to Hubble, an infrared Ultra Deep Field was obtained in 2009, revealing galaxies shining only 600 million years after the big bang. A decade later, in 2019, a deep field produced with NASA's Spitzer infrared space telescope was released. Both these images are rich with galaxies at the cosmic dawn.

Hubble's Frontier Fields campaign, completed in 2017, was the real prologue to JWST's first deep image. During this observational campaign, Hubble was pointed toward six large concentrations of galaxies. According to Einstein's theory of general relativity, a substantial density of mass along the line of sight can bend and thus amplify the light incoming from a background source, an effect called gravitational lensing. The Frontier Fields campaign used these galaxy clusters as a magnifying glass to see even farther away. Besides being filled with swarming galaxies, the Frontier Fields images are adorned with strange arcs of light, representing the stretched and amplified images of background galaxies much more distant than the cluster and possibly too faint to be directly observed with Hubble. These shots revealed some of the most distant galaxies and the first gravitationally lensed supernova.

It's been almost 200 years since the advent of photography, when humanity first managed to directly capture and record photons to make images. Today highly complex cameras onboard a space telescope one million miles away are shaking our knowledge of the universe, opening new windows onto space and time. A relatively short time separates these two events, but they are linked by the same goal: achieving a deeper understanding of nature by looking at what our eyes cannot see. SA

R. Williams/STScI, Hubble Deep Field Team and NASA/ESA

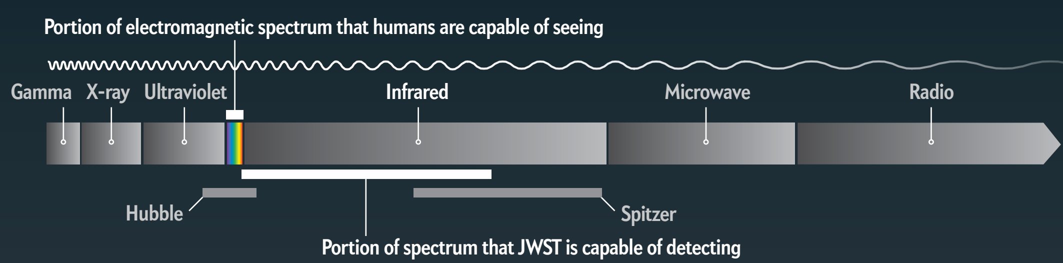
HUBBLE Space Telescope's first deep-field image, taken in 1995, surprised scientists with its horde of galaxies.

How JWST's images are made

Text by Clara Moskowitz | Graphics by Jen Christiansen

Behind the Pictures

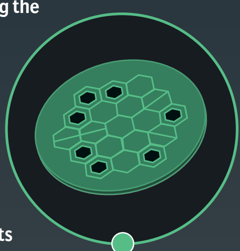
As light travels through space, it gets stretched by the expansion of the universe. This is why many of the most distant objects shine in infrared light, which is longer in wavelength than visible light. We can't see this ancient light with our eyes, but the James Webb Space Telescope (JWST) was designed to capture it, revealing some of the first galaxies ever to form.



Six Data Collection Components …

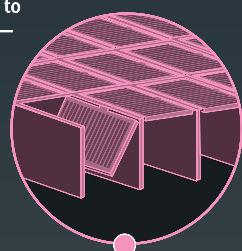
Aperture Masking

A perforated metal plate blocks some of the light entering the telescope, allowing it to simulate an interferometer, which combines data from multiple telescopes to achieve higher resolution than a single lens. The technique reveals more details of very bright objects close together, such as two stars nearby on the sky.



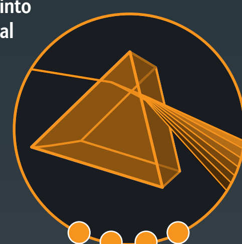
Micro Shutter Array

A grid of 248,000 small doors can open or close to measure spectra—light spread into its constituent wavelengths—from up to 100 points in a single frame.



Spectrographs

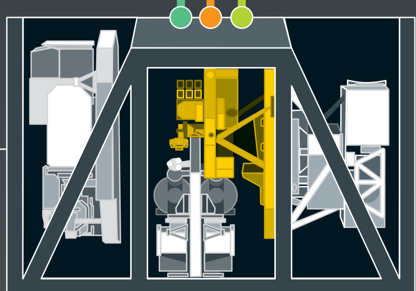
Gratings or prisms separate incoming light into spectra to reveal the intensity of individual wavelengths.



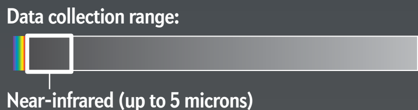
… Distributed across Four Instruments

Fine Guidance Sensor (FGS)/ Near-InfraRed Imager and Slitless Spectrograph (NIRISS)

The FGS is a guide camera that helps to point the telescope in the right direction. It's packaged together with the NIRISS, which has a camera and a spectrograph to take images and spectra in the near-infrared range.

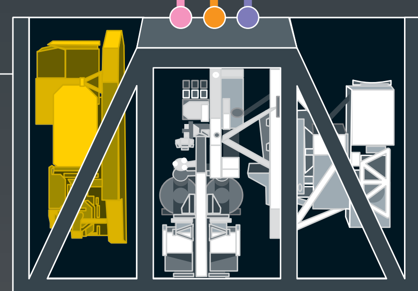


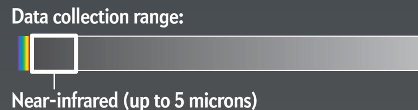
Rear view inside the instrument module

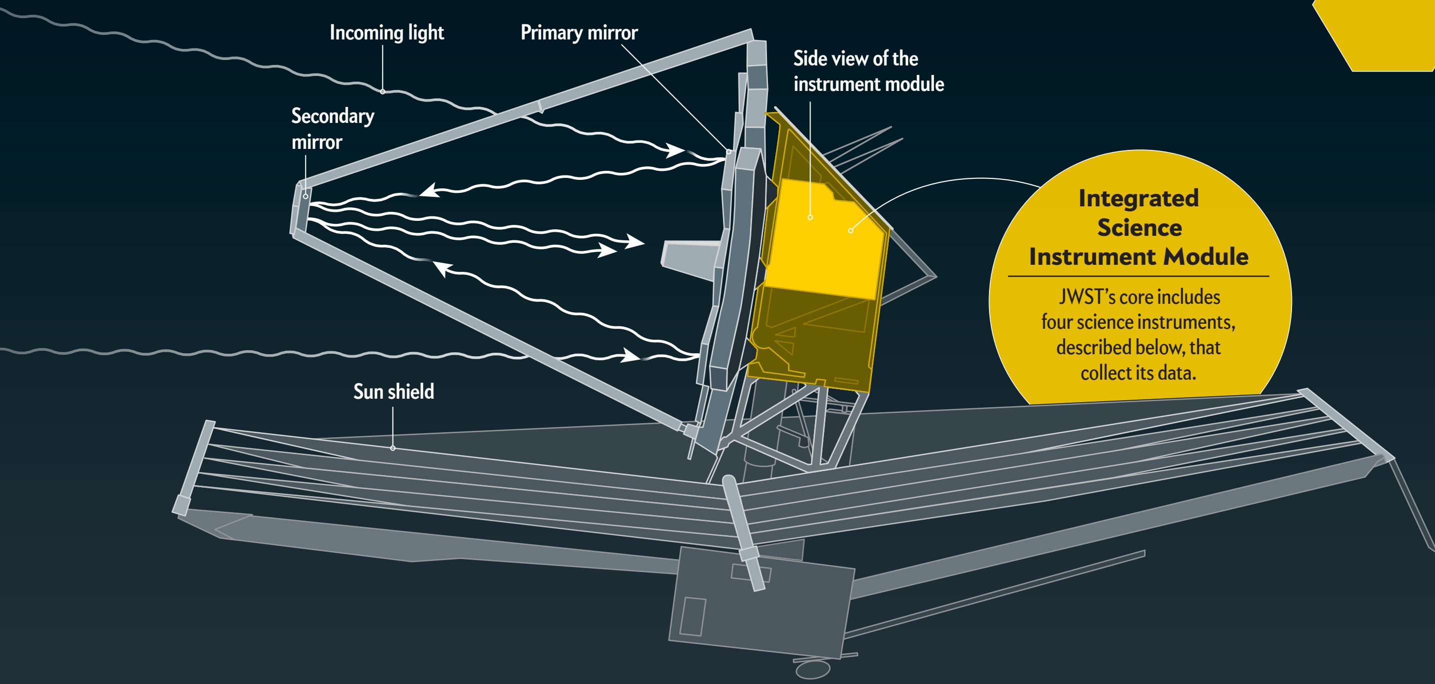


Near-Infrared Spectrograph (NIRSpec)

This dedicated spectrograph can capture 100 spectra simultaneously with its micro shutter array. It's the first space instrument capable of taking spectroscopy for so many objects at once.





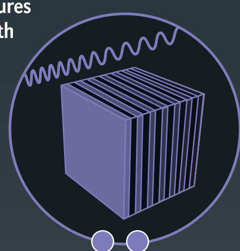


Cameras

JWST has three cameras—two that capture light in the near-infrared wavelength range and one that works in the mid-infrared.

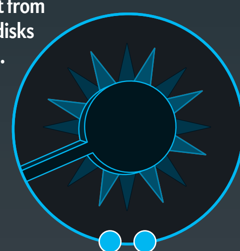
Integral Field Unit

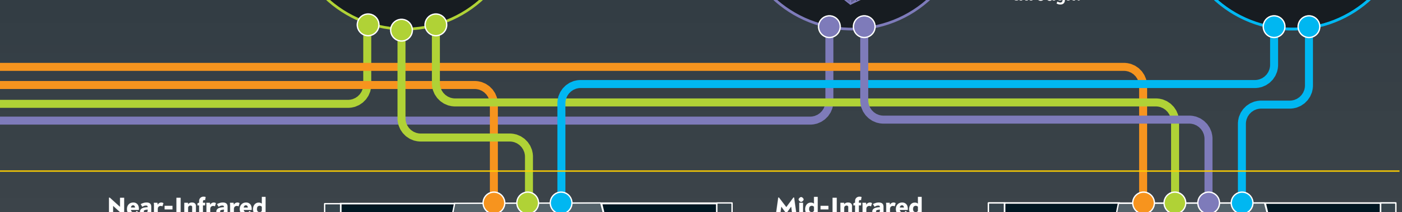
A combined camera and spectrograph captures an image, along with spectra for each pixel, revealing how the light varies across the field of view.



Coronagraphs

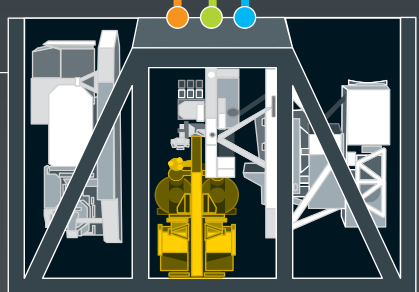
Glare from bright stars can blot out fainter light from planets and debris disks orbiting those stars. Coronagraphs are opaque circles that block that bright starlight to let the weaker signals through.

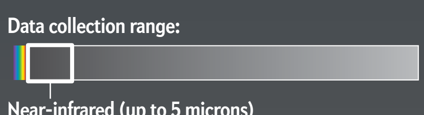




Near-Infrared Camera (NIRCam)

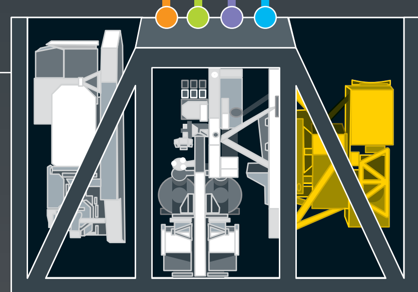
The only near-infrared instrument with a coronagraph, NIRCam will be a key instrument for studying exoplanets whose light would otherwise be drowned out by their nearby star's glare. It will capture high-resolution images and spectra in the near-infrared.

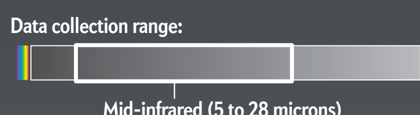




Mid-Infrared Instrument (MIRI)

This combination camera and spectrograph is JWST's only instrument capable of seeing in the mid-infrared, where cooler objects such as debris disks around stars and extremely distant galaxies emit their light.

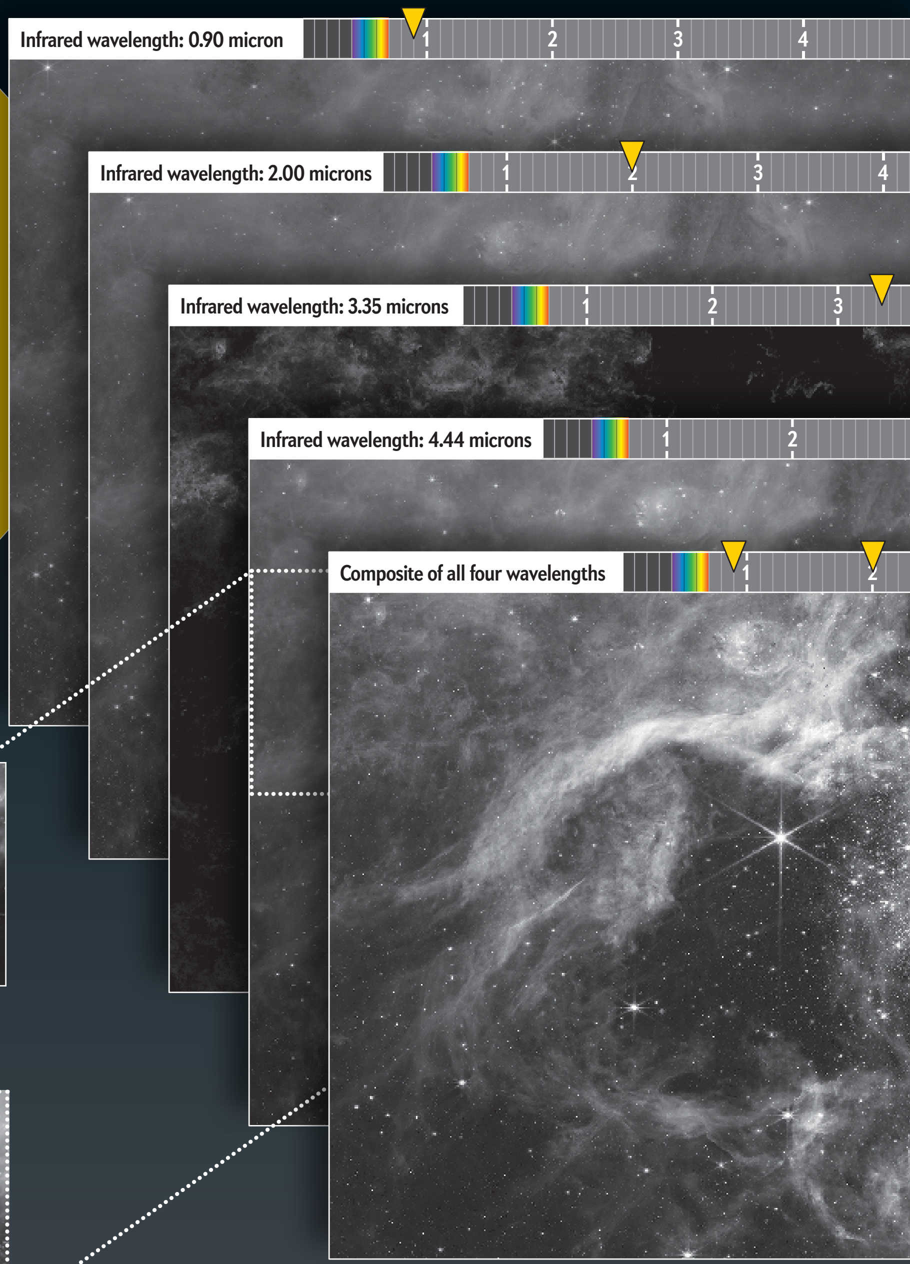


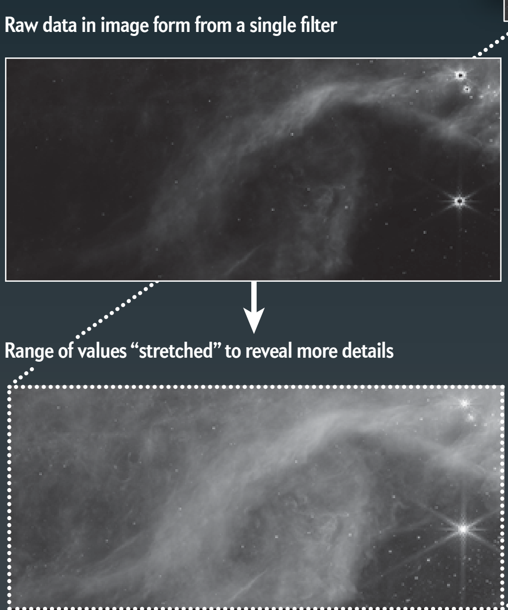


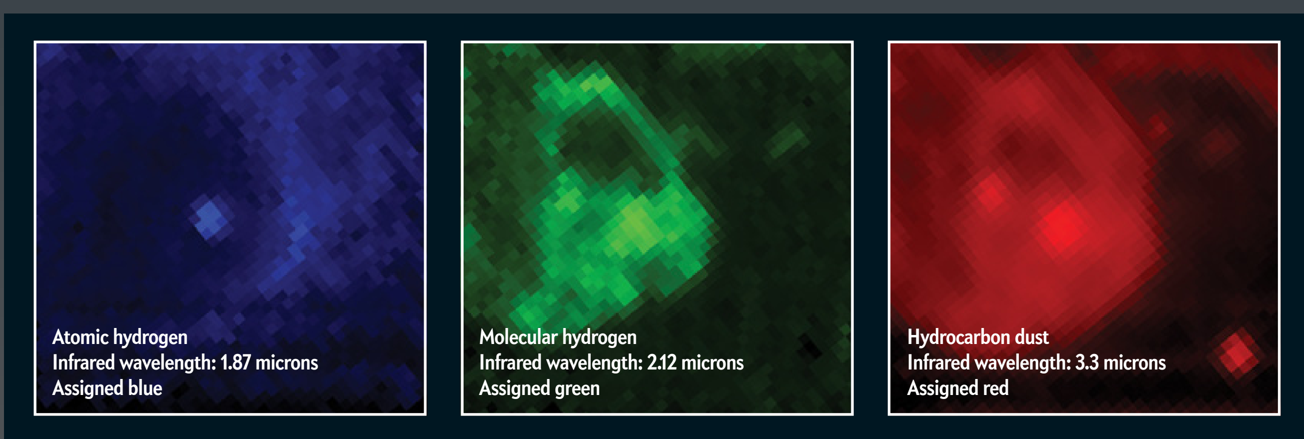
Sources: NASA; ESA; STScI; Andi James and J. Olmsted, STScI (*references*)

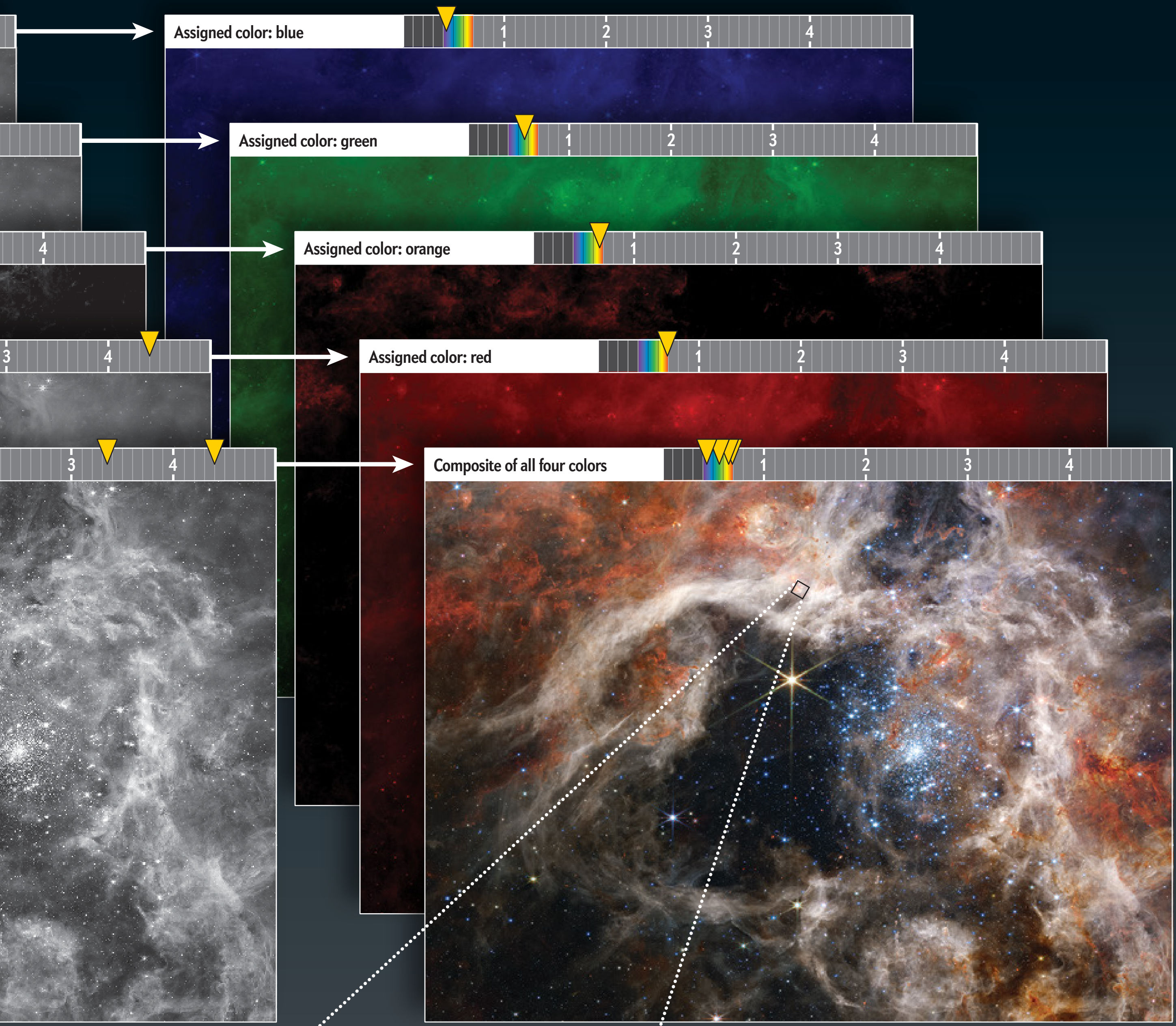
Are the Pictures "Real"?

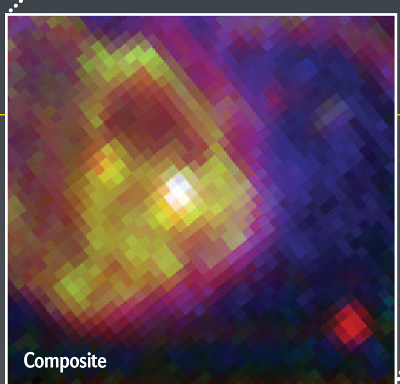
Scientists have to make adjustments to turn JWST's raw data into something human eyes can appreciate, but its photos are "real," says Alyssa Pagan, science visuals developer for the Space Telescope Science Institute. "Is this exactly what we'd see if we were there? The answer to that is no because our eyes are not built to see in infrared, and also the telescope is far more sensitive to light than our eyes." In that sense, the telescope's enhanced vision gives us a truer representation of what these cosmic objects look like than our relatively limited eyes could do. JWST can take images in up to 27 filters that capture different ranges of the infrared spectrum. Scientists first isolate the most useful dynamic range for a given image and scale the brightness values to unlock the most details. They then assign each infrared filter a color from the visible range of the spectrum—the shortest wavelengths get blue, and longer wavelengths move to green and red. After these are added together, all that's left are the normal white balancing, contrast and color adjustments that any photographer might make.











Data Details

Although the full-color images are captivating, many of the exciting discoveries show up one wavelength at a time. Here the NIRSpec instrument reveals different features of the Tarantula Nebula via different filters. The wavelength emitted by atomic hydrogen (*blue*), for instance, comes from a central star as well as from a bubble surrounding it. In between are the signatures of molecular hydrogen (*green*) and complex hydrocarbons (*red*). The data suggest that a cluster of stars in the frame's lower right is blowing a front of dust and gas toward the central star.

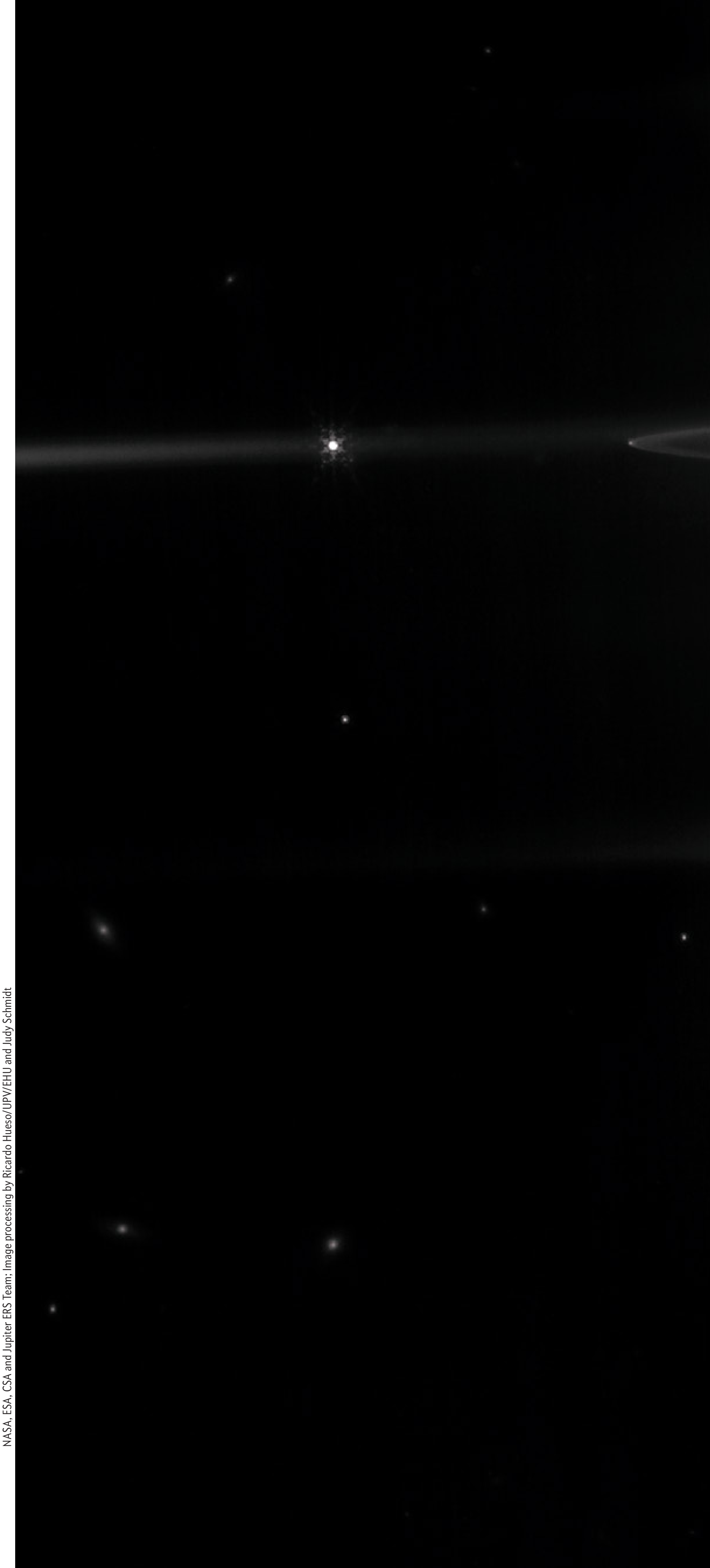
Image source: NASA, ESA, CSA, STScI and Webb ERO Production Team

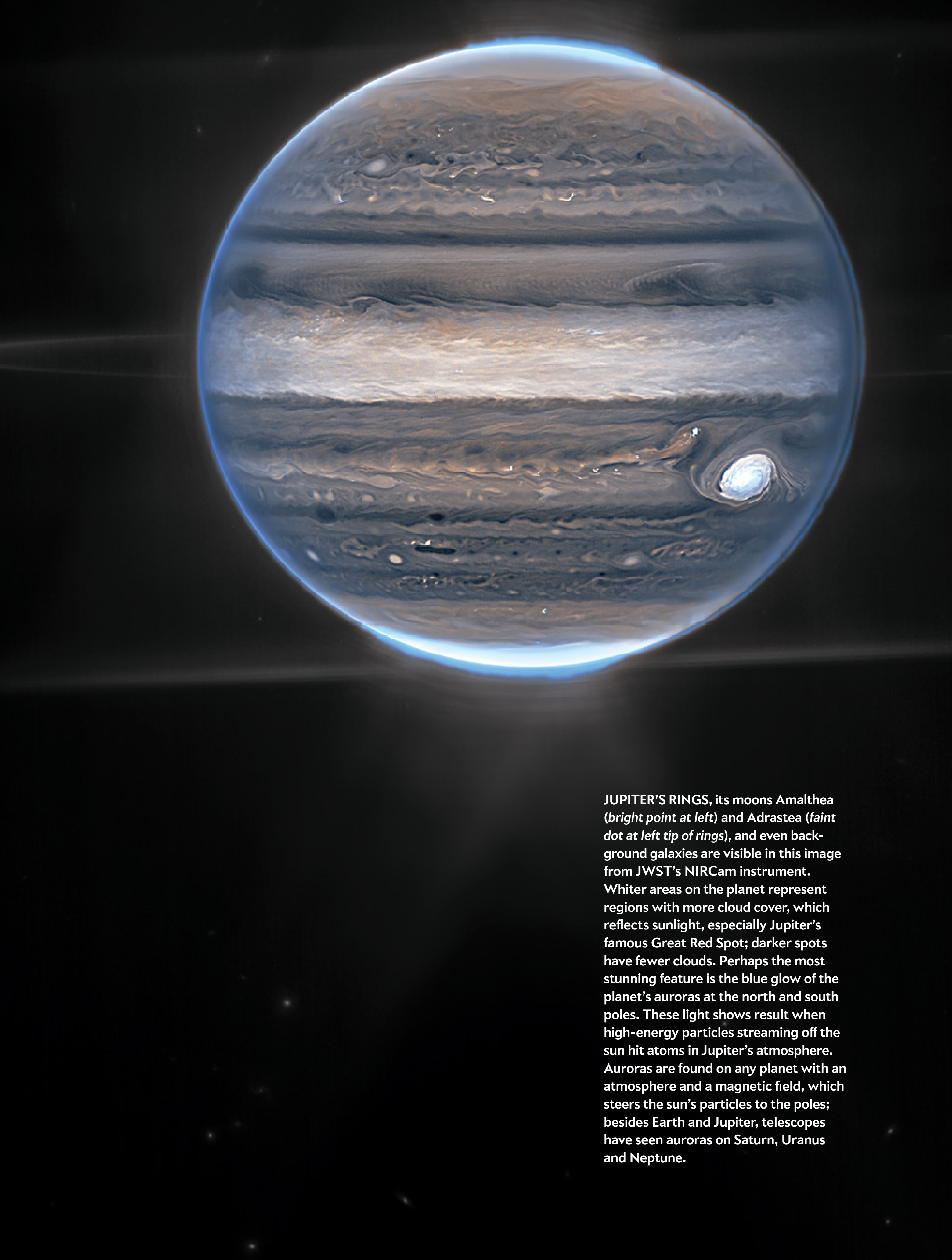
JWST's new views of familiar space sights reveal details never before seen

By Clara Moskowitz

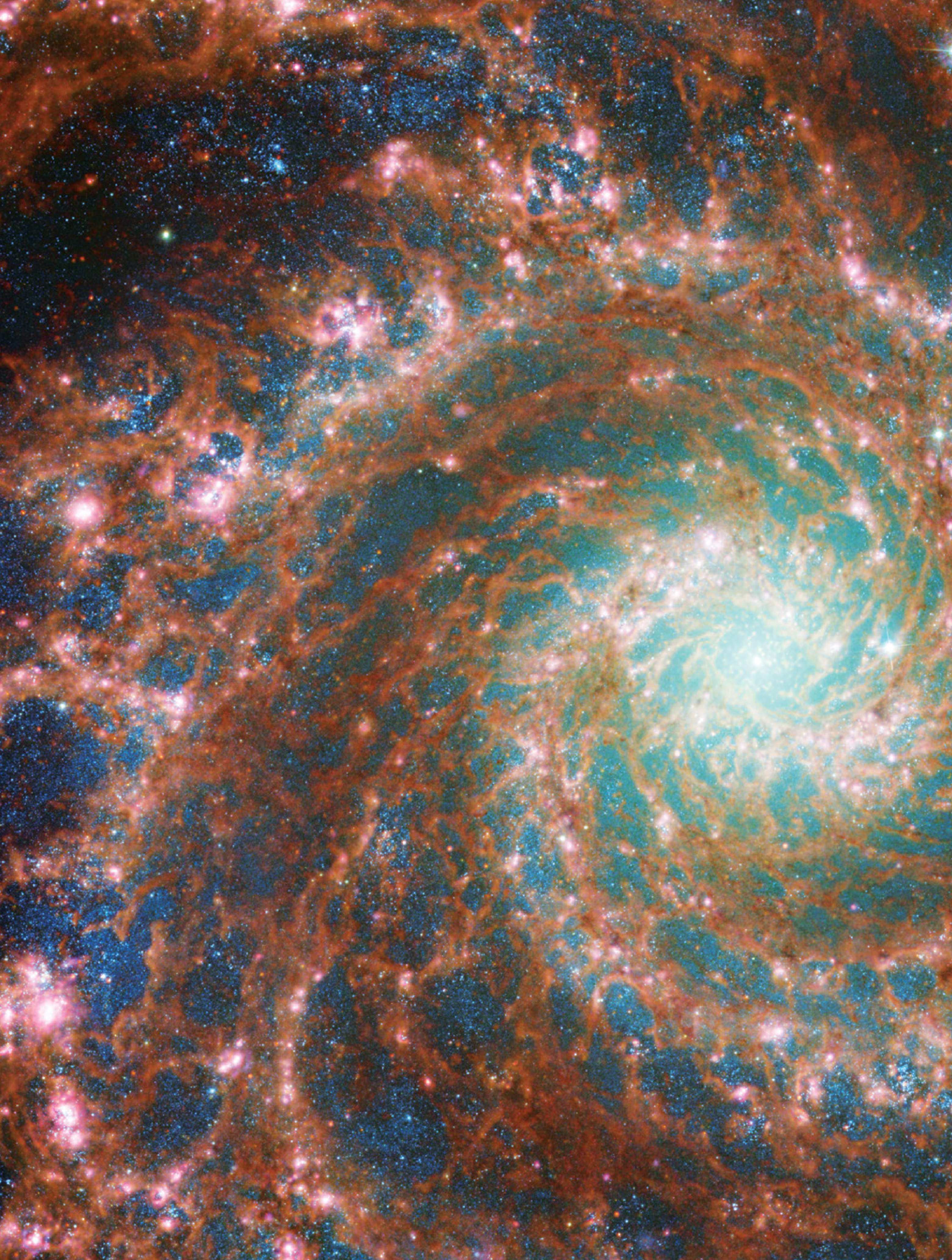
COSMIC PORTRAITS

NASA, ESA, CSA and Jupiter ERS Team; Image processing by Ricardo Hueso/UPV/EHU and Judy Schmidt



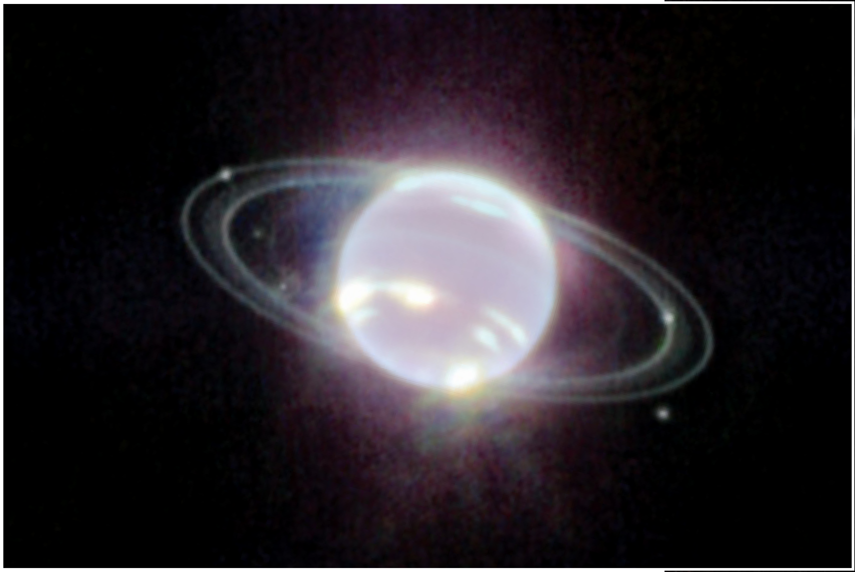


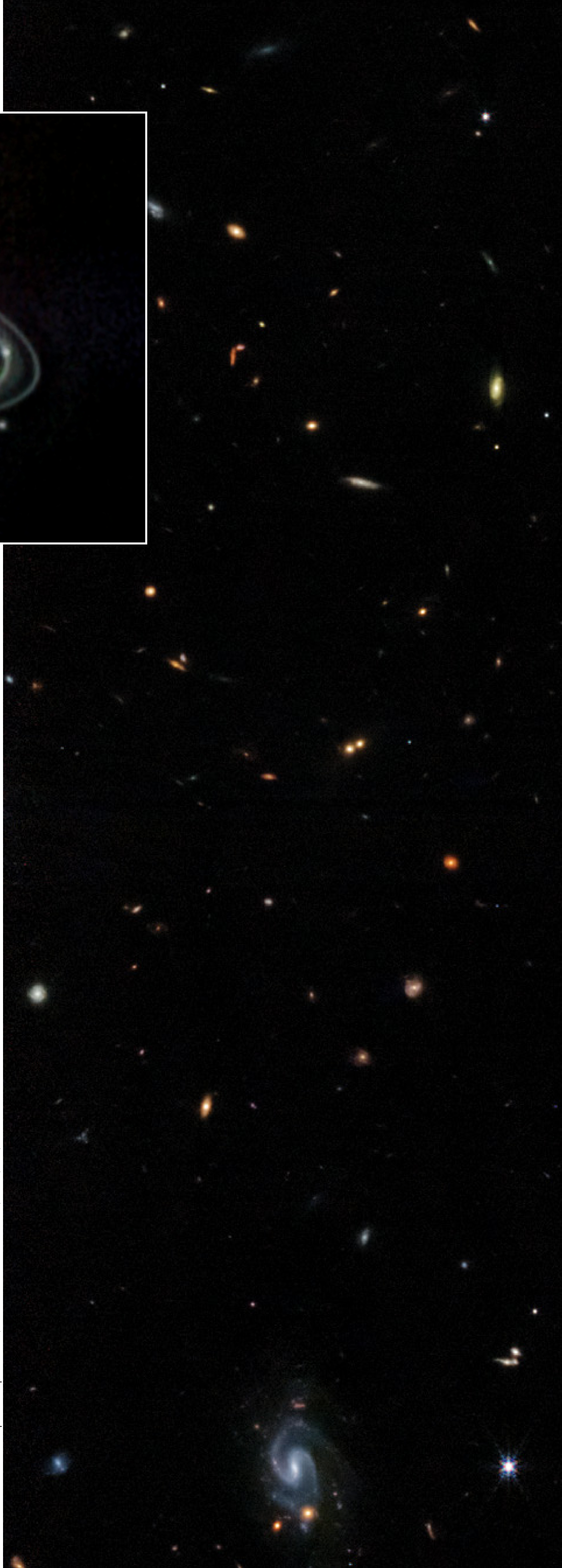
JUPITER'S RINGS, its moons Amalthea (*bright point at left*) and Adrastea (*faint dot at left tip of rings*), and even background galaxies are visible in this image from JWST's NIRCam instrument. Whiter areas on the planet represent regions with more cloud cover, which reflects sunlight, especially Jupiter's famous Great Red Spot; darker spots have fewer clouds. Perhaps the most stunning feature is the blue glow of the planet's auroras at the north and south poles. These light shows result when high-energy particles streaming off the sun hit atoms in Jupiter's atmosphere. Auroras are found on any planet with an atmosphere and a magnetic field, which steers the sun's particles to the poles; besides Earth and Jupiter, telescopes have seen auroras on Saturn, Uranus and Neptune.



THE PHANTOM GALAXY, M74, forms mesmerizing swirls in this photo combining observations from JWST and Hubble. Visible-light data from Hubble showcase the starlight in this spiral, including older, redder stars at the galaxy's glowing core and younger, bluer stars on its outskirts. The infrared light captured by JWST, however, highlights the gas and dust threaded through the spiral arms, as well as a bright cluster of stars at the heart of the galaxy. Each telescope sees a different aspect of this cosmic wonder, and the combined image offers a fuller picture than ever before.

ESA/Webb, NASA and CSA, J. Lee and PHANGS-JWST Team; ESA/Hubble and NASA, R. Chandar, Judy Schmidt





JWST ENABLED this first-ever view of Neptune's rings in infrared, revealing their delicate gossamer glow. The photo also shows seven of the planet's moons, including its largest satellite, Triton, the bright blue dot to Neptune's upper left. The moon's frozen nitrogen surface reflects 70 percent of the sunlight it receives, causing it to shine powerfully in the infrared. Distant galaxies sprinkle the background of this wide-field shot. In the inset, Neptune's layers of rings are clearly visible: two thin, bright ovals and two fainter, spread-out layers. Gleaming spots caused by methane ice clouds in the planet's atmosphere dapple its lower half.

Joseph DePasquale/STScI, Anton M. Koekemoer/STScI, NASA, ESA, CSA and STScI

FROM OUR ARCHIVES

Origami Observatory. Robert Irion; October 2010.
A Telescope's Long Journey. Clara Moskowitz and Matthew Twombly; January 2022.

scientificamerican.com/magazine/sa