35 BEST PRODUCTS OF THE YEAR p. 52

OCTOBER 2021

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NEXT-GEN ASTRONOMY ARRIVES!

LAUNCH OF THE WEBB SPACE TELESCOPE p. 14

» ALL ABOUT NEUTRON STARS p. 40

PLUS

Simple steps to beautiful astroimaging p. 22

Observe galaxies in the wrong places p. 48

Tucson's incredible club observatory p. 28

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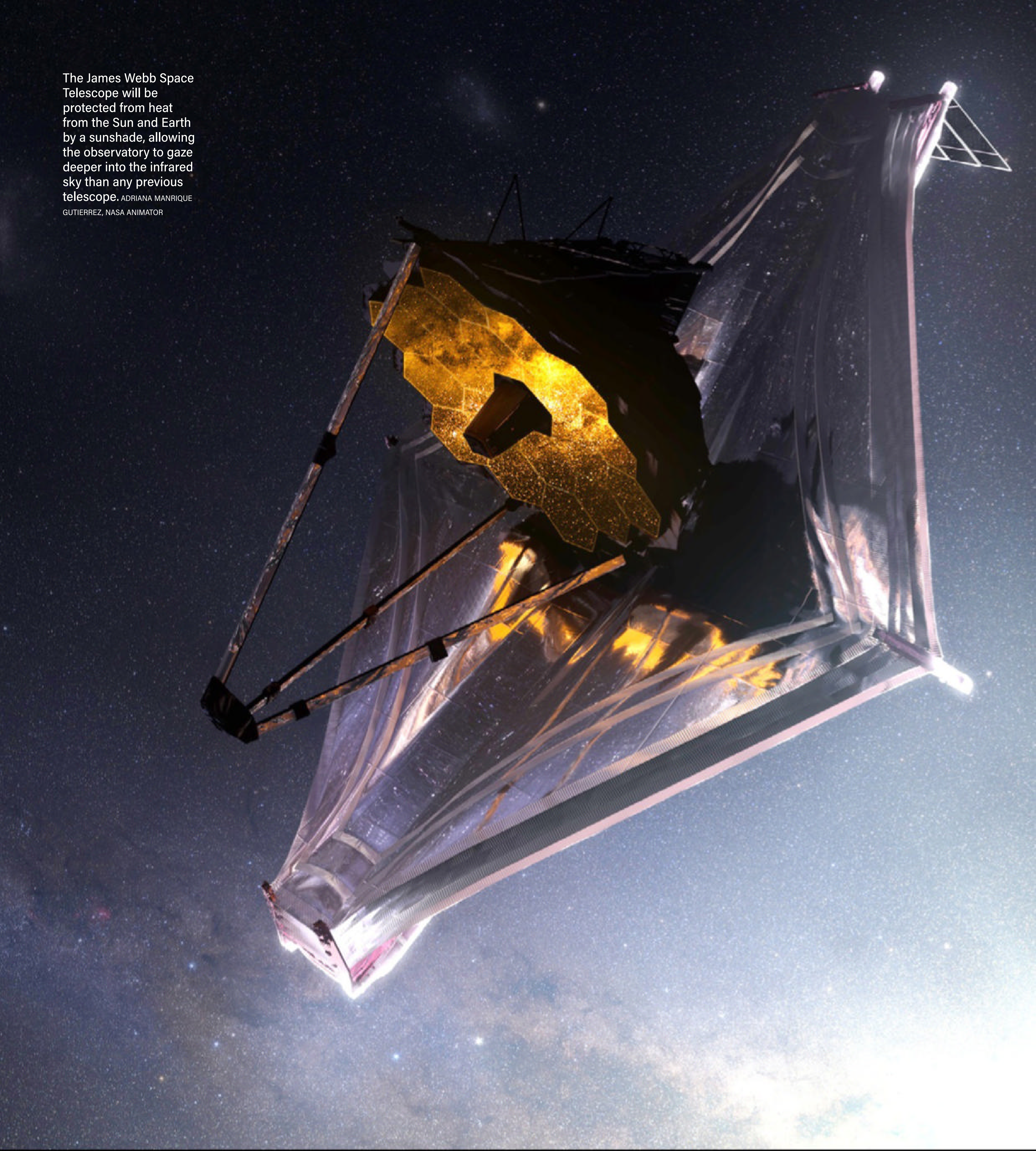
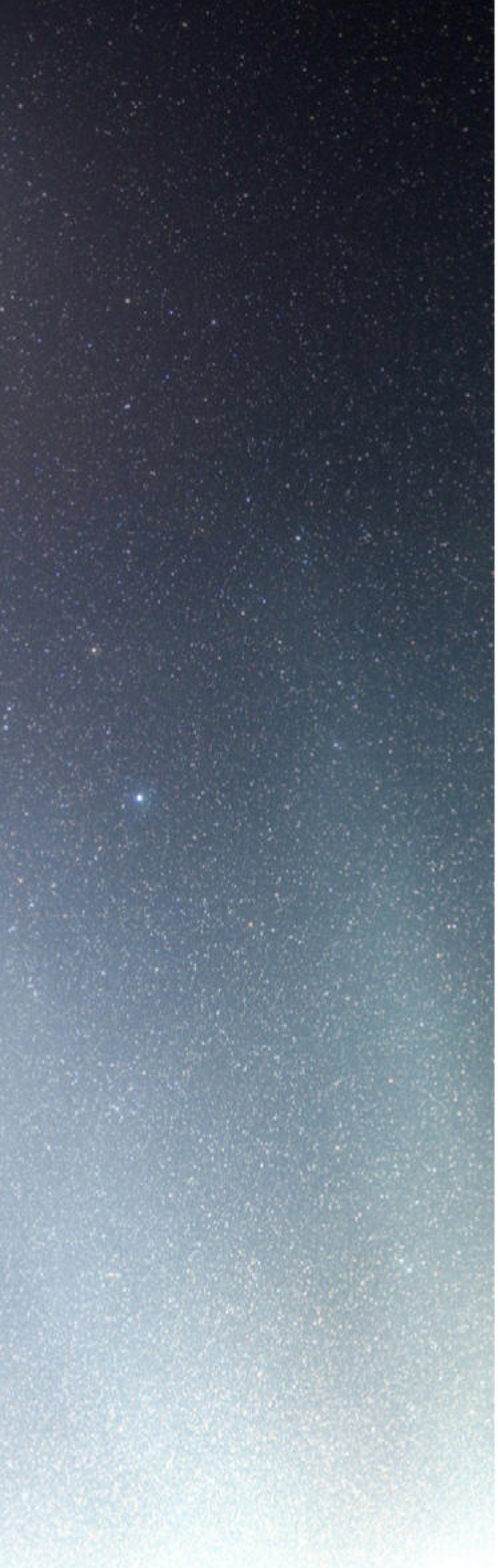
BONUS ONLINE CONTENT CODE p. 4

Vol. 49 • Issue 10

The James Webb Space Telescope will be protected from heat from the Sun and Earth by a sunshade, allowing the observatory to gaze deeper into the infrared sky than any previous telescope. ADRIANA MANRIQUE GUTIERREZ, NASA ANIMATOR



The James Webb Sp



ace Telescope lives!

The most powerful space telescope ever built, NASA's new flagship observatory will look deeper than Hubble and hunt for neighboring life.

BY JOHN MATHER

How did the Big Bang make you and me possible? Are we alone, and how close are the neighbors? The vast, unexplored cosmos is fertile ground for astronomers' imaginations. And yet, almost every important discovery came as a surprise.

The James Webb Space Telescope (JWST), set to launch as soon as November, will attempt to answer these questions — and the ones we don't even know to ask yet. It will crack open the treasure chest of the magnificent infrared sky, invisible to human eyes. With its great golden 6.5-meter primary mirror and its suite of cameras and spectrometers, the Webb can sense light ranging from the middle of the visible spectrum to the mid-infrared. If there were a bumblebee hovering in space at the distance of the Moon, the Webb could see both the sunlight it reflects and the heat that it emits.

As the telescope's senior project scientist, I've been working with the JWST team since we started in 1995. Our discoveries will be released as they are for the Hubble Space Telescope (HST) — some immediately, some after more detailed analysis — and everyone will be able to download our images. We know where we will look, we can guess what we will find, and there will be surprises.

We will look back in time by looking far away to hunt for the first galaxies, the first stars, the first supernovae, and the first black holes. Having grown from the pure hydrogen and helium available in the early universe, these objects were very different from today's modern examples.

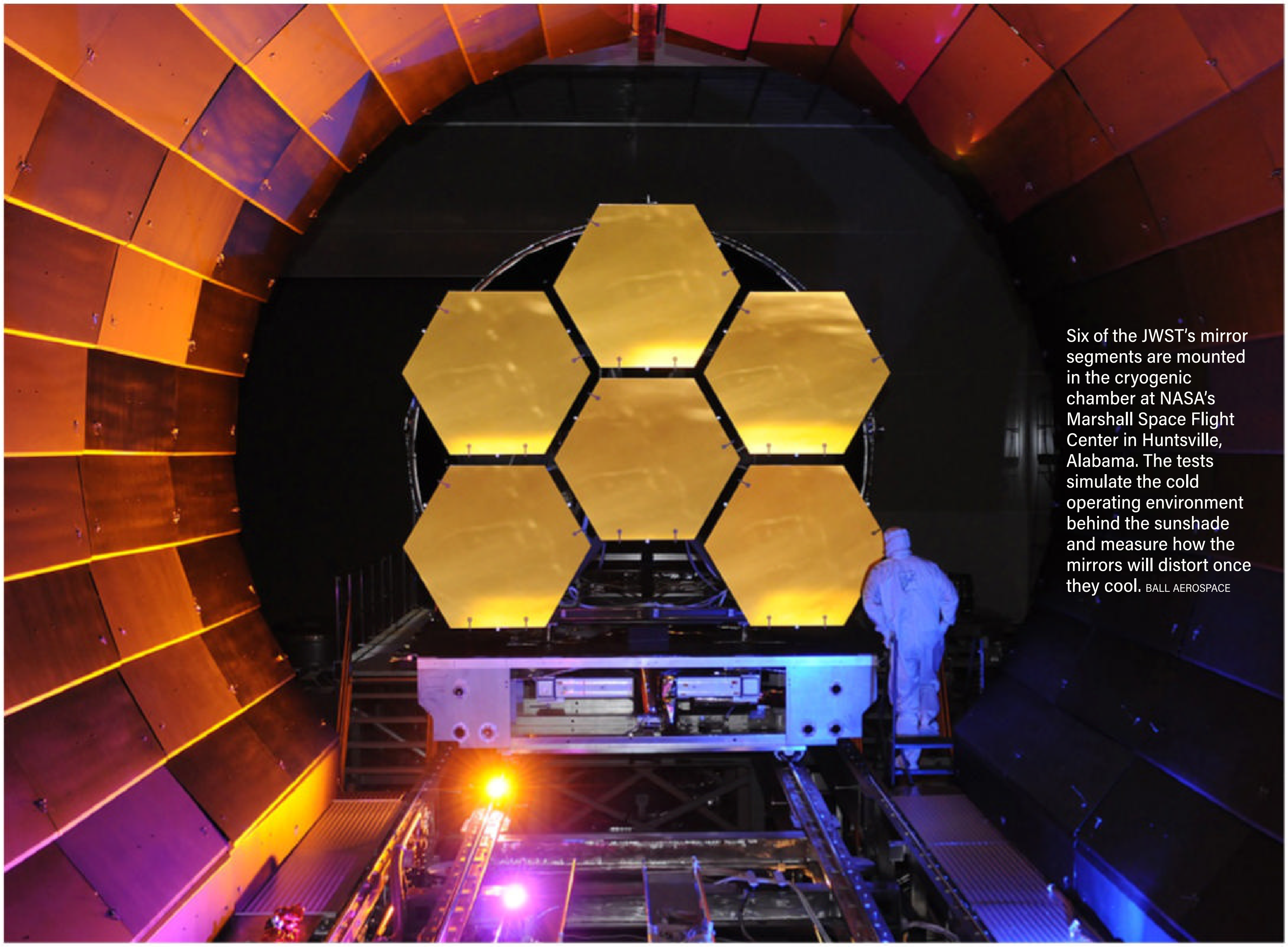
We will measure the effects of dark matter and dark energy, even though we can't see them. We will learn how galaxies grow by comparing young and old. We will watch new stars being born, looking inside the dusty clouds of gas, like the so-called Pillars of Creation, where they grow.

And we will ask how our solar system formed and how it evolved to support life. We will do this by looking at the planets and small bodies close to home, and by watching other solar systems. The infinite universe surely has life elsewhere, but where are the neighbors? If there are nearby exoplanets with liquid water, the JWST can find them.

Bigger and better

Even before the Hubble telescope was launched, astronomers met to consider its successor. In 1995, they produced a report titled "HST and Beyond," outlining the community's next steps. It proposed the concept and scientific requirements of what would become the JWST, and called for investment in the technology required to hunt for exoplanets similar to Earth.

Today, the Webb represents the culmination of a 25-year effort led by NASA with major contributions from the European and Canadian space agencies and a consortium of 14 European laboratories. The Space Telescope Science Institute (STScI) will operate Webb from Baltimore, where we are currently rehearsing every detail of the flight mission. Many thousands of engineers, scientists, technicians, managers, planners, accountants, and secretaries were on the teams that built it.



Six of the JWST's mirror segments are mounted in the cryogenic chamber at NASA's Marshall Space Flight Center in Huntsville, Alabama. The tests simulate the cold operating environment behind the sunshade and measure how the mirrors will distort once they cool. BALL AEROSPACE

The JWST extends and complements the capabilities and discoveries of the 2.4-meter Hubble Space Telescope and the pioneering 0.8-meter Spitzer Space Telescope. Spitzer was designed to see infrared but is now out of range of Earth; it was retired in January 2020.

Hubble is sensitive to a small portion of the infrared spectrum. But despite being in space, it is warm enough to glow at infrared wavelengths, which interferes with infrared observations.

Webb is not just a bigger version of Hubble: It will be kept cold, so it does not emit infrared radiation. That means that, unlike Hubble, the telescope cannot be enclosed — it must be open to space with its components exposed so it can maintain a low temperature without an active cooling system.

It also means the Webb cannot stay in low Earth orbit. Earth radiates heat that warms nearby satellites, and we could not find a design that would keep the Webb cold there. Instead, we will push the telescope out near the Sun-Earth L2 Lagrange point, which you can find by extending the line from the Sun to Earth 930,000 miles (1.5 million kilometers) farther. At this location, the combined gravity of the Sun and Earth will keep the Webb in an orbit around the L2 point. This is the nearest place to Earth where a single umbrella (called a sunshade) can protect the telescope from the heat of the Sun, Earth, and the Moon.

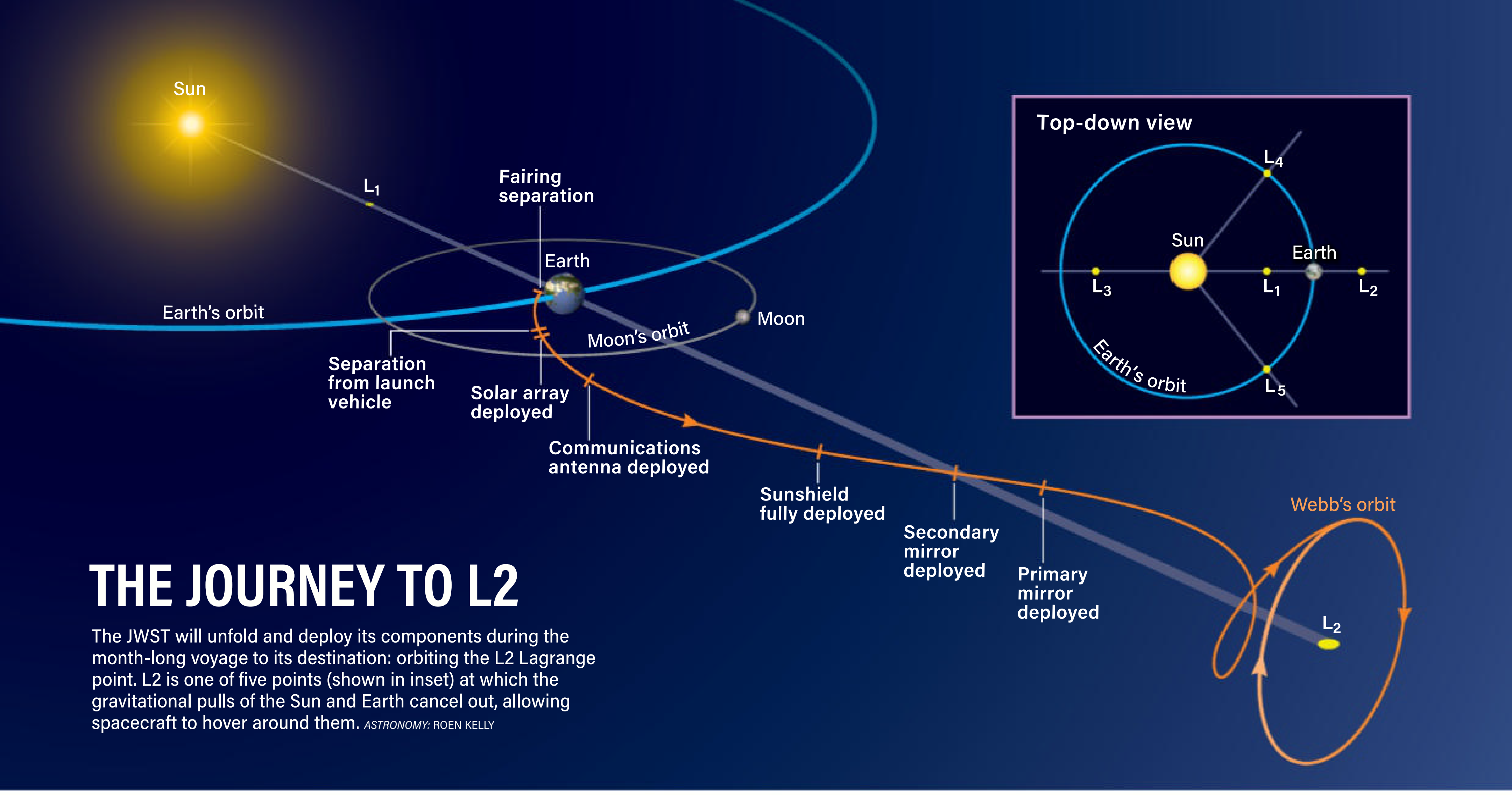
The JWST also must be much larger than Hubble because the targets it will observe are faint and far away. The Webb is so large that it must be folded up for launch, and even then, it barely fits inside the fairing of the Ariane 5 rocket. To allow for folding, the 6.5-meter-wide primary mirror had to be made of 18 smaller hexagons, which, once in place, will function as though they were one unit.

The whole package

JWST's instrument suite covers the whole infrared wavelength range — from 0.6 to 28.8 microns — with imaging cameras, spectrometers, and a fine-guidance camera. All the instruments are passively cooled to –387 degrees Fahrenheit (–233 degrees Celsius, or 40 kelvins). The exception is the Mid InfraRed Instrument (MIRI), a camera and spectrograph that requires active cooling to –447 F (–266 C, or 7 kelvins).

The Webb's Near Infrared Spectrometer (NIRSpec) can take spectra of 100 galaxies at a time by using tiny shutters that only let in the light from target objects and block everything else. Spectroscopy breaks light apart into its full spectrum like a prism, allowing us to identify different elements absorbing or emitting light at various wavelengths. From these spectral signatures, we can determine the chemical composition, the temperatures, and the motions of these targets. Spectroscopy puts the "fizz" in astrophysics.

The Near Infrared Camera (NIRCam), MIRI, and the Near Infrared Imaging



THE JOURNEY TO L2

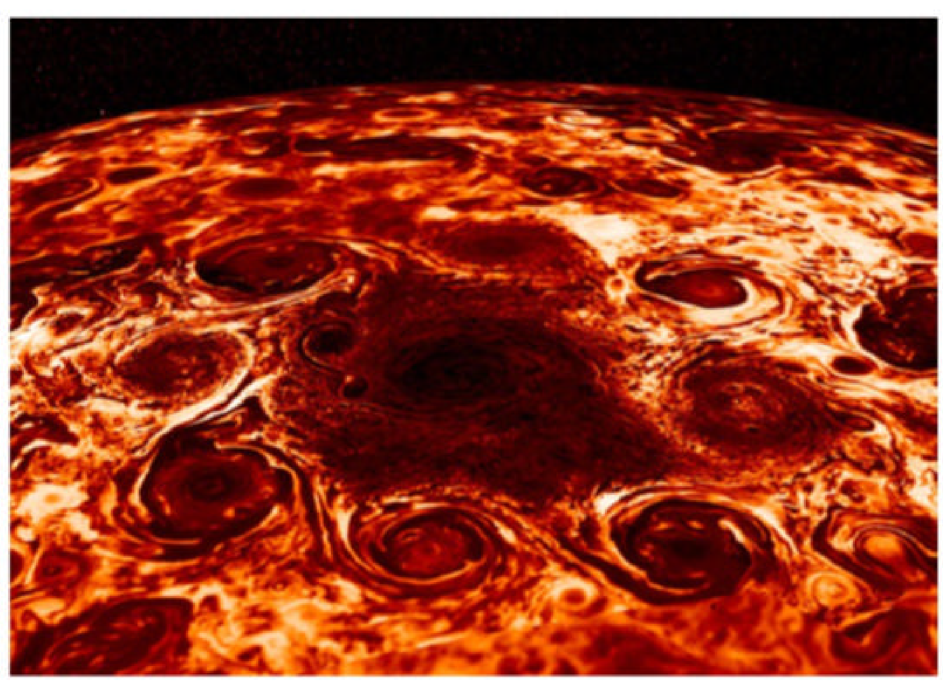
The JWST will unfold and deploy its components during the month-long voyage to its destination: orbiting the L2 Lagrange point. L2 is one of five points (shown in inset) at which the gravitational pulls of the Sun and Earth cancel out, allowing spacecraft to hover around them. *ASTRONOMY:* ROEN KELLY

Slitless Spectrometer (NIRISS) all have coronagraphic capabilities, meaning they can block the light of a bright star to look for orbiting exoplanets or blot out light from a quasar to get a better view of things falling into its black hole. NIRSpec and MIRI can also search for signs of planetary atmospheres: By monitoring stars with transiting exoplanets, they can watch for changes in their spectrum as the exoplanet's atmosphere absorbs certain wavelengths of the star's light.

All of the JWST's detectors are designed to be more resilient than Hubble's. When Hubble's detectors read out an image, they must transfer each pixel's accumulated charge down to the amplifiers at the bottom of the sensor to be read, line by line. But the sensor's ability to process charge degrades over time. On the JWST, the detectors avoid this by reading out every pixel individually.

Bringing Webb online

If all goes to schedule, around 7 A.M. EST one morning in late November, the Ariane 5 launch vehicle will lift off from Kourou in French Guiana, located near the equator in South America, setting Webb on a trajectory for L2. Soon after



ABOVE: A series of storms pirouette around Jupiter's north pole, imaged in infrared light by NASA's Juno spacecraft. The Webb will target Jupiter, its faint rings, and moons Ganymede and Io as part of its initial set of observing programs. NASA/JPL-CALTECH/SWRI/ASI/INAF/JIRAM

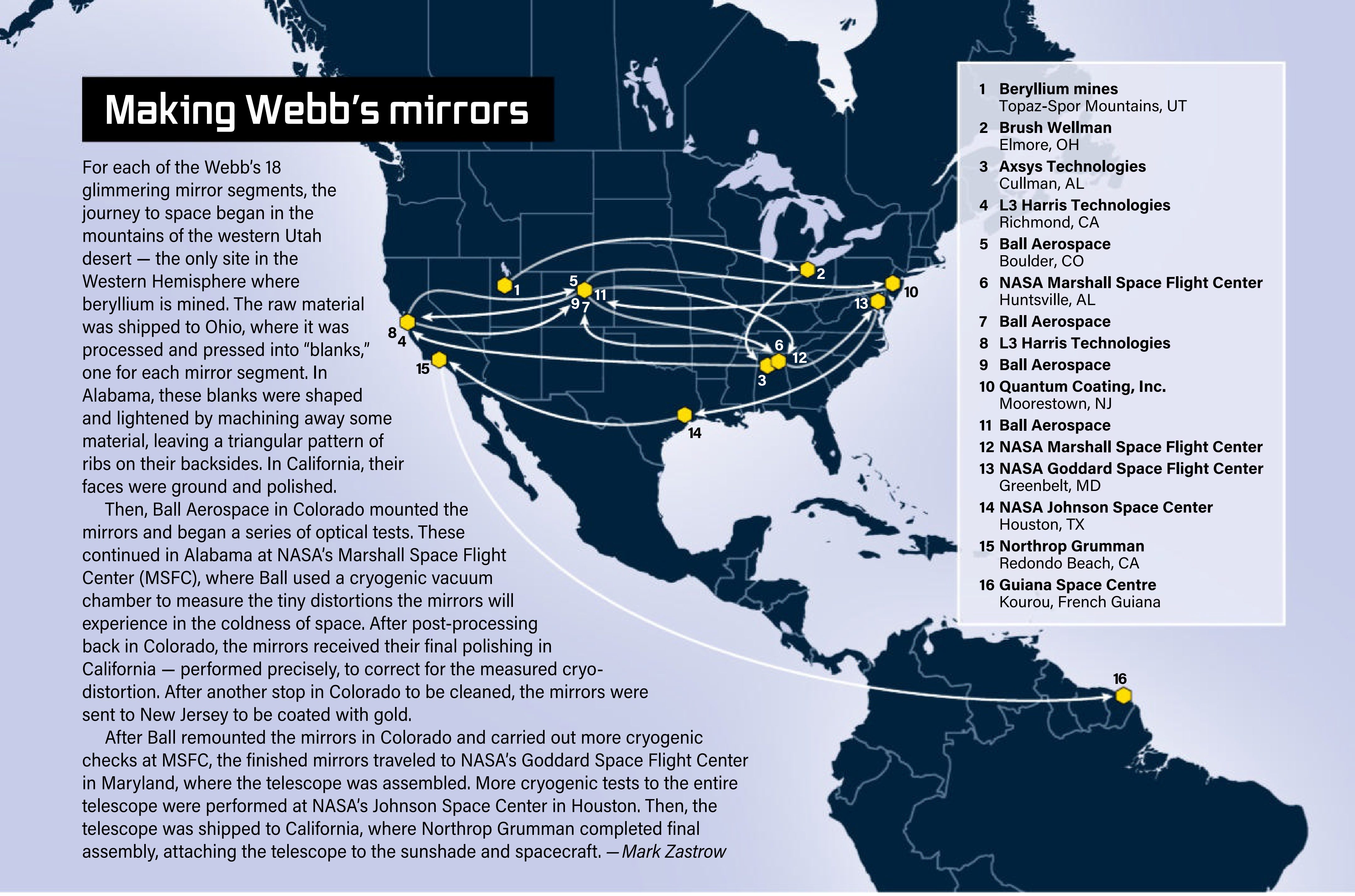
LEFT: Abell 2744 — also known as Pandora's Cluster — is a massive group of four galaxy clusters that act as a gravitational lens, bending light rays from background objects and magnifying them. Some of these lensed objects are visible in this image, appearing as arcs or rings. The JWST will use this to its advantage and study distant objects that date to the early universe. NASA

Making Webb's mirrors

For each of the Webb's 18 glimmering mirror segments, the journey to space began in the mountains of the western Utah desert — the only site in the Western Hemisphere where beryllium is mined. The raw material was shipped to Ohio, where it was processed and pressed into "blanks," one for each mirror segment. In Alabama, these blanks were shaped and lightened by machining away some material, leaving a triangular pattern of ribs on their backsides. In California, their faces were ground and polished.

Then, Ball Aerospace in Colorado mounted the mirrors and began a series of optical tests. These continued in Alabama at NASA's Marshall Space Flight Center (MSFC), where Ball used a cryogenic vacuum chamber to measure the tiny distortions the mirrors will experience in the coldness of space. After post-processing back in Colorado, the mirrors received their final polishing in California — performed precisely, to correct for the measured cryo-distortion. After another stop in Colorado to be cleaned, the mirrors were sent to New Jersey to be coated with gold.

After Ball remounted the mirrors in Colorado and carried out more cryogenic checks at MSFC, the finished mirrors traveled to NASA's Goddard Space Flight Center in Maryland, where the telescope was assembled. More cryogenic tests to the entire telescope were performed at NASA's Johnson Space Center in Houston. Then, the telescope was shipped to California, where Northrop Grumman completed final assembly, attaching the telescope to the sunshade and spacecraft. *—Mark Zastrow*



1 **Beryllium mines**
Topaz-Spor Mountains, UT
2 **Brush Wellman**
Elmore, OH
3 **Axsys Technologies**
Cullman, AL
4 **L3 Harris Technologies**
Richmond, CA
5 **Ball Aerospace**
Boulder, CO
6 **NASA Marshall Space Flight Center**
Huntsville, AL
7 **Ball Aerospace**
8 **L3 Harris Technologies**
9 **Ball Aerospace**
10 **Quantum Coating, Inc.**
Moorestown, NJ
11 **Ball Aerospace**
12 **NASA Marshall Space Flight Center**
13 **NASA Goddard Space Flight Center**
Greenbelt, MD
14 **NASA Johnson Space Center**
Houston, TX
15 **Northrop Grumman**
Redondo Beach, CA
16 **Guiana Space Centre**
Kourou, French Guiana

ALL ILLUSTRATIONS: *ASTRONOMY:* ROEN KELLY

The Webb's sunshield consists of five layers, each made of a high-performance plastic film called Kapton and coated with aluminum and doped silicon. NORTHRUP GRUMMAN

launch and while en route to L2, the telescope will unfold its antenna and solar arrays and start communicating with us in the control center in Baltimore.

Over the next few weeks, we will send commands to unfold the sunshade and the telescope's mirror, pausing to carefully check that each one is carried out correctly. (This is a luxury — when Mars landers tear through the Red Planet's atmosphere, they don't have time to phone home for help.)

Ensuring the observatory will unfold properly has required an extremely thorough test program, since we currently have no ability to visit L2 for repairs. To that end, the observatory is designed with electronic redundancy wherever possible — there are two ways to turn on every motor or to set off the release mechanisms that hold everything in place for launch.

After unfolding the telescope, we must focus it by precisely positioning each of the 18 hexagonal mirrors so they can work as one. The focusing algorithm was originally developed by Hubble scientists and engineers to correct that telescope's optics when it was launched out of focus; from lemons we made lemonade.

After all 18 hexagonal primary mirror segments and the secondary mirror are properly aligned, the telescope will be diffraction-limited at wavelengths of 2 microns and longer, meaning images at those wavelengths will be the sharpest that classical physics allows. If we are fortunate, the performance might be that good across an even wider range of wavelengths, but we won't know until we reach orbit and focus the telescope.

One month after launch, Webb will be close enough to L2 to begin orbiting around it, avoiding Earth's shadow so that solar power is always available. A week later, the telescope will have cooled enough to start focusing it. Three months after launch, all the instruments will be cold, and a month after that, focusing will be complete. Commissioning the instruments will take two more months, after which the scientific observing program will commence.

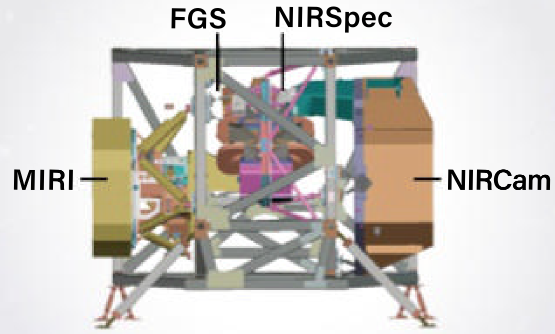
Where we'll look

The first scientific results will come from the Early Release Science program, based on 13 proposals chosen from over 100 teams that include over 4,000 astronomers from around the world. (All astronomers everywhere were eligible to submit their ideas.)

We also have an observing program designed by the teams who built the instruments, interdisciplinary scientists chosen by NASA, and 286 teams from

HOW JWST WORKS

Integrated Science Instrument Module (ISIM)

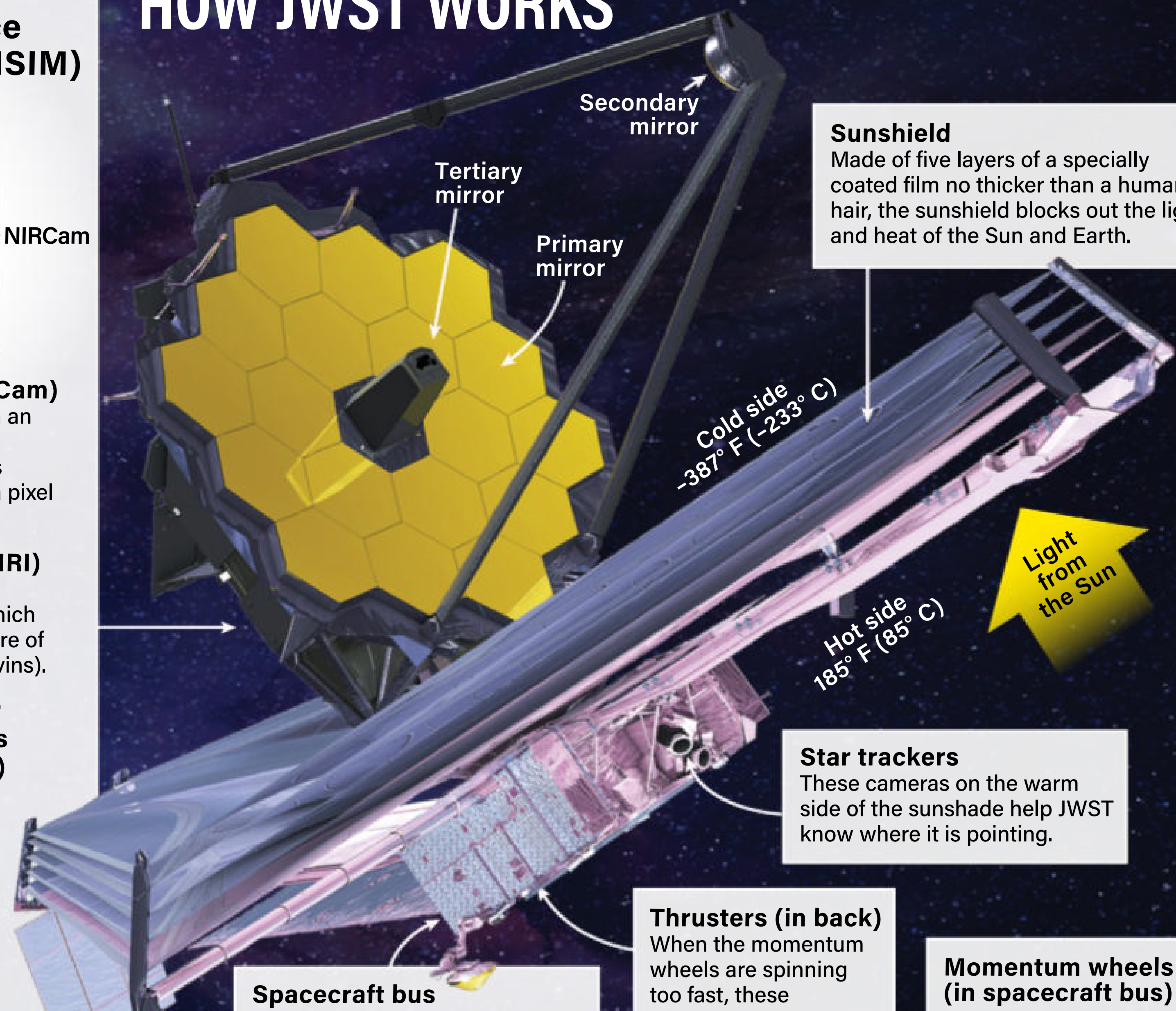


Near-Infrared Camera (NIRCam)
NIRCam pulls double duty as both an imager and the primary sensor for focusing the telescope. It's JWST's highest-resolution detector, with a pixel size of 0.032".

Mid-Infrared Instrument (MIRI)
MIRI is the only JWST instrument equipped with an active cooler, which allows it to operate at a temperature of just −447° F (−266° C or just 7 kelvins).

Fine Guidance Sensor/Near InfraRed Imager and Slitless Spectrograph (FGS/NIRISS)
To enable JWST to capture sharp images, FGS locks the telescope's line of sight onto a reference star in the field of view. The camera can track stars as faint as magnitude 18 and hold the telescope's aim to within a few milliarcseconds.

Near-Infrared Spectrograph (NIRSpec)
This unique spectrometer uses a microshutter array that can take spectra of 100 galaxies at a time.



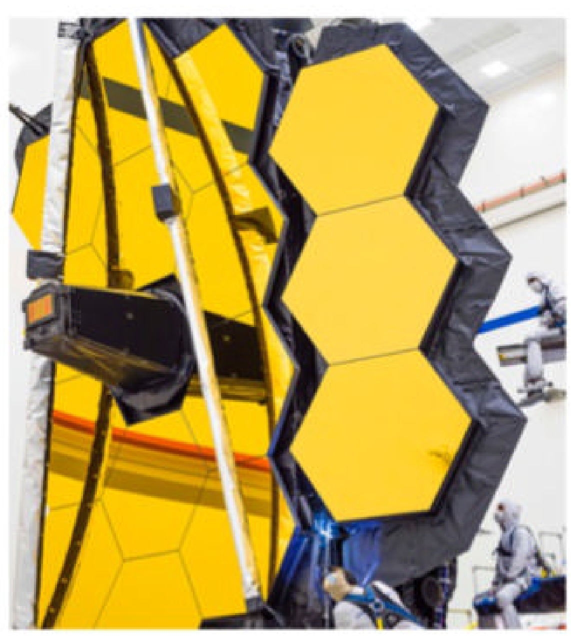
Sunshield
Made of five layers of a specially coated film no thicker than a human hair, the sunshield blocks out the light and heat of the Sun and Earth.

Star trackers
These cameras on the warm side of the sunshade help JWST know where it is pointing.

Spacecraft bus
The bus (main body) contains supporting equipment and electronics. It's placed on the warm side of the sunshield so its heat doesn't affect observations.

Thrusters (in back)
When the momentum wheels are spinning too fast, these hydrazine rocket jets are occasionally fired to help shed the wheels' accumulated angular momentum.

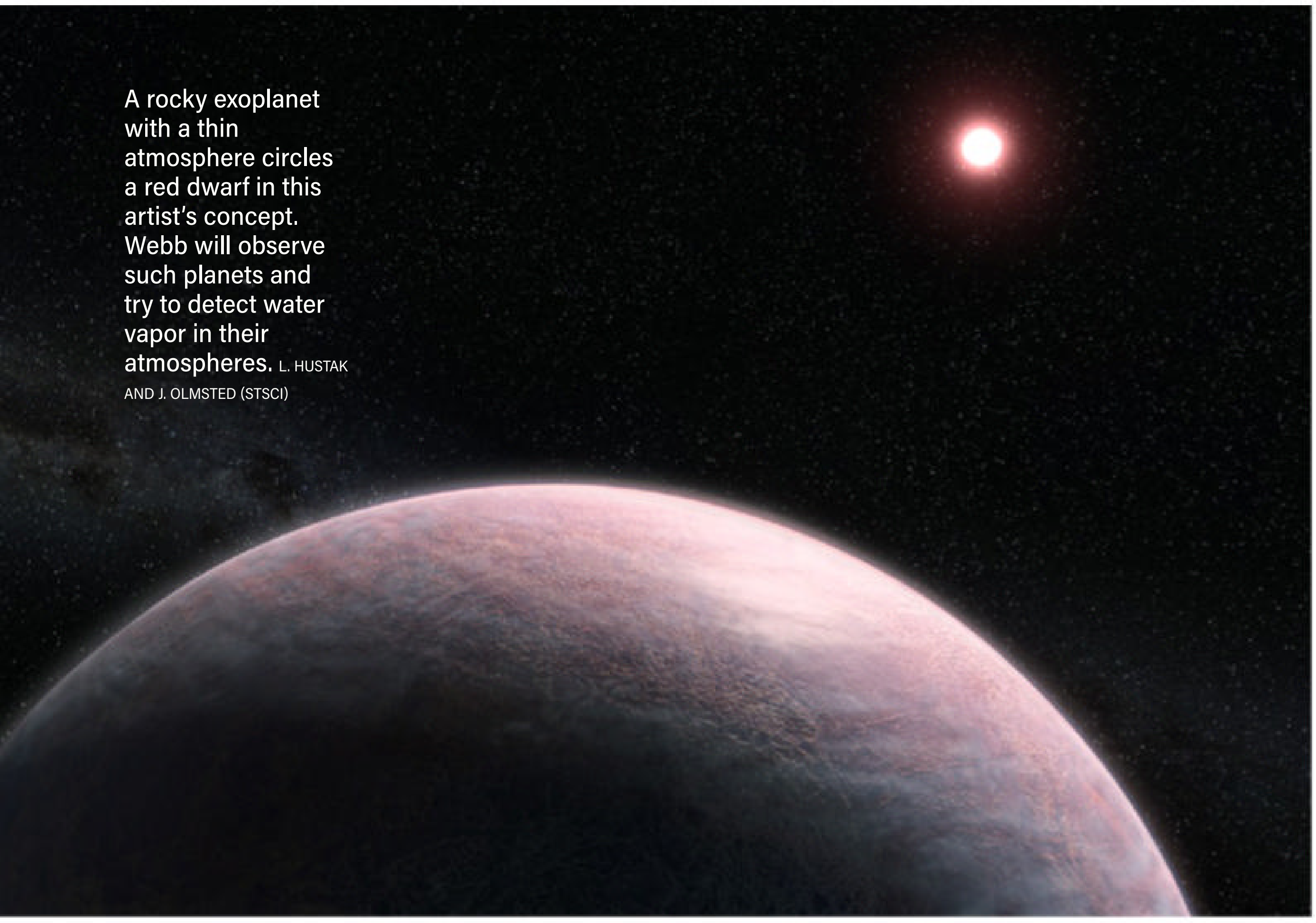
Momentum wheels (in spacecraft bus)
JWST orients itself with these flywheel-like devices, which spin up to generate torque and cause the craft to rotate.



LEFT: The JWST is lifted in folded configuration onto a stand in the clean room at Goddard Space Flight Center April 20, 2017. The primary mirror's "wings" are tucked back and the secondary mirror is also stowed, mounted to the two support struts straddling the center of the primary. NASA/CHRIS GUNN

ABOVE: The Webb's mirror was unfolded and deployed for its final pre-launch check April 21, 2021, at Northrop Grumman's facility in Redondo Beach, California. NASA/CHRIS GUNN

The Webb telescope and its sunshade were fully folded up in their launch configuration for vibration testing at Northrop Grumman in this photo taken Aug. 20, 2020. NORTHROP GRUMMAN



A rocky exoplanet with a thin atmosphere circles a red dwarf in this artist's concept. Webb will observe such planets and try to detect water vapor in their atmospheres. L. HUSTAK AND J. OLMSTED (STSCI)

At the heart of spiral galaxy NGC 4151 is a black hole with the mass of tens of millions of Suns, gorging itself on surrounding material. In its initial observing campaign, the Webb will measure the black hole's mass by watching how stars in the galaxy's central region move. NASA, ESA, AND J. DEPASQUALE (STSCI)

the research community chosen from 1,172 proposals. About 70 percent of the Webb's observing time will be for spectroscopy. (If a picture is worth a thousand words, a spectrum is worth a thousand pictures.) In addition, 20 teams were chosen for archival research and theoretical work.

Altogether, this initial series of observations will cover a vast range of astronomical targets and subjects.

We'll look at the solar system, including Mars, Jupiter, Saturn, Uranus, Neptune, Pluto, Eris, Sedna, Enceladus, Titan (where NASA is sending a helicopter), and Europa (where NASA is sending a probe to look for organic molecules in the moon's warm water geysers).

We'll look to Proxima Centauri — itself about the size of Jupiter — with at least one planet of its own, as well as Alpha Centauri, which also might have planets. We'll look at transiting worlds around red dwarf stars like TRAPPIST-1, and hunt for signs of planetary atmospheres.

We'll look into the famous Deep Fields pioneered by HST to peer further back in time and see — we hope — signs of the first galaxies being born.

We'll look through nature's telescopes: gravitational lenses, which are clusters of galaxies whose gravitational pull magnifies the images of even more distant galaxies behind them. Some of these lenses magnify their backgrounds by a factor of 10,000, which gives us a chance to see individual stars in the early universe.

Closer to home, we'll look at the Trapezium, the star cluster that makes up the middle "star" in Orion's sword. Where Galileo saw three stars by pressing his eye to his tiny telescope, our infrared camera will reveal a thousand newborn stars. And really close to home, when another interstellar interloper like 'Oumuamua comes by, we'll be ready to see if it's really a solid nitrogen pancake.

But what might we find that is completely unexpected? Dark matter, dark energy, and the black holes at the centers of most galaxies stand out as truly special, and have won their discoverers a rash of Nobel Prizes in the last decade.

I'm guessing that perhaps there were some kinds of objects formed in the early universe that have all disappeared, so we can't find them now. Maybe there were immense stars, thousands or millions of times the mass of the Sun, but burning out and turning into black holes and flying debris. Maybe dark matter was turning directly into black holes. Or maybe these strange objects are still here, but masquerading as something else.

Or perhaps there's something about exoplanets. Today, we know of thousands of them. We know that planets about the size and temperature of Earth are common, and maybe 20 percent of all stars

Are we alone?

In 1950, over a lunch with colleagues at Los Alamos National Laboratory, the Italian-American physicist Enrico Fermi famously asked, "But where is everybody?" He was referring to what we now call the Fermi paradox: If extraterrestrial civilizations exist, why haven't we seen them?

Here, I hazard my own guess: I think Earth is truly special, but the conditions for life are common elsewhere in the universe.

The evidence is simple but sparse. Geologists have fossil records showing that Earth was alive within a few hundred million years after it had oceans. But it took billions more years for the oxygen level in the atmosphere to begin to rise, and billions more yet for complex life with eyes and legs to turn up. And our own kind has been here for only a few hundred thousand years, a mere jot in the timescape. Altogether, our complex civilization took 4.6 billion years after the formation of the solar system to appear.

My answer to Fermi's question is that life is common — but complex life is rare, and life as complex as people is extremely rare. Furthermore, the distance between stars is immense. Even if we were to build a very patient, intelligent robot, it would have to travel for thousands to hundreds of thousands of years to reach another stellar system. If I were such an intelligent robot, I would prefer to stay home with my robot and human friends (and enemies). *—J.M.*

Onlookers gather around a full-scale model of the JWST at the South by Southwest conference, perched in front of the skyline of Austin, Texas. NASA/CHRIS GUNN

have them. With the Webb, we will search these planets for evidence of water, which we suspect is a requirement for life. Searching for oxygen is harder and we probably won't see it, but it would be a strong sign of photosynthesis.

What's next?

Just as Webb was conceived before Hubble even left Earth's surface, astronomers and engineers are already planning for the next generation of telescopes in space and on the ground.

The European Space Agency's 1.2-meter Euclid telescope (with U.S.-built detectors) is scheduled to launch in 2022 and will survey much of the sky to hunt for evidence of dark matter and dark energy. NASA's larger Nancy Grace Roman Space Telescope, with a 2.4-meter mirror (the same size as Hubble's), is planned for launch around 2026 and will take in 100 times as much sky in one bite as Hubble.

On the ground, the 8.4-meter Vera C. Rubin Observatory and its 3-gigapixel camera will survey the whole observable sky from its location every three nights, finding millions of short-lived transient events on every sweep, like supernovae, near-Earth objects, and matter falling into black holes. (JWST is ready and able to serve as a follow-up telescope for these finds: If a new discovery needs immediate response, we can do it within two days or less.)

Even larger ground-based telescopes — the 24-meter Giant Magellan Telescope, the Thirty Meter Telescope, and the 39-meter Extremely Large Telescope — are under construction. They are perfect for spectroscopy, which requires more light than taking images, and will be capable of imaging exoplanets (though not quite as small as Earth) around nearby stars.

For the next generation of space telescopes, the astronomical community will consult the recommendations of the 2021 Decadal Survey prepared by a committee of the U.S. National Academy of Sciences. Four projects are already under study by NASA: the far-infrared Origins Space Telescope, cooled to –452 F (–269 C, or 4 kelvins); the Lynx X-ray telescope, with much better mirrors and detectors than any of its predecessors; and the Habitable Exoplanet Observatory and Large UV/Optical/IR Surveyor telescopes, operating at near-ultraviolet, visible and near-infrared wavelengths, and optimized for directly imaging exoplanets.

None will be easy to build, but all are possible. In my opinion, each project is worthy of astronomers' time and effort. Together they could keep us fully occupied for at least half a century. Future generations will celebrate their accomplishments. More treasures await!

John Mather *is the senior project scientist for the James Webb Space Telescope. He led the Cosmic Background Explorer team that measured the spectrum of the Big Bang radiation and discovered its hot and cold spots, earning a Nobel Prize in 2006. His first computer was a circular slide rule and his first telescope had lenses from Edmund Scientific.*

Observe JWST yourself

Serious astrophotographers will be able to image the JWST in its orbit around L2, although it will appear only as a tiny speck. Its brightness will be quite variable as its orientation tilts relative to Earth and the oncoming sunlight, but typically will be around 16th to 18th magnitude.

When the Webb is tilted just right, the flat solar panels or the stretched sunshield will reflect the Sun directly toward Earth, and its brightness will dramatically increase, possibly to 5th magnitude. Perhaps the thruster firings will be visible as well.

The JWST will move about 1" every 24 seconds relative to the background stars as it goes around the sky once a year. Amateurs could compute the craft's orbit from a series of images, starting with determining the parallax — and therefore, its distance — as Earth rotates. —*J.M.*