

**UNFOLDING THE UNIVERSE:
INITIAL SCIENCE RESULTS
FROM THE JAMES WEBB SPACE TELESCOPE**

HEARING
BEFORE THE
SUBCOMMITTEE ON SPACE AND AERONAUTICS
OF THE
COMMITTEE ON SCIENCE, SPACE,
AND TECHNOLOGY
OF THE
HOUSE OF REPRESENTATIVES
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**UNFOLDING THE UNIVERSE:
INITIAL SCIENCE RESULTS
FROM THE JAMES WEBB SPACE TELESCOPE**

WEDNESDAY, NOVEMBER 16, 2022

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON SPACE AND AERONAUTICS,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittee met, pursuant to notice, at 10:33 a.m., in room 2318, Rayburn House Office Building, Hon. Don Beyer [Chairman of the Subcommittee] presiding.

**SUBCOMMITTEE ON SPACE AND AERONAUTICS
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
U.S. HOUSE OF REPRESENTATIVES**

HEARING CHARTER

Unfolding the Universe: Initial Science Results from the James Webb Space Telescope

November 16, 2022
10:30 a.m.

Hybrid: 2318 Rayburn House Office Building and Remotely on Zoom

PURPOSE

The purpose of the hearing is to receive testimony on the initial science, scientific findings and discoveries of National Aeronautics and Space Administration's James Webb Space Telescope, as well as plans for future scientific investigations.

WITNESSES

- **Dr. Mark Clampin**, Astrophysics Division Director, National Aeronautics and Space Administration (NASA)
- **Dr. Steven L. Finkelstein**, Professor of Astronomy, University of Texas at Austin
- **Dr. Natalie Batalha**, Professor of Astronomy and Astrophysics and Director of Astrobiology, University of California, Santa Cruz

OVERARCHING QUESTIONS

- *What are the initial scientific results from the data obtained by the James Webb Space Telescope (JWST)?*
- *What have scientists learned so far from the initial observations, and how has the telescope contributed to our better understanding of the universe?*
- *What new questions in the field of astronomy and astrophysics have been raised by the data obtained by JWST so far?*
- *What are the plans for future scientific investigations with JWST?*

BACKGROUND

NASA, along with its international partners, the European Space Agency (ESA) and the Canadian Space Agency (CSA), launched the James Webb Space Telescope (JWST or Webb) on December 25, 2021, on board an Ariane 5 rocket to its destination at the second Lagrange point,

or L2,¹ nearly one million miles away from Earth. After more than 20 years of design, development, and testing, one month of an incredibly complex on-orbit deployment that included 344 potential single-point failures, and six months of commissioning activities, JWST is now conducting science operations as the largest and most powerful telescope humans have ever sent to space.

JWST is a large, infrared, space-based telescope managed within the Astrophysics Division of NASA's Science Mission Directorate. The telescope is intended to be a complement and scientific successor to the Hubble Space Telescope and the Spitzer Space Telescope, two of NASA's Great Observatories.² JWST's unprecedented improvements in sensitivity and resolution allow astronomers to see the Universe in greater detail and at further distances. NASA formally authorized the start of project formulation for the Next Generation Space Telescope (NGST), as the mission was then named, in 1999. In 2000, the NGST was recommended as the top-priority major initiative of the decadal survey in astronomy and astrophysics and envisioned as an 8-meter-class infrared space telescope "designed to detect light from the first stars and to trace the evolution of galaxies from their formation to the present" that "will revolutionize understanding of how stars planets form in our galaxy today."³ Those themes have carried through as the scientific thrusts of the JWST mission today.

The Committee on Science, Space, and Technology held multiple oversight hearings during the development of the James Webb Space Telescope, including in 2011, 2015, and 2018. Today's hearing is the Committee's first hearing on the early science and scientific results of the telescope's observations.

Infrared Astronomy

JWST is optimized to observe infrared light. The human eye detects visible, or optical, light, while infrared light has a longer wavelength and lies just beyond the red end of the optical portion of the electromagnetic spectrum, as shown in Figure 1. Infrared light is used in astronomy to study cooler objects, such as young stars that have not yet begun burning hydrogen or planets forming in disks around stars. Astronomers also observe in the infrared range to see through dust—which usually blocks optical light—within nebula or star-forming clouds. The light from the first stars and galaxies in the Universe is originally emitted as optical or ultraviolet light, but it arrives to Earth in the form of infrared light because it is stretched to a longer wavelength by traveling great distances across an expanding universe. Astronomers refer to this stretching effect as "redshift."

¹ Lagrange Points are five positions where the gravitational forces of two large objects—such as the Earth and the Sun—equals the centripetal force required for a small object—such as a spacecraft—to orbit in place relative to the two larger objects. In the Earth-Sun system, L2, or the second Lagrange Point, is directly opposite the Earth from the Sun, one million miles from Earth.

² The Great Observatories are a series of space-based telescopes launched over the course of two decades and comprised of the Hubble Space Telescope, Compton Gamma-Ray Observatory, Chandra X-Ray Observatory, and Spitzer Space Telescope.

³ National Research Council. *Astronomy and Astrophysics in the New Millennium*. Washington, DC: The National Academies Press, 2001. Available at: <https://doi.org/10.17226/9839>.

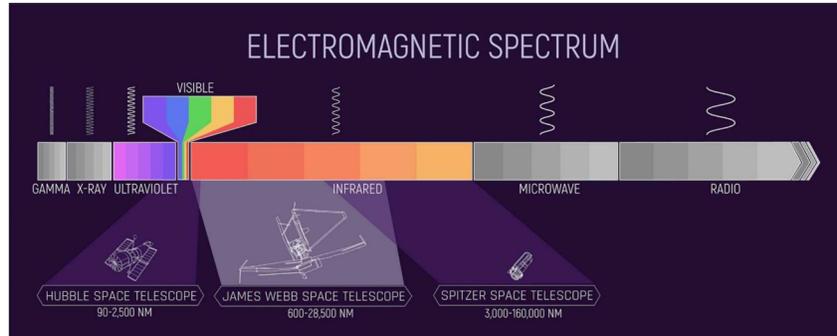


Figure 1: JWST observes infrared light, which is just beyond the red end of the visible portion of the electromagnetic spectrum. Credit: NASA and J. Olmstead (STScI).

Astronomers subdivide the infrared spectrum into three categories, defined by wavelength: near-infrared, mid-infrared, and far-infrared. JWST observes in near- and mid-infrared wavelengths. Near-infrared light has the shortest wavelength, closest to the red end of the optical portion of the electromagnetic spectrum; cooler stars are brightest in the near-infrared, and dust is typically transparent. In the mid-infrared range, astronomers can see and study the dust itself when it is warmed up by starlight, and planetary bodies, including planets, asteroids, and comets. As shown in Figure 1,⁴ NASA's Hubble telescope observes in the ultraviolet, visible, and near-infrared ranges, while the Spitzer Space telescope, decommissioned in 2020 after a sixteen-year mission, observed in the mid- and far-infrared.

Science of the JWST Mission

As a large flagship mission, JWST is expected to address a wide range of scientific questions across astronomy and astrophysics. The mission's key science objectives are divided into four science themes:^{5,6}

- The End of the Dark Ages: First Light and Reionization:** According to theory and observations, right after the Big Bang, in a period astronomers call the Dark Ages, the early Universe was hot, dark, and made up of uncombined protons, electrons, and neutrons. After up to a few hundred million years, atoms and then molecules formed and eventually formed the first stars and galaxies, the first light sources. As those stars and galaxies formed and evolved, all of the hydrogen in between galaxies went from being neutral to ionized (having charge) by approximately one billion years after the Big Bang, and that hydrogen remains ionized today. Within the first light and reionization theme,

⁴ Available at: <https://webbtelescope.org/contents/media/images/4188-Image>.

⁵ Gardner, J.P., Mather, J.C., Clampin, M. *et al.*, "The James Webb Space Telescope," 2006, *Space Sci Rev* **123**, 485–606. Available at: <https://doi.org/10.1007/s11214-006-8315-7>.

⁶ Space Telescope Science Institute, "JWST's Science Focus." Available at: <https://www.stsci.edu/jwst/about-jwst/science-themes>.

JWST's key science objective is to find and understand these very first stars and galaxies and the ionization history of the early universe.

- **The Assembly of Galaxies:** Models and observations show that small galaxies were the first to form, and, over a process that continues today, become larger through interactions and with one another. Black holes at the centers of galaxies, star formation, and the explosions or collisions of stars all are theorized to play a role in this process of galaxy assembly. Within the assembly of galaxies theme, JWST's key science objective is to observe galaxies across cosmic time, from the earliest era (Reionization) to present to better understand how they evolve and how their compositions change over time.
- **The Birth of Stars and Protoplanetary Systems:** Large clouds of gas and dust, into which it is difficult to see, form dozens or hundreds of stars at a time as the gas and dust gravitationally condenses and eventually ignites nuclear fusion. Most stars are found in pairs, called binaries, or in larger multi-star systems. Planets generally form in the material leftover from star formation, which forms disks around young stars, called protoplanetary disks. For the birth of stars and protoplanetary systems theme, JWST's key science objective is to study, in detail, the complex process that form individual stars and eventual planetary systems and the distinct phases of those processes.
- **Planetary Systems and the Origins of Life:** Searches using both ground-based and space-based telescopes have identified thousands of planets that orbit stars other than our Sun—exoplanets—and have shown that most stars have at least one planet. Many stars have planetary systems that look very different from our own Solar System, such as having Jupiter-sized exoplanets closer to the star than Mercury is to the Sun. The physical characteristics of different exoplanets and planetary systems—such as planet size, number and arrangement of planets—as well as their chemical compositions may reflect how they formed and evolved and the means through which life can form. For this theme on planetary systems and the origins of life, JWST's key science objective is to characterize planets and planetary bodies in our own Solar System and in systems around other stars, which includes investigating the potential for the origins of life.

JWST Observatory and Scientific Instruments

The primary mirror of JWST is 6.5 meters across at its widest point and comprises 18 hexagonal, gold-coated segments. The primary mirror initially collects light, which is then focused onto a secondary mirror and then directed into the scientific instruments. A five-layer sunshield, approximately the size of a tennis court, prevents heat and light from external sources—such as the Sun and other planets as well as the telescope's own spacecraft hardware—from reaching the telescope optics and scientific instruments. With the sunshield in place, the telescope mirrors and scientific instruments operate at a temperature of 37 Kelvin (-395°F), which is necessary to observe in the infrared.

The observatory has four scientific instruments:

- **Near-Infrared Camera (NIRCam)** takes images in near-infrared wavelengths, and it is equipped with multiple coronagraphs, which can block the light from a very bright object, like a star, to allow imaging of a nearby faint object, like a companion brown dwarf or distantly orbiting planet. NIRCam will be used to study early galaxies, young

stars in our own Milky Way, and the small, icy bodies in the Kuiper Belt of our own Solar System.

- **Near-Infrared Spectrograph (NIRSpec)** disperses near-infrared light into individual wavelengths of light to create a spectrum, onto which atoms and molecules imprint unique features that can reveal detailed characteristics about an astronomical object, such as temperature, rotation speed, and chemical composition. The NIRSpec microshutter array,⁷ has approximately 250,000 individual microshutters, or tiny windows that open and close individually to allow the instrument to collect spectra simultaneously from up to 100 different objects. NIRSpec will characterize very faint, distant objects, like the first galaxies to form after the Big Bang, as well as the atmospheres of exoplanets.
- **Mid-Infrared Instrument (MIRI)** is both a camera and a spectrograph for mid-infrared observations. MIRI will be able to take wide images of large, resolved objects, like nebulae and star-forming regions in the Milky Way. To observe in the mid-infrared, MIRI needs to be further cooled to 7 K (-441°F), which is accomplished by a cryocooler, which acts essentially as a refrigerator.⁸ Spectroscopy with MIRI will enable further detailed study of star formation in distant galaxies and exoplanet atmospheres.
- **Fine Guidance Sensor/Near-Infrared Imager and Slitless Spectrograph (FGS/NIRISS)** is a single instrument module comprising a coupled pair of instruments. The FGS is optimized for extreme accuracy and stability to ensure JWST is pointing precisely for all of its scientific observations. NIRISS collects near-infrared imagery and spectroscopy that complements JWST's other near-infrared instruments. NIRISS being directly coupled with FGS enables unique observations that rely on extremely high stability, such as imagery of fine detail or distinct spectra of objects very close together. NIRISS will observe exoplanet atmospheres as well as galaxies, including early galaxies whose appearances on the sky are enlarged but also warped by a phenomenon called gravitational lensing.⁹

Initial Science Observations

On July 12, 2022, NASA released the first scientific images from JWST after a six-month process of testing and commissioning the instruments to ensure they operate and perform as designed. At that point, the mission commenced full scientific operations of the telescope. JWST observing time is allocated by specific science investigations, and potential observers submit proposals to define observations needed for science investigations. Observing programs are typically allocated over approximately one-year cycles designated by number (Cycle 1, Cycle 2, *et cetera*). General Observer (GO) programs are the largest category of scientific observations, and are programs openly solicited from the scientific community and selected through peer review. Guaranteed Time Observations (GTO) programs are defined by the instrument and telescope science teams and associated interdisciplinary scientists. A Director's Discretionary

⁷ Microshutters are a new technology that was developed for JWST. The 250,000 microshutters on the NIRSpec array are each 100 micrometers (µm) long by 200 µm wide. NASA, "Webb Innovations: Microshutters." Available at: <https://www.jwst.nasa.gov/content/about/innovations/microshutters.html>.

⁸ NASA, "Webb Innovations: Cryocooler." Available at: <https://webb.nasa.gov/content/about/innovations/cryocooler.html>.

⁹ Gravitational lensing occurs when a distant object—such as an early galaxy—is blocked behind a large, nearby object—such as a massive galaxy or cluster of galaxies—as viewed from Earth. The light from the distant object can be bent by the gravity around the massive object and produce a magnified, but distorted image of the distant object.

Time allocation is used to conduct time-critical observations that cannot be performed through a GO or other proposal cycle. In addition, a small allocation is reserved for ongoing calibration programs that support all of the science programs and instruments.

Chairman BEYER. Good morning. The hearing will come to order. We welcome our guests. Without objection, the Chair is authorized to declare a recess at any time.

And before I want to deliver my opening remarks, I want to note that, today, the Committee is meeting both in person and virtually. And I want to announce a couple of reminders to Members about the conduct of this hearing. First, Members and staff who are attending in person may choose to be masked, but it is not required. And—however, if you—any individual with symptoms, a positive test, or exposure to someone with COVID-19 should wear a mask while present.

Members who are attending virtually should keep their video feed on as long as they are present in the hearing, and Members are responsible for their own microphones. Please also keep your microphones muted unless you are speaking. And if Members have documents they wish to submit for the record, please email them to the Committee Clerk, whose email address was circulated prior to the hearing.

I'd also like to note that Subcommittee Chair Suzanne Bonamici has asked to wave on to the the elite exclusive Space Subcommittee for this meeting. And without objection, she is waved on. And if there are other Members who so desire, we'll recognize that at the time.

And before we start, I just want to take a moment to recognize the thrilling, first successful test launch of the integrated Space Launch System and the Orion crew vehicle Artemis 1—very, very exciting, first time in 50 years—Cape Canaveral at 1:47 this morning. This is a momentous achievement for NASA (National Aeronautics and Space Administration), for Democrats, for Republicans, for the Nation, for the world. It's a huge step forward toward sending our astronauts back to the Moon and then to Mars. So on the behalf of my colleague Dr. Babin and all of our Members of the Space Subcommittee, I want to congratulate all those at NASA and its industry and international partners on this historic Artemis 1 launch that will send Orion on a test flight journey to the Moon and back.

Now, we get to turn to another thrilling success. Good morning and welcome to today's hearing on "Unfolding the Universe: Initial Science Results from the James Webb Space Telescope." I want to welcome our esteemed panel of witnesses. We are so pleased that you're joining us today and you're joining us in person, which is a rarity in the last 2 1/2 years, so very exciting. Most of us are here in person and watching it online have seen the awe-inspiring images that James Webb Space Telescope (JWST) has, the Tarantula Nebula, the Cartwheel Galaxy, the Cosmic Cliffs, Stephan's Quintet, just to name a few. The visual impact of JWST's images alone with the unprecedented clarity and detail provides an inspirational value that I hope will draw a new generation of scientists and explorers into astronomy, astrophysics, and the sciences.

Today's hearing will delve into what those stunning images tell us. What questions will those mesmerizing pictures answer? What new mysteries will they help reveal? And how will JWST's observations help us understand how our Universe came to be, the birth and evolution of stars, planets, galaxies, and how the conditions

arose for life to exist on this planet, maybe in the solar system, and in this galaxy.

I'm really eager to hear from our witnesses on what they're learning in just the first few months of JWST's science operations, which began officially July 12, 2022, because the science is just the beginning, but the journey to get here has been decades in the making. Recommended as the top priority for major new investments in the National Academies of Science, Engineering, and Medicine's 2000 Decadal Survey—just 22 years ago—for astronomy and astrophysics, JWST's design, development, integration, and testing on the ground spanned more than 20 years and required 10 technology miracles along the way.

Challenges were many, successes was never a guarantee. Even following a successful launch on the Ariane 5 rocket, the telescope's complex deployment sequence over 29 days involved 344 potential single-point failures. So I think we're all very proud of the dedication and commitment of the many scientists, engineers, international partners, contractors, that brought us here to celebrate the first science of JWST—the most powerful and complex telescope humans have ever sent into space. And while the initial results and first imagery have been nothing short of awesome, I'm confident there's much more to come and much more than we can even imagine.

So thank you for being here in person for what I predict will be a fascinating discussion.

[The prepared statement of Chairman Beyer follows:]

Before we begin, I want to take a moment to recognize the thrilling first successful test launch of the integrated Space Launch System and Orion crew vehicle-Artemis 1—from Cape Canaveral that occurred early this morning. This is a momentous achievement for NASA and for the Nation. And it's a huge step forward toward sending our astronauts back to the Moon and on to Mars. Congratulations to all those at NASA and its industry and international partners on this historic Artemis 1 launch that will send Orion on a test flight journey to the Moon and back.

Now turning to another thrilling success, good morning, and welcome to today's hearing on Unfolding the Universe: Initial Science Results from the James Webb Telescope. I also want to welcome our esteemed panel of witnesses. We are so pleased you are joining us today.

Most of us here in person and watching online have likely seen the awe-inspiring images obtained by the James Webb Space Telescope—the Tarantula Nebula, the Cartwheel Galaxy, the Cosmic Cliffs, and Stephan's Quintet, just to name a few.

The visual impact of JWST's images alone, with unprecedented clarity and detail, provides an inspirational value that I hope will draw a new generation of scientists and explorers into astronomy, astrophysics, and the sciences.

Today's hearing will delve into what those stunning images tell us.

What questions will those mesmerizing pictures answer and what new mysteries will they reveal?

How will JWST's observations help us understand how our Universe came to be, the birth and evolution of stars, planets, and galaxies, and how the conditions arose for life to exist on this planet, in this Solar System, and in this galaxy?

I'm eager to hear from our witnesses on what they are learning in just the first months of JWST's science operations, which officially began on July 12, 2022.

While JWST's science is just beginning, the journey to get here has been decades in the making.

Recommended as the top priority for major new investments in the National Academies of Science, Engineering, and Medicine's 2000 decadal survey for astronomy and astrophysics, JWST's design, development, integration, and testing on the ground spanned more than twenty years and required ten technology "miracle" innovations along the way.

The challenges were many and success was not a guarantee. Even following its successful launch on an Ariane 5 rocket, the telescope's complex deployment sequence over 29 days involved 344 potential single-point failures.

I'm proud of the dedication and commitment of the many scientists, engineers, international partners, and contractors that have brought us here to celebrate the first science of JWST, the most powerful and complex telescope humans have ever sent into space.

While the initial results and first imagery have been nothing short of stunning, I am confident that there is much more to come, and much we cannot even imagine.

In closing, thank you again to our witnesses for being here-and in person-for what I predict will be a fascinating discussion.

Chairman BEYER. And let me now recognize my friend, Dr. Babin, for an opening statement.

Mr. BABIN. Thank you very much, Mr. Chairman. I appreciate this opportunity to be able to hear from you expert witnesses about this fantastic project.

But good morning. I want to welcome you witnesses here before us today. And also I would like to mention the successful launch of Artemis 1 early this morning. Once again, our Nation has captured the world's attention by venturing back to the Moon with the pursuit of going even further where no one has ever gone before. Our successful launch of Artemis 1 is a remarkable feat made possible by so many brilliant minds across this great land of ours, including hardworking men and women at Johnson Space Center, which I am very privileged to represent. As a longtime supporter of the Artemis program, I want to congratulate everyone involved in this launch and wish them a successful mission.

But now back to another fantastic achievement, the James Webb Space Telescope, also known as JWST, finally launched last Christmas morning with great fanfare. The flagship mission is the culmination of over 2 decades of very hard work and \$10 billion in taxpayer investment. The successful development, launch, and deployment of JWST is a testament to the engineers, the scientists, and the technicians who were so committed to this great project. NASA and its contractors once again demonstrated that the impossible is within reach.

JWST also shows that the United States is still capable of building and operating large-scale, highly technical systems. This fact cannot be overstated. And while it's great to take a victory lap with a successful check out of JWST systems, we must also be vigilant in maintaining this capability in the future. We can't take for granted that we will be able to build cutting-edge systems in the future just because we were able to do so in the past. It will require ongoing congressional support and oversight to maintain key capabilities to build these world class systems. This is imperative not only for our scientific leadership, but also our national and economic security, as the dual-use nature of space impacts our citizens' lives every single day.

Just as with the Hubble Space Telescope and NASA's other great observatories, we expect great things. JWST was touted as potentially rewriting the textbooks. And as breathtaking images and results have come in from JWST over the last 4 months, we're finally starting to see the fruits of our hard labor.

Today's hearing is an opportunity to review these findings and to think about the future. With the spacecraft operating and providing data, what are the lessons learned from JWST that can be applied to future missions like the Nancy Grace Roman Space Telescope or future follow-on observatories? How can Congress help en-

sure that those lessons learned are implemented and followed through because the last thing we want to do is to make the same mistakes twice.

Cost overruns and schedule delays have real-world impacts. They delay the start of other new and exciting missions and sometimes prevent them from even starting. The recent example of the Psyche mission comes to mind. Developed under the cost cap Discovery Program and NASA's Planetary Science Division, Psyche missed its planned launch date earlier this year and will not launch before next October. This will result in the program exceeding its cost cap and delaying the next Discovery-class mission Veritas by at least 3 years. It also raises the question of whether Discovery missions really have a cost cap or whether the caps are just recommendations.

A recent Discovery mission InSight also exceeded its cost cap after issues with the partner-provided instrument resulted in a missed launch window to Mars. The moral hazard caused by specifying a cost cap but not holding missions accountable to that cap is directly applicable to how NASA will manage future astronomy missions after JWST.

These are all issues that we need to remain focused on going forward. But today, I am very interested in hearing from our expert panel on some of the more interesting results that we have derived from JWST's first year. And I look forward to their testimony, and I yield back the balance of my time, Mr. Chairman. Thank you.

[The prepared statement of Mr. Babin follows:]

Good morning. Thank you, Mr. Chairman. I want to welcome to our witnesses for appearing before us today

The James Webb Space Telescope—also known as JWST—finally launched last Christmas morning with great fanfare. The flagship mission is the culmination of over two decades of hard work and \$10 billion in taxpayer investment. The successful development, launch, and deployment of JWST is a testament to the engineers, scientists, technicians that were so committed to the project. NASA and its contractors once again demonstrated that the impossible is within reach.

JWST also shows that the U.S. is still capable of building and operating large-scale highly technical systems. This fact can't be overstated. While it is great to take a victory lap with the successful check-out of JWST's systems, we must also be vigilant in maintaining this capability in the future. We can't take for granted that we will be able to build cutting-edge systems in the future just because we were able to do so in the past. It will require ongoing Congressional support and oversight to maintain key capabilities to build these world-class systems. This is imperative not only for our scientific leadership, but also our national and economic security, as the dual-use nature of space impacts our citizens' lives every day.

Just as with the Hubble Space Telescope and NASA's other "great observatories", we expect great things. JWST was touted as potentially rewriting textbooks. As breath-taking images and results have come in from JWST over the last four months, we are finally starting to see the fruits of our labor. Today's hearing is an opportunity to review these findings and think about the future.

With the spacecraft operating and providing data, what are the lessons learned from JWST that can be applied to future missions like the Nancy Grace Roman Space Telescope or future follow-on observatories? How can Congress help ensure that those lessons learned are implemented and followed through on? Because the last thing we want to do is make the same mistakes twice. Cost overruns and schedule delays have real-world impacts. They delay the start of other new, exciting, missions, and sometimes prevent them from even starting.

The recent example of the Psyche mission comes to mind. Developed under the cost-capped Discovery program in NASA's Planetary Science division, Psyche missed its planned launch date earlier this year and will not launch before next October. This will result in the program exceeding its cost cap and delaying the next Discovery-class mission, VERITAS, by at least three years. It also raises the question of whether Discovery missions really have a cost cap, or whether the caps are just

recommendations. A recent Discovery mission, InSight, also exceeded its cost cap after issues with the partner-provided instrument resulted in a missed launch window to Mars. The moral hazard caused by specifying a cost cap but not holding missions accountable to that cap is directly applicable to how NASA will manage future astronomy missions after JWST.

These are all issues that we need to remain focused on going forward, but today I am interested in hearing from our expert panel on some of the more interesting results that we have derived from JWST's first year. I look forward to their testimony and yield back the balance of my time.

Chairman BEYER. Thank you, Congressman, very much.

Mr. BABIN. Yes, sir.

Chairman BEYER. At this time, I'd like to introduce the witnesses. Dr. Mark Clampin is the Astrophysics Division Director in the Science Mission Directorate (SMD) at NASA Headquarters in Washington. Previously, Dr. Clampin was the Director of the Sciences and Exploration Directorate at the Goddard Space Flight Center. At Goddard, he also previously served as the JWST Observatory Project Scientist and as Director of the Astrophysics Science Division. Dr. Clampin is a co-investigator with the Transiting Exoplanet Survey Satellite, TESS, and the Advanced Camera for Surveys science team. His research interests focus on the study and the formation and evolution of planetary systems. Dr. Clampin graduated from the University of London with a B.S. in physics and from the University of St. Andrews in Scotland with a Ph.D. in astronomy.

Dr. Steven Finkelstein is an Associate Professor at the University of Texas at Austin. His research focuses on the formation and evolution of galaxies in the early universe and the interplay of these sources with reionization. He makes use of the largest ground and space-based observatories and is the Principal Investigator for JWST Early Release Science observing program, the Cosmic Evolution Early Release Science Survey (CEERS). Dr. Finkelstein received his B.S. degree from the University of Washington in astronomy and physics and his Ph.D. in physics from Arizona State University.

And finally, Dr. Natalie Batalha is a Professor of Astronomy and Astrophysics and the Director of the Astrobiology at the University of California Santa Cruz. Dr. Batalha's research focuses on exoplanet science, including both detection and characterization. She's the Principal Investigator for the Transiting Exoplanet Community Early Release Science program with JWST to collect spectra of the atmospheres of a diverse set of exoplanets. Dr. Batalha was previously at NASA Ames, and served as the Project Scientist for the Kepler mission. She earned her bachelor's degree in physics and astronomy from the University of California, Berkeley, and her Ph.D. in astronomy from the University of California, Santa Cruz.

As our witnesses should know, you will each have five minutes for your spoken testimony. Your written testimony will be included in the record for the hearing. And when you've all completed your spoken testimony, we will begin with questions. Each Member will have five minutes to question the panel.

So we will begin with Dr. Mark Clampin.

**TESTIMONY OF DR. MARK CLAMPIN,
ASTROPHYSICS DIVISION DIRECTOR,
NATIONAL AERONAUTICS
AND SPACE ADMINISTRATION (NASA)**

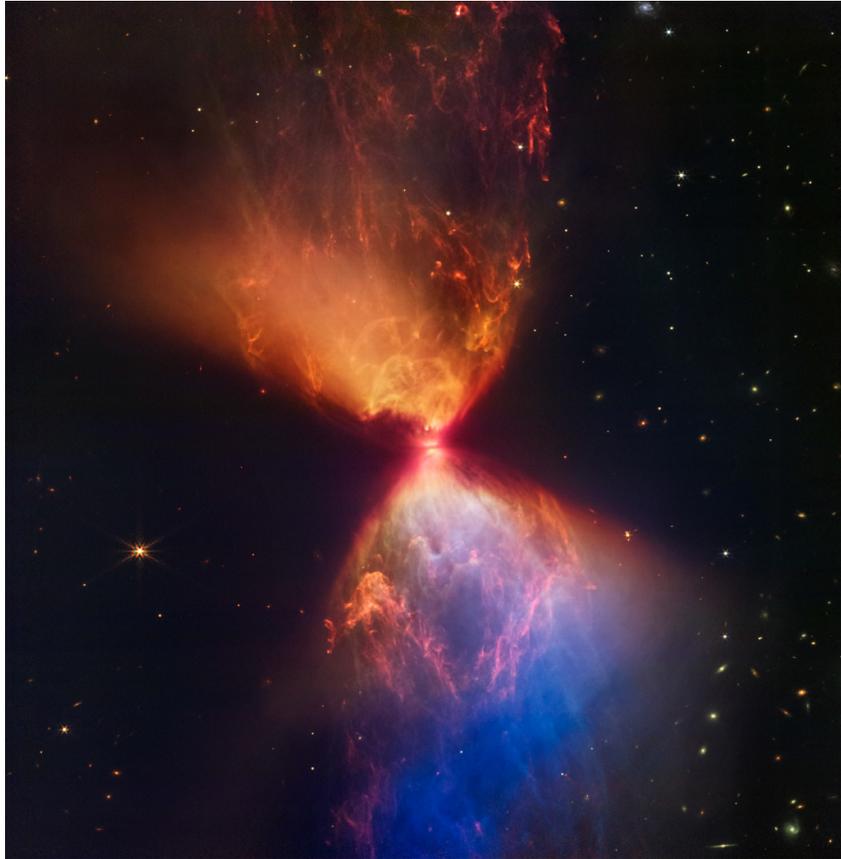
Dr. CLAMPIN. Chairman Beyer, Ranking Member Babin, and Members of the Committee, good morning. My name is Mark Clampin, and I'm the Director of the Astrophysics Division and NASA Science Mission Directorate. This is a great day for NASA, as you've all mentioned. As one of the many people who worked on the James Webb Space Telescope, I'm thrilled to join you this morning to share the groundbreaking science NASA and our partners, the European Space Agency (ESA) and the Canadian Space Agency (CSA), are beginning to explore. NASA's JWS team—JWST team was excited to join with audiences across the Nation and indeed across the world for its launch and then in July for the first science image rollout events.

JWST was designed to discover the first galaxies and stars that formed in the universe, providing a view of the most distant light that we can see. Its discoveries will unravel how galaxies form and evolve. It will allow us to peer into stellar nurseries and study the lifecycle of stars and the planetary systems that form around stars. And it will set us on the path to searching for evidence of habitable planets outside our solar system by providing a first look at the atmospheres of small rocky planets outside our solar system.

JWST is already setting a rapid pace with new discoveries previously beyond our reach, and its very first full-color image, the galaxy cluster SMACS 723, NASA's scientists were amazed to see the deepest and sharpest infrared images of the universe ever taken. The combined mass of the foreground cluster of galaxies, which acts to gravitationally bend and magnify light from even more distant background galaxies, allows us to see somewhere when the universe was much less than a billion years old.

So today, I'm pleased to reveal the once-hidden features of a protostar within the dark cloud L1527, which you will see on the monitor, as it's just been imaged by JWST. Protostars are very young stars that are forming inside their parent molecular clouds. And this first image of this protostar with JWST shows that while the protostar itself is hidden, the view within the neck of this hour-glass shape you see a protoplanetary disk as a dark line across the middle of the neck, and to the top and the bottom you see light from the protostar illuminating the cavities within the surrounding outflows of gas and dust from this object.

[Slide.]



Dr. CLAMPIN. JWST's unmatched sensitivity is also revealing new hints about the worlds outside our solar system. JWST confirmed the first clear evidence that carbon dioxide in the atmosphere of the gas giant planet called WASP-39b. This planet's discovery in 2011 was based on ground-based detections of the subtle periodic dimming of light from its host star as the planet transits in front of the star, essentially a mini-eclipse. And JWST has now studied WASP-39 and discovered this carbon dioxide feature. So we expect the JWST will play a key role in starting the search for potentially habitable planets outside our solar system during the decade.

Mr. Chairman, I'm always asked what is next and how do we build on the national investment made in JWST and its success. So firstly, we will be making lots of new discoveries with the unprecedented capabilities at the James Webb Space Telescope. In the new—near future, NASA plans to launch the Roman Space Telescope, which will conduct widefield surveys to help us to understand the nature of dark energy, the mysterious force which is causing the universe to accelerate as it expands. And a key recommendation in the National Academies for Science Decadal Survey in Astrophysics, known as Astro2020, is the call for NASA to develop a new large space telescope able to survey an image, habitable worlds around sunlike stars, and then examine their atmospheres for evidence of life, what I will call a habitable worlds observatory.

JWST, like Hubble before it, establishes U.S. leadership in space science, and a habitable worlds observatory will continue U.S. leadership in space science and scientific discovery by building on the breakthroughs in technology and science of the James Webb Space Telescope.

It's truly an exciting time in astrophysics. Every day, one of my colleagues shares a new JW image or scientific result that is astonishing. Seeing JWST's first science images displayed in Times Square really show that JWST science has captured the American public's imagination.

So I would like to just conclude by acknowledging the contribution to this program by NASA's Nobel Prize winner, Dr. John Mather, who was an inspirational leader for the life of this program for the James Webb Space Telescope.

Mr. Chairman, I'd be happy to respond to any questions you or other Members of the Committee may have.

[The prepared statement of Dr. Clampin follows:]

HOLD FOR RELEASE
 UNTIL PRESENTED
 BY WITNESSES
 Nov. 16, 2022

Statement of

**Dr. Mark Clampin, Astrophysics Division Director
 Science Mission Directorate**

National Aeronautics and Space Administration

**before the
 Committee on Science, Space, and Technology
 U.S. House of Representatives**

INTRODUCTION

My name is Mark Clampin, and I am the Director of the Astrophysics Division of NASA's Science Mission Directorate. As one of the many people who have worked on the James Webb Space Telescope (JWST) over the years, I could not be happier to join you this morning to share some tantalizing science. NASA and our partners at the European and Canadian Space Agencies are set to explore using JWST: about the earliest, most distant light we can see; how galaxies form and evolve; the lifecycle of stars; and planetary systems and the origin of life.

I know many of you were excited to see us come together with our partners and audiences around the world for JWST's major milestones so far – from launch, provided by the European Space Agency and ArianeSpace, to the first images rollout events at NASA's Goddard Space Flight Center, here on the Hill, and at the Space Telescope Science Institute in Baltimore, which operates the telescope. The anticipation of what the world's premier space science observatory might deliver is beginning to come to fruition. In just the first few months of using its amazing American, Canadian, and European instruments: a Near-Infrared Camera, Near-Infrared Spectrograph, Mid-Infrared Instrument, and Fine Guidance Sensor and Near Infrared Imager and Slitless Spectrograph; we already have myriad results showing that JWST will dramatically advance our understanding of the universe. As is always true with NASA science, our need to explore further only deepens with each new discovery.

The End of the Dark Ages: First Light and Reionization

NASA's JWST is already setting this stage with new discoveries that were previously beyond our reach. In one of its very first full-color images, the observatory delivered the deepest and sharpest infrared image of the distant universe so far. JWST's First Deep Field was galaxy cluster SMACS 0723, an image teeming with thousands of galaxies – including the faintest objects ever observed in the infrared. The combined mass of this cluster of galaxies acts as a gravitational lens, magnifying more distant, background galaxies, including some seen when the universe was much less than a billion years old.

Within this first deep field, scientists have already identified the most distant globular clusters ever seen. These clusters are dense groups that contain millions of stars, some of which may be the first and oldest stars in the universe. We are now seeing the details of the earliest phase of star formation, advancing immediately beyond what was possible with previous Hubble Space Telescope (HST) imaging.

New results also point to some of the most distant galaxies ever observed, using only a few days' observation time. Some likely date back to nearly 350 million years after the Big Bang. And while the distances of these early sources still need to be confirmed, astronomers have been surprised to find that many of these early galaxies are extremely compact and bright. This brightness poses a serious science question for us: What was more common in the early universe – many large, low-mass stars, or fewer, blazingly bright stars?

Assembly of Galaxies

JWST is also already offering insights about how galaxies form and evolve over time. One surprising discovery was a cluster of massive galaxies in the process of forming around an extremely red quasar, a powerfully active galactic nucleus that existed 11.5 billion years ago. JWST's extremely sensitive instruments allowed simultaneous spectroscopic measurement of a wide enough area to show how the quasar and a cluster of at least three galaxies around it, in an area likely full of dark matter, interact in what is one of the densest known areas of galaxy formation in the early universe.

JWST is revealing new perspectives on previously studied targets, thanks to its infrared instruments' ability to peer through dust. The Cartwheel Galaxy, a large pink, speckled galaxy resembling a wheel, is the result of a high-speed intergalactic collision, and now sports two rings — a bright inner ring and a surrounding, colorful ring. JWST has been able to uncover how the expanding rings drive star formation, as well as peer at hydrocarbons, silicates, and other compounds in the dust in the spokes of the wheel.

The Birth of Stars and Protoplanetary Systems

The Pillars of Creation, famously imaged by HST in 1995, is a region where many new stars are forming within dense clouds of gas and dust. But JWST can help us understand how many emerging stars can be found there with much more precision. Its newest view of the Pillars of Creation will help researchers revamp models. Over time, we will begin to better understand how stars form and burst out of these dusty pillars over millions of years. JWST's ability to observe and quantify gas and dust also helps us understand the properties of this rapidly changing area in sharper detail than ever.

Astronomers studying Wolf-Rayet stars have also recently discovered the best evidence yet that the huge amounts of gas pushed into space by these powerful late-stage stars produce carbon-rich dust. And the dust shells that JWST can spot tell us that this dust can remain in the hostile environment between stars and supply material for future stars and planets.

The Tarantula Nebula is the largest and brightest star-forming region near our Milky Way, and it is home to the hottest, most massive stars known. The nebula has a similar type of chemical composition as the gigantic star-forming regions observed when the cosmos was only a few billion years old and star formation was at its peak. JWST is providing astronomers the opportunity to compare and contrast star formation in the Nebula with that of distant galaxies from the actual era of peak star formation, called "cosmic noon."

Planetary Systems and the Origin of Life

Excitingly, JWST's unmatched infrared sensitivity is also revealing new hints about worlds outside our solar system. JWST confirmed the first clear evidence of carbon dioxide in the atmosphere of a planet called WASP-39 b. The planet's discovery, reported in 2011, was made based on ground-based detections of the subtle, periodic dimming of light from its host star as the planet transits in front of the star, and previous observations from NASA's HST and the Spitzer Space Telescope revealed the

presence of water vapor, sodium, and potassium in the planet's atmosphere. JWST has studied WASP-39 b's atmosphere in unprecedented detail, offering evidence that this powerful observatory may also be able to detect and measure carbon dioxide in the thinner atmospheres of smaller rocky planets.

JWST also captured the distinct signature of water in the atmosphere of a hot, puffy gas giant planet called WASP-96 b. While HST has analyzed many exoplanet atmospheres over the past two decades, capturing the first clear detection of water in 2013, JWST's immediate and more detailed observations hint at the significant role the telescope will play in the search for potentially habitable planets in coming years. JWST's powerful new view of this planet also showed evidence of haze and clouds that previous studies of this planet did not detect.

A true highlight of our early research is JWST's ability to take a direct image of a planet outside our solar system. Taking direct images of exoplanets is challenging because stars are so much brighter than planets. HIP 65426 b is an exoplanet discovered in 2017 using the SPHERE instrument from the European Southern Observatory's Very Large Telescope. HIP 65426 b is more than 10,000 times fainter than its host star in the near-infrared, and a few thousand times fainter in the mid-infrared. JWST was able to image such a dim object so early in its mission, thanks to the coronagraphs on its instruments, which served to suppress the light of the host star – a capability that points toward exciting new observations of other worlds in the future.

Closer to home, JWST images of Jupiter have been able to showcase several levels of its auroras and clouds, from high-altitude auroras above to the northern and southern poles to swirling hazes and deeper main clouds. Streaks and spots identified in JWST data likely reflect convective storms. Wider field images capture Jupiter's faint rings and tiny nearby moons. Planetary scientists are already working out what these new data mean for Jupiter's chemistry and atmosphere.

JWST's first image of Neptune captured the clearest view of this distant planet's rings in more than 30 years. Some of these rings had not been detected since NASA's Voyager 2 first observed Neptune during its flyby in 1989, along with Neptune's dust band. High-quality images show a vortex at Neptune's southern pole and more subtly suggest other weather activity. JWST also imaged Neptune's highly reflective icy moon Triton, with plans to image this system again in the coming year.

Conclusion

Since it began observations, JWST has simply been amazing. We have been very pleased with its better-than-expected performance and observations. We are managing the observatory in such a way that we expect it to provide dramatic scientific surprises for many years to come. But we at NASA are far from satisfied with what we have learned, insofar as it tells us there is infinitely more to learn from the heavens. We continue to learn from observations gained from missions like Hubble, Chandra, TESS, and IXPE, among many others. In the future, you should expect great things from the Roman Space Telescope, COSI, GUSTO, and the missions we build toward in response to the 2020 Astrophysics Decadal Survey. In just a few years, I hope you will invite us back to see the first results of Roman's massive infrared survey so we can discuss how these systems can provide complementary observations to target future JWST missions. We will, as always, be prepared to share with you and the public everything that we and the scientific community are able to find with these complementary assets.

Mr. Chairman, we would be happy to respond to any questions you or the other Members of the Subcommittee may have.

**Dr. Mark Clampin, Director, Astrophysics Division
Science Mission Directorate
National Aeronautics and Space Administration (NASA)**



Dr. Mark Clampin is the Astrophysics Division Director in the Science Mission Directorate at NASA Headquarters in Washington, DC. Until August 2022, Dr. Clampin was the Director of the Sciences and Exploration Directorate (SED) at the Goddard Space Flight Center (GSFC) where he led the Astrophysics, Solar System, Heliophysics and Earth Science Divisions, together with the high performance computing office.

At GSFC, he previously served as the James Webb Space Telescope (JWST) Observatory Project Scientist, and subsequently as Director of the Astrophysics Science Division and Deputy Director of SED. Prior to joining GSFC, Dr Clampin was the Advanced Camera for Surveys (ACS) Group Lead at the Space Telescope Science Institute (STScI), where he worked on the first four Hubble Space Telescope (HST) Servicing Missions.

Dr. Clampin is a Co-Investigator with the Transiting Exoplanet Survey Satellite (TESS), and the Advanced camera for Surveys (ACS) science team and served as the Detector Scientist, responsible for the delivery of three focal plane camera systems. His research interests focus on studying the formation and evolution of planetary systems. Dr. Clampin has also designed ground-based telescope instruments including adaptive optics systems, coronagraphs and detectors.

Dr. Clampin graduated from the University of London with a BS in Physics and from the University of Saint Andrews in Scotland, with PhD in Astronomy. Dr. Clampin is the recipient of the Meritorious Presidential Rank Award, NASA's Exceptional Achievement and Scientific Achievement Medals, and is a Fellow of SPIE and the Royal Astronomical Society,. Until recently he was the Chief Editor of the SPIE peer-reviewed Journal of Astronomical Telescopes, Instruments and Systems, a position he held for 7 years. He is married with one daughter, and enjoys running and his lifelong passion scuba diving.

Chairman BEYER. Dr. Clampin, thank you very much. Wonderful overview. We appreciate it.

Dr. Finkelstein, the floor is yours.

**TESTIMONY OF DR. STEVEN L. FINKELSTEIN,
PROFESSOR OF ASTRONOMY,
UNIVERSITY OF TEXAS AT AUSTIN**

Dr. FINKELSTEIN. Thank you. Good morning, Mr. Chairman and Members of the Subcommittee. My name is Steven Finkelstein. I'm a Professor of Astronomy at the University of Texas at Austin. I'm also the Principal Investigator of one of JWST's Early Release Science programs. It's my great pleasure to be here today to share with you the early discoveries from our program, which is called the Cosmic Evolution Early Release Science Survey, or CEERS.

[Slide.]



CEERS

Dr. Steven Finkelstein

Professor of Astronomy at the University of Texas at Austin

House Subcommittee on Space and Aeronautics Hearing on Nov 16, 2022:
Unfolding the Universe: Initial Science Results from the James Webb Space Telescope

Dr. FINKELSTEIN. CEERS targets galaxies forming in the early universe using several of JWST's instruments. I would like to take a moment to explain how the study of the early universe is even possible. This is thanks to two helpful features of nature, the first of which is our cosmic speed limit, the speed of light. When we look at distant objects, the light we see has traveled large distances to reach our telescopes, so we see these objects as they were in the past. While this is inconsequential in the nearby universe, when we look at distant galaxies, this allows us to see them as they were billions of years ago.

The second way the universe helps us is that it is expanding. All galaxies are moving away from one another, and as light from galaxies travels through expanding space, the light waves stretch out. This makes galaxies appear redder than they should be with the amount of reddening proportional to the distance. Astronomers assign this redshift a single number, which can be thought of as a time indicator. The most distant galaxies that the iconic Hubble Space Telescope can see are at a redshift number of about 10, where we are seeing them as they were over 13 billion years into the past. The universe is only 13.8 billion years old, so this is quite a feat from Hubble.

However, Hubble is not capable of reaching greater distances. At redshifts greater than 10, light from these more distant galaxies is stretched so far to the red that Hubble, which is optimized for visible light, cannot see them. This means that the earliest phases of the universe when the first galaxies form and evolve, have remained elusive. When did the first galaxies form out of the cosmic dark ages? What did they look like? Are there stars similar to those in our own Milky Way or fundamentally different in some way?

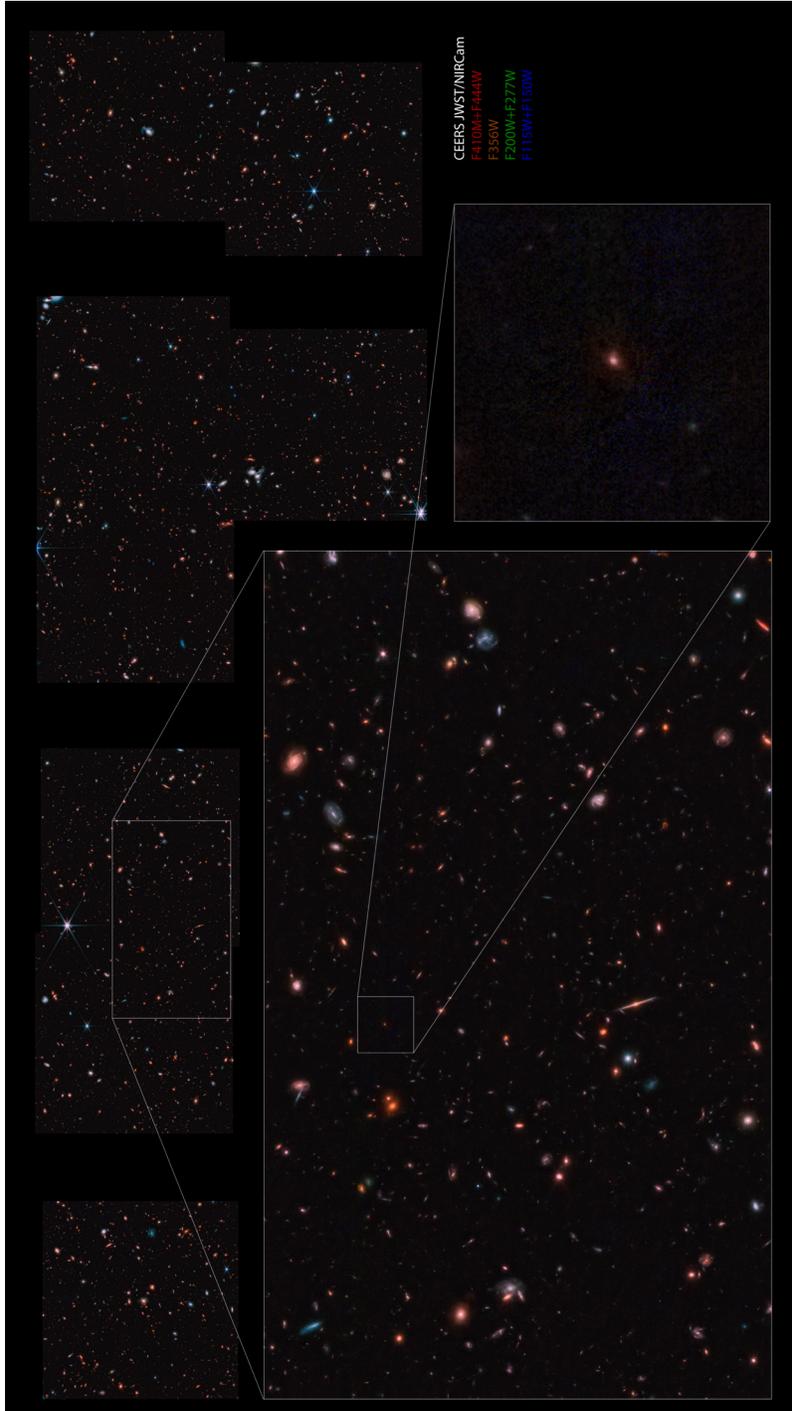
Enter JWST. With its larger mirror and sensitivity to infrared light, JWST was designed to target this early cosmic era, and that is exactly what we are doing with CEERS. We were fortunate enough to receive a portion of our data in mid-July and I'm excited to share with you this beautiful image of the CEERS field. This image you see now shows a region of the sky about 8 times larger in area than Webb's first deep field containing over 40,000 galaxies. The images at the bottom show a gallery of galaxies highlighting the exquisite level of detail achievable with JWST.

[Slide.]



Dr. FINKELSTEIN. As we analyze these data in late July, one galaxy jumped out at us in particular. We continued to improve the quality of our images, and we became convinced that we were seeing a galaxy with a redshift number of 12 more distant than anything humanity had seen before. Here in this image I present to you Maisie's galaxy.

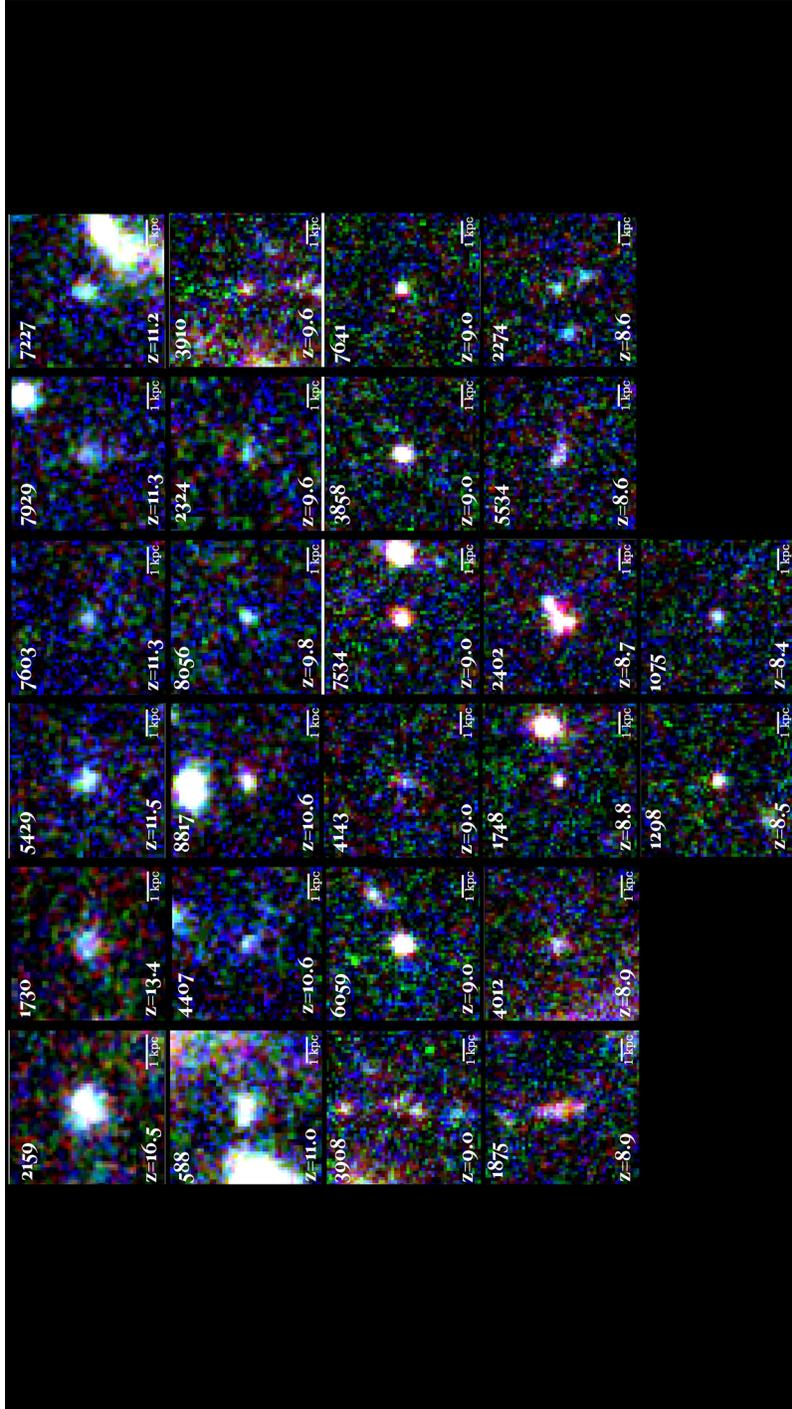
[Slide.]



Dr. FINKELSTEIN. Maisie's galaxy, which is named after my daughter as we both discovered it on her 9th birthday, and she had been asking me for months to name a galaxy after her, it's shown in the zoomed in panel, the small red dot. Here you are seeing light which has been traveling to us from a time only 370 million years after the Big Bang, looking back over 97 percent of the history of the universe.

And a paper just submitted last week, we can now confirm that Maisie is not alone. Here I show you a compilation of 26 extremely distant galaxies discovered in our CEERS data, including an amazing galaxy at the top left, which appears to be at a redshift number of 16, which means that it's coming to us from a time only 250 million years after the Big Bang.

[Slide.]



Dr. FINKELSTEIN. This high abundance of early galaxies is surprising and indicates that something is fundamentally different about stars in these galaxies. While our Sun is a pretty typical star in our own Milky Way Galaxy, it has been theorized that early galaxies, due to their very small amount of heavy atomic elements, would have much greater typical star masses. These massive stars would lead to galaxies being more blue intrinsically and more luminous, allowing more galaxies to be seen in our images. And you can see that many of these galaxies appear blue in this image, indicating that we may be entering an epoch when galaxies are dominated by completely different types of stars than today.

Given the unexpected nature of these galaxies, confirmation of their extreme distances is a must. This can be accomplished with spectroscopy, which is a type of observation where we take the light from an object and split it apart with a dispersive element like a prism to split the light into its component wavelengths, revealing significantly more information. JWST is scheduled to take a spectrum of many of these sources in the CEERS field just next month. These data will provide the needed confirmation of these redshifts.

I would like to leave you with one of my favorite images, the Stephan's Quintet early release observation. While this image features several nearby galaxies, if you look close enough, you can see plenty of galaxies in the background. JWST is so powerful that every field is a deep field.

[Slide.]



Dr. FINKELSTEIN. It is amazing to me that just 4 months ago we had no idea that our universe started forming stars and galaxies so early. We are living in a transformative time in astrophysics, and JWST is truly revolutionizing our view of the universe. I thank you for your time and would be pleased to answer any questions.
[The prepared statement of Dr. Finkelstein follows:]



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Exploring the End of the Cosmic Dark Ages with JWST

Dr. Steven Finkelstein, Professor of Astronomy, The University of Texas at Austin

Written Testimony for House Subcommittee on Space and Aeronautics Hearing on Nov 16, 2022:

Unfolding the Universe: Initial Science Results from the James Webb Space Telescope

While humankind has looked to the stars and wondered about our origins for millennia, it was only 100 years ago that we first realized that those fuzzy “spiral nebulae” in the night sky were not in our own Milky Way Galaxy, but rather were “island universe”, or galaxies, all their own. This transformation in our fundamental understanding of the universe — that our Galaxy was not alone — was technology driven. It was Edwin Hubble who used the (then new) 100” Hooker Telescope at Mount Wilson Observatory to measure the distance to the Andromeda Galaxy, our nearest neighbor, and proved it lied well beyond the confines of the Milky Way.

Fast forward a century, and astronomical discoveries are still tied to technological advances. Over the past 30 years *Hubble* (the space telescope) has revolutionized our understanding of galaxies, from the nearby universe to the distant universe. However, the earliest phases of the universe, when the first galaxies form and evolve, have remained elusive. When did the first galaxies form out of the dark ages? What did they look like? Are their stars similar to our own Milky Way, or fundamentally different in some way?

Answering such questions relies on another leap in technological capabilities. While *Hubble* has been, and continues to be, transformative, it is not capable of observing these early galaxies for two reasons - they are too faint and too red. The *JWST*, with its seven times larger light-gathering power and infrared sensitivity, was built for this. Science Goal #1 for JWST is “First Light in the Universe.” In this document I will share how, with just a few months of scientific data, *JWST* is already delivering on this ambitious goal, and is transforming our understanding of the universe, just as Edwin Hubble did 100 years ago.

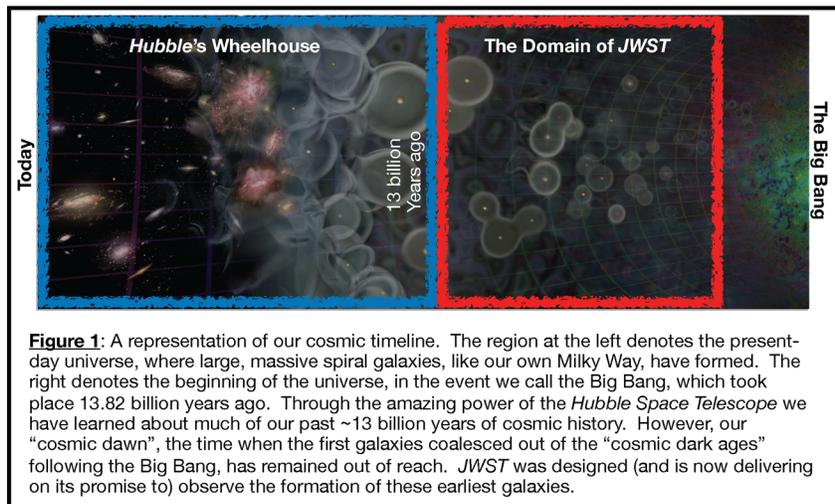


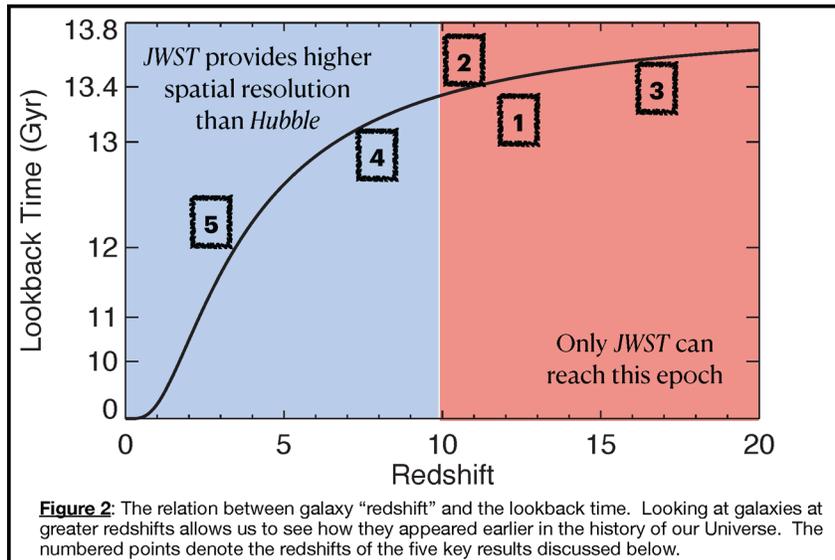
Figure 1: A representation of our cosmic timeline. The region at the left denotes the present-day universe, where large, massive spiral galaxies, like our own Milky Way, have formed. The right denotes the beginning of the universe, in the event we call the Big Bang, which took place 13.82 billion years ago. Through the amazing power of the *Hubble Space Telescope* we have learned about much of our past ~13 billion years of cosmic history. However, our “cosmic dawn”, the time when the first galaxies coalesced out of the “cosmic dark ages” following the Big Bang, has remained out of reach. *JWST* was designed (and is now delivering on its promise to) observe the formation of these earliest galaxies.

A Primer on Observing the Early Universe

The fact that we can even study early galaxies is astonishing, and relies on two curious features about our universe. The first is the nature of light itself - light cannot travel instantaneously from one place to another. Rather, it travels at a certain speed: the speed of light. This speed is fast in terrestrial terms (nearly one billion miles per hour), but is fairly crawling on astronomical scales. This means that when we look at distant objects, we don't see them as they are now, but rather we see them as they were in the past. This is inconsequential for the nearby universe; we see the Sun as it was eight minutes ago, and the nearest bright star Sirius as it was eight years ago. However, move to large enough scales and one begins to truly look significantly back in time. The *Hubble Space Telescope* has seen galaxies from over 13 billion years in the past, peering out over 90% of the history of the universe. At these limits of this amazing 30 year old facility, *Hubble* continues to see galaxies.

The knowledge of the second curious feature of our universe also dates back to Edwin Hubble, who also used his state-of-the-art telescopes to show that all galaxies are moving away from each other, with more distant galaxies moving more quickly. This discovery means that our Universe is expanding. This has an effect on the light we receive from these receding galaxies. As the light moves through expanding space, the light waves get stretched, meaning that the light we observe is *redder* than it was when it was emitted, with the amount of *red-shifting* proportional to a galaxy's distance. This means that all galaxies, by the time we observe their light here on Earth, look a little redder than they would if they were not moving away from us, and the most distant galaxies look the most red. Astronomers call this quantity the "redshift" of a galaxy, and it is analogous to distance. The most redshifted galaxies, those with the highest redshift number, have the greatest distance.

However, while distance is useful, a more intuitive quantity is time. Figure 2 below shows the "lookback time" - how far back in time we are seeing - versus the redshift number of a galaxy.



This is an extremely useful feature - one can observe a galaxy, and by examining how redshifted it looks, we can place it at its correct time in our cosmic history. This “redshift” quantity is something we can estimate fairly well with imaging, and very precisely with spectroscopy (spectroscopy is a type of observation where we take the light from an object and use a dispersive element (like a prism) to split the light into its component wavelengths, revealing significantly more information). Together, the ability to peer back in time coupled with the ability to determine distances due to redshift allows us to pursue *the study of galaxy evolution*, and truly understand how galaxies form and evolve.

Why does this matter? This is our true origins story. Humans have long wondered where we came from and why are we here. The study of galaxy evolution pushes this desire to understand our origins to its limits. Not just where did humans come from, or our Earth, or our Solar System, but where did our *Galaxy* come from?

Moving into the First 500 Million Years with JWST

The *Hubble Space Telescope* has produced several iconic images related to the early universe, none more so than the Hubble Ultra Deep field. Its predecessor, the Hubble Deep Field, showed humanity what happens if you point a powerful telescope at an otherwise empty region of the sky, and open the camera’s shutter for hundreds of hours. This program, which was somewhat controversial at the time (some astronomers thought we would see nothing!) showed us that the universe is **filled** with galaxies! Our best estimate today is that our observable universe contains **trillions** of galaxies.

Through a number of legacy *Hubble* programs, we have learned a great deal about galaxy evolution. However, as *Hubble* is primarily a visible light telescope, it is unable to see galaxies at redshifts beyond 10. At greater redshifts, all of the light from those extremely distant galaxies is redshifted out of the visible wavelength regime, and into the infrared. These galaxies are also quite faint (not only are they at extremely great distances, they are intrinsically much smaller and fainter than our Milky Way), meaning that a more powerful telescope is needed to collect their photons.

With the immensely successful launch and deployment of *JWST*, that telescope is here. The 6.5 meter diameter primary mirror of *JWST* is seven times the area of *Hubble*’s mirror, allowing us to see much fainter objects. *JWST*’s mirror and instruments are also optimized to detect infrared photons, perfect for studying the early universe. With *JWST*, we can thus now, for the first time in human history, look to our ultimate origins - when did the first galaxies form out of the cosmic dark ages?

The Cosmic Evolution Early Release Science Survey

Some of the first science data collected by *JWST* was for a suite of 13 “Early Release Science” (ERS) programs, designed to obtain data across all areas of astronomy with all *JWST* instruments, all of which would be immediately publicly available. Here I will show some key early results from one of these surveys, called the “Cosmic Evolution Early Release Science Survey” (or CEERS), for which I am the Principal Investigator. CEERS targets the early universe by obtaining imaging with two of *JWST*’s cameras (the Near-Infrared Camera, NIRC*am*, and the Mid-Infrared Imager, MIRI). CEERS will also, next month, obtain spectroscopy with the Near-Infrared Spectrograph (NIRSpec) as well as with a spectroscopic mode of NIRC*am*. With the redder light that these instruments are sensitive to, CEERS was designed to perform a census of the redshift of 10 universe, and push our cosmic horizons back into the cosmic dark ages. We show a color image of our current CEERS dataset in Figure 3.

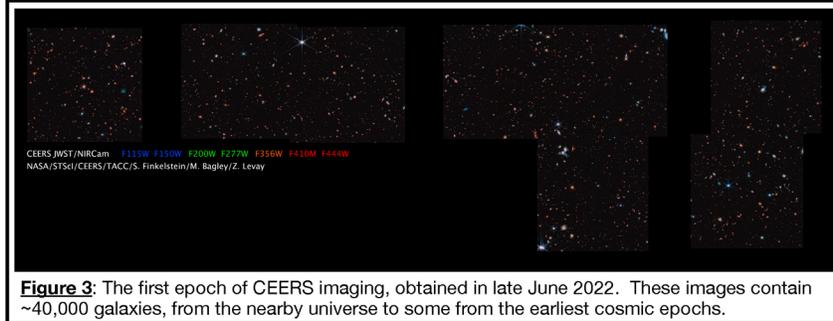
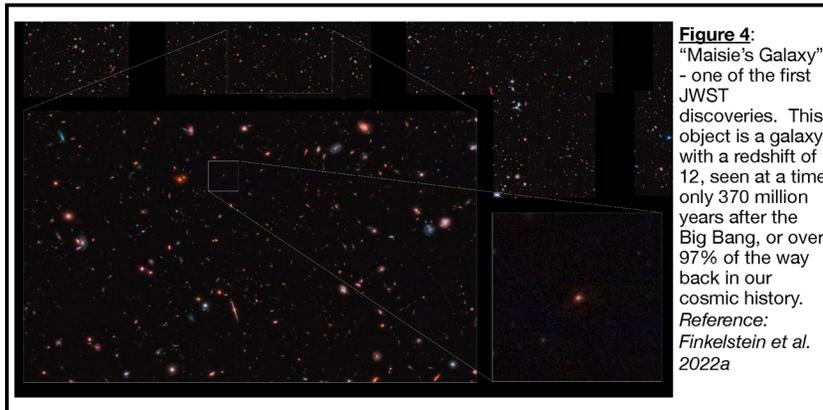


Figure 3: The first epoch of CEERS imaging, obtained in late June 2022. These images contain ~40,000 galaxies, from the nearby universe to some from the earliest cosmic epochs.

Science Result 1: An Unexpectedly Early Object - “Maisie’s Galaxy”

The first CEERS data were obtained in late June, and released in mid-July following NASA’s Early Release Observation press release. A group of six astronomers met on the campus of the University of Texas at Austin to reduce the data (the process of taking the raw data frames and combining them into the data ready for scientific measurements). Within a matter of days, it became clear that there was an unexpectedly distant galaxy present. While *JWST* was built to find the earliest galaxies, these ERS programs were limited in size, thus our team did not believe that the CEERS would be deep enough to push much beyond a redshift of 11.

To our surprise, as we analyzed this object, we realized it was a redshift of 12 galaxy! This means that the light we are seeing left this galaxy about 370 million years after the Big Bang, and has been traveling for over 13.4 billion years to reach our telescopes. What did we call this astounding object? It had been discovered on my daughter’s birthday, and she had been asking me to name a galaxy after her. Though I told her we didn’t usually do that, in what started as a nickname for the object the collaboration eventually decided to adopt the name “Maisie’s Galaxy” for this amazing galaxy. While it is difficult to make sweeping conclusions from just one galaxy, the simple fact that we can see Maisie’s Galaxy at this extremely early time places the best constraints yet on the end of the cosmic dark ages. We show a zoom in on Maisie’s Galaxy in Figure 4. This paper, led by the CEERS team, has been accepted to the *Astrophysical Journal Letters*, as the first paper in a Focus Issue on the CEERS project.



Science Result 2: Massive Monsters at Cosmic Dawn

Two other studies from this summer found something else very surprising - very bright galaxies which appeared to come from a redshift of 17! Such galaxies are completely unexpected — no modern theoretical simulation predicts that our universe could form such massive “monster” galaxies just ~250 million years after the Big Bang. In Figure 5 we show these galaxies. The first one, originally shared in a submitted paper led by a group at the University of Edinburgh, was identified in the CEERS field. The second one, shared in a submitted paper by a group at the University of Tokyo, was found in the Stephan’s Quintet field. This latter field was taken as part of *JWST*’s Early Release Observation program. What is amazing is that these latter data were not intended to study the early universe, but *JWST* is so powerful that every field is a deep field! Given the unexpected nature of these sources, confirmation of their extreme redshifts is a must. *JWST* is already scheduled to take a spectrum of the source in the CEERS field (along with Maisie’s Galaxy) in December; these data will provide a precise redshift.

The Stephan’s Quintet galaxy was recently observed at millimeter wavelengths with the Atacama Large Millimeter Array (ALMA). In a paper just submitted for publication by a University of Texas at Austin postdoctoral researcher, they found that this galaxy had no detectable emission at these very long wavelengths in the ALMA data, which rules out many alternative redshifts, making an extremely high redshift more likely. These observations also highlight the synergies between NASA’s space telescopes and NSF’s ground-based portfolio. Finally, should our universe truly crank out these massive monsters, they will make excellent targets for study with NASA’s upcoming *Nancy Grace Roman Space Telescope*, which will study areas of the sky much wider than *JWST*, allowing better characterization of the abundance of rare, bright galaxies.

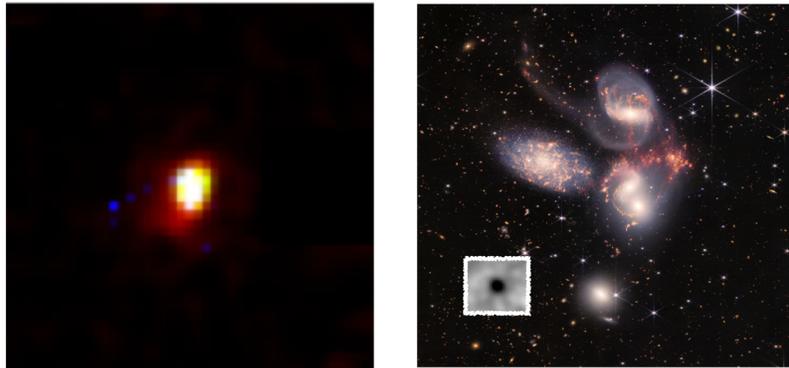


Figure 5: Two objects which appear to be galaxies at the amazing redshift of 17. If these redshifts are confirmed, they are coming from a time less than 250 million years after the Big Bang, surprisingly early. The galaxy on the left was discovered in the CEERS imaging, serendipitously close to Maisie’s Galaxy, allowing them both to be followed up with spectroscopy in December. The galaxy on the right was discovered in the Stephan’s Quintet Early Release Observation data. *References: Donnan et al. 2022; Harikane et al. 2022*

Science Result 3: A Population of Early Galaxies - Are Early Stars Different?

Maisie was just the beginning - as we continue to work on the CEERS *JWST* imaging data, and are able to produce better and more accurate measurements, we have begun to build up a true representative sample of early galaxies. The CEERS team has just submitted a paper for publication showcasing a sample of 26 very distant galaxies, ranging from redshifts of 9 to nearly 17 (shown in Figure 6 below). We compared to a wide variety of theory-based predictions, and found that nearly all models failed to predict this high abundance of such early galaxies (this paper has been submitted to the *Astrophysical Journal Letters*). This is exciting, as it means that the physical processes dominant in these early galaxies are different than what the models assume, pointing to very different physical conditions for star formation.

One exciting solution would be if the stars in these early galaxies are different from those today. In the Milky Way galaxy, the average mass of a star is about that of our Sun. However, it has been predicted that the early galaxies, due to their very small amount of heavy atomic elements, would have typical star masses of $\sim 10\text{-}50X$ that of our Sun. As more massive stars are brighter and bluer, this would lead to these galaxies being more luminous, and thus perhaps easy to detect. In Figure 6 below, you can see these galaxies appear quite blue, thus this is not unlikely! Our upcoming spectroscopy can confirm this exciting implication.

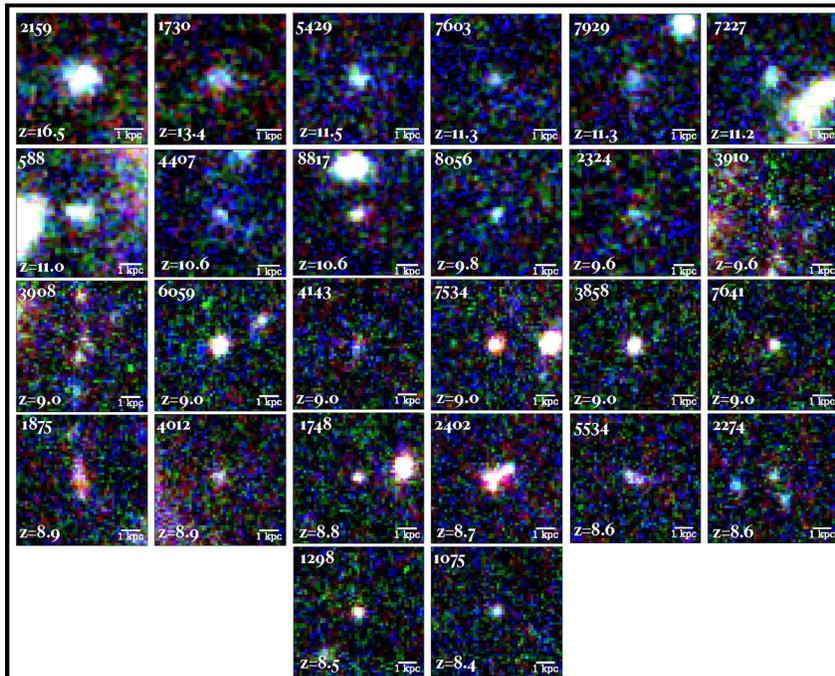


Figure 6: A compilation of an amazing 26 early galaxies, ranging in redshift from 8.4 to 16.5, all discovered in CEERS. The colors are chosen to show the intrinsic colors of these galaxies, highlighting that many are very blue. The abundance of these sources, should their distances be confirmed with spectroscopy, indicates that stars in the very early universe are fundamentally different from those in our Milky Way. *Reference: Finkelstein et al. 2022b*

Science Result 4: Seeing the True Nature of Hubble's Earliest Discoveries

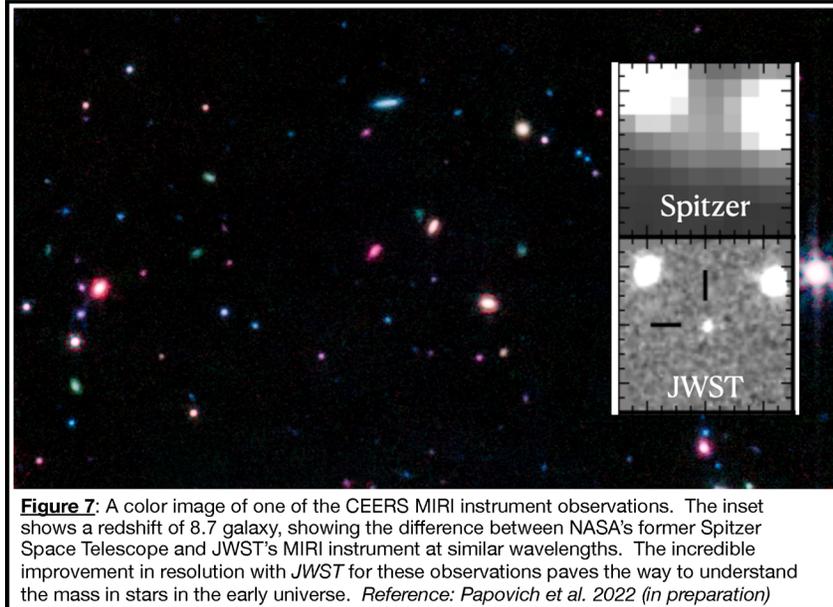


Figure 7: A color image of one of the CEERS MIRI instrument observations. The inset shows a redshift of 8.7 galaxy, showing the difference between NASA's former Spitzer Space Telescope and JWST's MIRI instrument at similar wavelengths. The incredible improvement in resolution with JWST for these observations paves the way to understand the mass in stars in the early universe. *Reference: Papovich et al. 2022 (in preparation)*

In addition to imaging with NIRCcam, which operates at slightly redder wavelengths than *Hubble*, CEERS also obtained imaging with MIRI, which observes at even longer wavelengths. Figure 7 above shows a color compilation of a portion of our MIRI imaging. These MIRI data are critical for a variety of analyses, from star-formation and black hole activity in the nearby universe which is obscured by cosmic dust, to emission from older stars in the early universe.

The inset image shows an example of the latter - the top portion shows the image of a galaxy at a redshift of 8.7. This galaxy was originally discovered with *Hubble* data, but *Hubble* was only sensitive to the light from young stars, so the total mass of this galaxy was uncertain. NASA's Spitzer Space Telescope is sensitive to light from older stars, but its resolution was too poor (as shown in the top inset panel) to accurately measure the emission from this galaxy. The bottom inset panel shows the CEERS/MIRI image of this galaxy at wavelengths ~4X longer than accessible to *Hubble*. While the previous Hubble+Spitzer constraints allowed this galaxy to have a very high mass, with the improved JWST observations we can constrain this mass to be fairly low. These observations pave the way for larger MIRI surveys to constrain the total amount of mass in stars formed in the early universe.

Science Result 5: A Complexity of Galactic Structure at Cosmic Noon

The improved spatial resolution afforded by JWST allows the first true invitations into the morphological structure of galaxies beyond a redshift of 2. We find that galaxies at high redshift (>3, more than 11 billion years into the past) have a wide diversity of morphologies,

including galaxies with disks, bulges, those that look like spheroids, and those that are irregular. Some galaxies have morphologies that are different between *HST* and *JWST*. This is due to the difference in image depth between CEERS and the previous *HST* imaging, the difference in rest-frame wavelength, and the difference in resolution. Sometimes, this difference means that we can see disks in the *JWST* imaging that were not apparent in the *HST* imaging (see examples in Figure 8). With *HST* imaging alone, some of these galaxies look very irregular or like spheroids since the disks themselves were too faint to detect. This means that even at these early times, disks were already in place for some galaxies.

Further analysis will show how these disks compare to those in today's universe and to determine when in the universe's history they were able to form.

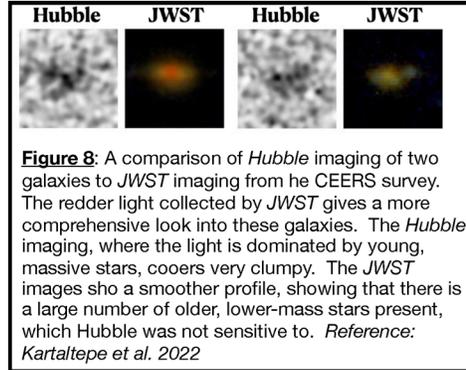


Figure 8: A comparison of *Hubble* imaging of two galaxies to *JWST* imaging from the CEERS survey. The redder light collected by *JWST* gives a more comprehensive look into these galaxies. The *Hubble* imaging, where the light is dominated by young, massive stars, coarsens very clumpy. The *JWST* images show a smoother profile, showing that there is a large number of older, lower-mass stars present, which *Hubble* was not sensitive to. Reference: Kartaltepe et al. 2022

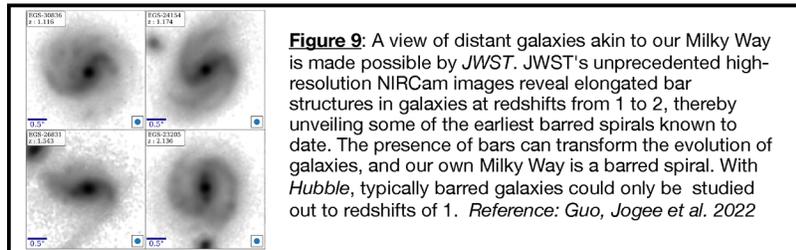


Figure 9: A view of distant galaxies akin to our Milky Way is made possible by *JWST*. *JWST*'s unprecedented high-resolution NIRC2 images reveal elongated bar structures in galaxies at redshifts from 1 to 2, thereby unveiling some of the earliest barred spirals known to date. The presence of bars can transform the evolution of galaxies, and our own Milky Way is a barred spiral. With *Hubble*, typically barred galaxies could only be studied out to redshifts of 1. Reference: Guo, Jogee et al. 2022

Stellar bars – central elongated features in the disk of spiral galaxies – are important structures that shape the evolution of galaxies by channeling gas into their central regions where it is rapidly converted into new stars in "starburst" episodes. Most spiral galaxies in the present-day Universe, including our Milky Way, host a bar feature, but a long-standing question is: when did such features first appear in the Universe? With *Hubble*, typically bars could only be robustly identified out to redshifts of ~ 1 , when the Universe was $\sim 40\%$ of its present age. *JWST*'s unprecedented high-resolution mid-infrared images are now unveiling barred spirals out to redshifts of at least 2, when the Universe was almost twice as young, as shown in Figure 9. This has profound implications for theoretical models of the formation of barred galaxies, possibly akin to our own Milky Way, and for galaxy evolution pathways.

What Comes Next?

The CEERS survey, by its very definition, is our first look into our cosmic beginnings. The remainder of *JWST*'s first year of observations contains a wide portfolio of observations, from the first *JWST* ultra-deep fields (two of them!) to an early universe survey wider than the full moon on the sky (known as COSMOS-Web). And even this first year is just the tip of the iceberg, with many years of exciting *JWST* observations to come.

Most exciting for the near future will be spectroscopy. First and foremost, this will allow astronomers to precisely measure the redshift of a galaxy (by measuring the observed wavelengths of redshifted spectral features like atomic emission lines). This step of “spectroscopic confirmation” is extremely necessary to validate the exciting science results (#1-3) presented above. The CEERS project has a spectroscopic component, with data coming in during the second half of December. The Space Telescope Science Institute has also authorized a “Director’s Discretionary Time” spectroscopic observation of both Maisie’s Galaxy and the redshift of 17 object in CEERS described above, also happening in December. For those galaxies that we can confirm to be in the early universe, these spectra will also be rich with information on the types of stars (are they more massive?), and the abundance of heavy elements (are these galaxies nearly chemically pristine?).

While the knowledge gained from these early *JWST* observations has truly been transformative across all of astronomy, with the vast amounts of new data to come, this firehouse of knowledge gained will not slow for the foreseeable future.

Disclaimer: This text represents the thoughts and opinions of the author, and does not represent the University of Texas at Austin.

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- Finkelstein, S., Bagley, M., Arrabal Haro, P. et al. 2022a, “A Long Time Ago in a Galaxy Far, Far Away: A Candidate $z \sim 12$ Galaxy in Early *JWST* CEERS Imaging”, Accepted to the Astrophysical Journal Letters (preprint available at: <https://arxiv.org/abs/2207.12474>)
- Finkelstein, S., Bagley, M., Ferguson, H. et al. 2022b, “CEERS Key Paper I: An Early Look into the First 500 Myr of Galaxy Formation with *JWST*”, Submitted to the Astrophysical Journal Letters (preprint available at: <https://arxiv.org/abs/2211.05792>)
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- Kartaltepe, J., Rose, C., Vanderhoof, B. et al. 2022, “CEERS Key Paper IV: The Diversity of Galaxy Structure and Morphology at $z = 3 - 9$ with *JWST*”, Submitted to the Astrophysical Journal Letters (preprint available at: <https://arxiv.org/abs/2210.14713>)
- Papovich, C., Cole, J., Yang, G. et al. 2022, “CEERS Key Paper VI: Stellar Populations and Star-Formation Histories of Star-Forming Galaxies at $4 < z < 9$ from rest-frame >1 micron imaging”, in preparation for submission to the Astrophysical Journal Letters

Steven L. Finkelstein

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ACADEMIC POSITIONS	<p>The University of Texas at Austin, Austin, TX</p> <p>Professor Fall 2022 – Present Associate Department Chair Fall 2019 – Present Associate Professor Fall 2017 – Summer 2022 Assistant Professor Fall 2012 – Summer 2017</p> <p>The University of Texas at Austin, Austin, TX Hubble Fellow • Faculty Contact: Professor Karl Gebhardt</p> <p>Texas A&M University, College Station, Texas Postdoctoral Research Associate • Faculty Advisor: Professor Casey Papovich</p>	<p>Sept. 2011 – Aug. 2012</p> <p>Sept. 2008 – Aug. 2011</p>
EDUCATION	<p>Arizona State University, Tempe, Arizona Ph.D. Physics, Emphasis in Astronomy • Advisor: Professor James E. Rhoads • Dissertation: Physical Properties and Dust Effects in High-Redshift Lyman Alpha Galaxies</p> <p>University of Washington, Seattle, Washington B.S. Astronomy and Physics</p>	<p>August 2008</p> <p>June 2003</p>
HONORS AND AWARDS	<ul style="list-style-type: none"> • 2020 UT Austin Provost's Teaching Fellowship • 2017-2018 Dads' Association Centennial Teaching Fellowship • 2017 Asa Briggs Visiting Fellow, University of Sussex • 2016 UT Austin College of Natural Sciences Teaching Excellence Award • 2015-2016 McDonald Observatory Board of Visitors Teaching Excellence Award • Hubble Prize Postdoctoral Fellowship (awarded in 2011) 	
PUBLICATIONS	<p>Summary: 220 papers published in or submitted to peer-reviewed journals, with an h-index of 58. Of these, I am the lead author on 23 papers, which have >2500 citations combined. Recent important papers are:</p> <ol style="list-style-type: none"> 1. Finkelstein, S. L. et al. 2022, <i>CEERS Key Paper I: An Early Look into the First 500 Myr of Galaxy Formation with JWST</i>, Submitted to the Astrophysical Journal Letters 2. Bagley, M., Finkelstein, S. L. et al. 2022, <i>CEERS Epoch 1 NIRCam Imaging: Reduction Methods and Simulations Enabling Early JWST Science Results</i>, Submitted to the Astrophysical Journal Letters 3. Finkelstein, S. L. et al. 2022, <i>A Long Time Ago in a Galaxy Far, Far Away: A Candidate $z \sim 12$ Galaxy in Early JWST CEERS Imaging</i>, Astrophysical Journal Letters, in press 	

4. Finkelstein, S. L. and Bagley, M. **2022**, *On the Co-Evolution of the AGN and Star-Forming Galaxy Ultraviolet Luminosity Functions at $3 < z < 9$* , *Astrophysical Journal*, in press
5. Larson, R., Finkelstein, S., Hutchison, T. et al. **2022**, *Searching for Islands of Reionization: A Potential Ionized Bubble Powered by a Spectroscopic Overdensity at $z = 8.7$* , *Astrophysical Journal*, 930, 104
6. Finkelstein, S. L. et al. **2022**, *A Census of the Bright $z = 8.5-11$ Universe with the Hubble and Spitzer Space Telescopes*, *Astrophysical Journal*, 928, 52
7. Finkelstein, S. L. et al. **2019**, *Conditions for Reionizing the Universe with A Low Ionizing Photon Escape Fraction*, *Astrophysical Journal*, 879, 36
8. Livermore, R., Finkelstein, S., & Lotz, J. **2017**, *Directly Observing the Galaxies Likely Responsible for Reionization*, *Astrophysical Journal*, 835 113

MENTORSHIP
EXPERIENCE

- 2021–Present: Advisor of graduate student Alexa Morales, who is working on chemical enrichment in the early universe.
- 2020–Present: Advisor of graduate student Oscar Chavez Ortiz, who is studying Lyman alpha emission and reionization.
- 2020–Present: Advisor of graduate student Katie Chworowsky, who is working on quiescent galaxies at high redshift.
- 2020–Present: Advisor of postdoc Gene Leung, who is leading my groups work on HETDEX and SHELA.
- 2019–2022: Advisor of graduate student Adam McCarron, who is studying the physical properties of high-redshift galaxies identified by HETDEX.
- 2016–Present: Advisor of graduate student Rebecca Larson, who is working on two *HST* grism spectroscopic surveys I am involved in, searching for Ly α emission lines in the epoch of reionization.
- 2018–Present: Advisor of postdoc Micaela Bagley, who is leading my groups preparation for the CEERS *JWST* program.
- 2013 – 2019: Advisor of graduate student Matthew Stevans, who studied the growth of galaxy stellar masses using a 24 deg² *K*-band imaging survey in the SHELA field. He went on to the data science sector
- 2013 – 2019: Advisor of graduate student Intae Jung, who used using high-resolution *Hubble* imaging to study resolved stellar populations at high redshift, and performed spectroscopic studies of Ly α as a probe of reionization. He went on to a prize NASA Postdoctoral Program fellow at Goddard Space Flight Center.
- 2013 – 2018 : Co-advisor of graduate student Jason Jaacks, who used simulations to study the tracking of galaxy progenitors and descendants, as well as to make predictions for a *JWST* Deep Field. He went on to a job in the data science sector.
- 2012–2016: Advisor of graduate student Mimi Song, who led a project on near-infrared spectroscopic observations of LAEs discovered in the HETDEX pilot survey, and stellar mass functions of very high-redshift galaxies. She went on to a prize NASA Postdoctoral Program fellow at Goddard Space Flight Center.
- 2014 – 2018: Advisor of postdoc Isak Wold, who will work on the HETDEX project. He is currently building our photometric catalog in the SHELA field, and will ultimately

study the evolution of the Ly α luminosity function. He went on to a prize NASA Postdoctoral Program fellow at Goddard Space Flight Center.

- 2013 – 2017: Advisor of postdoc Rachael Livermore, who led my group’s work on the Hubble Frontier Fields. Rachael went on to an ARC prize postdoctoral fellow at Melbourne University.
- I have worked with 15 undergraduate students while at UT Austin.

AWARDED
GRANTS AND
FELLOWSHIPS

Summary: Total of \$6.2M awarded as PI since starting as faculty in 2012. Recent highlights are:

2022 UT Austin Spark Grant, \$200,000 (Finkelstein PI)

- *Solving Reionization with ERMOS on the Giant Magellan Telescope*

JWST Cycle 1 General Observer Grant, \$309,297 (Finkelstein Co-PI),

- *NGDEEP: Next Generation Deep Extragalactic Exploratory Public Survey*

2021 NASA ADAP Grant, \$495,418 (Finkelstein PI; C. Casey Co-PI)

- *Leveraging Spitzer and VIRUS to Investigate Reionization and the Growth of Massive Cosmic Structures*

JWST Cycle 1 Early Release Science Grant, \$1.3M (Finkelstein PI, Individual grant \$430,470)

- *Cosmic Evolution Early Release Science Survey*

2020 NSF AAG Grant, \$229,660 (Finkelstein PI)

- *The Onset of Star-Formation Quenching in Massive Galaxies in the Early Universe*

2019 NSF AAG Grant, \$459,079 (Finkelstein PI)

- *Leveraging the Hobby Eberly Telescope Dark Energy Experiment to Understand Ly α Emission, Galaxy Evolution, and Reionization*

RECENT INVITED
TALKS

Hebrew University of Jerusalem, Seminar (remote), November 2022

Santa Cruz Galaxy Formation Workshop, Santa Cruz, CA, August 2022

EAS Annual Meeting, June 2022

Flatiron Institute CCA, Seminar, May 2022

UC Riverside, Colloquium, April 2022

Colby College, Colloquium, Sept 2021

UC Santa Barbara, Colloquium, Dec 2020

NASA Goddard Space Flight Center, Colloquium, Oct 2020

SELECTED
PROFESSIONAL
EXPERIENCE

Member, Executive Committee, NASA Cosmic Origins Analysis Group (2019–2022)

James Webb Space Telescope Review Panel Member, Cycle 1

Chair, HETDEX Galaxies and AGN Science Working Group (2019–2021)

Member, Hubble Space Telescope Users Committee (2019–2022)

Member, NASA IRTF Keck Users Committee (2018–2021)

PI, JWST ERS Program (2017–Present)

SELECTED
TEACHING
EXPERIENCE

INSTRUCTOR, The University of Texas at Austin 2013 – Present

- Instructor of AST301, a 200-student astronomy survey course.
- Instructor of AST358, an upper-level undergraduate course on galaxies.
- Instructor of AST376, an under/graduate experiential telescope observing course.
- Instructor of AST386, a graduate course on galaxy evolution at high redshift.

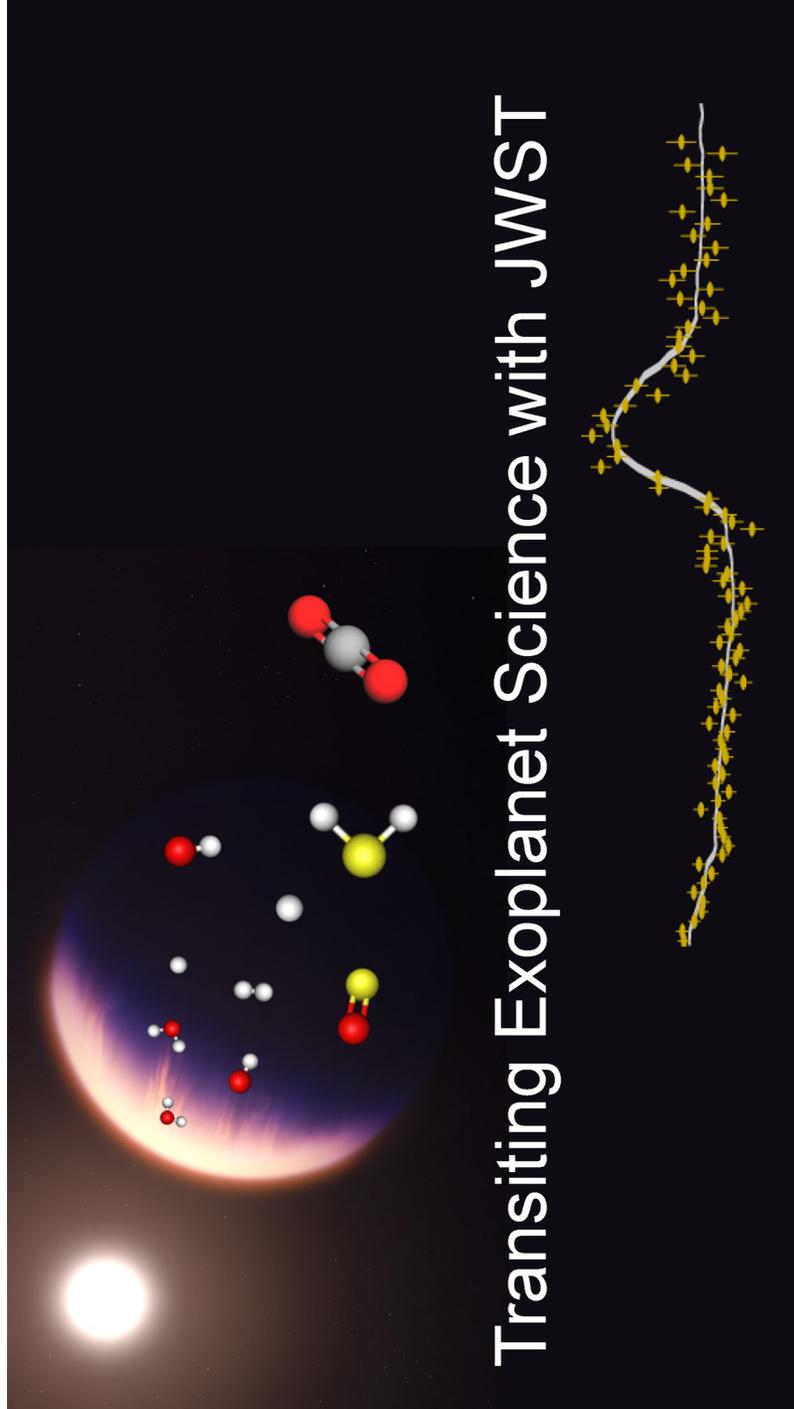
Chairman BEYER. Thank you, Dr. Finkelstein. So already they're finding galaxies older than your daughter. That's amazing. It's very cool, though. I hope you have other children.

Dr. Batalha, the floor is yours.

**TESTIMONY OF DR. NATALIE BATALHA,
PROFESSOR OF ASTRONOMY AND ASTROPHYSICS
AND DIRECTOR OF ASTROBIOLOGY,
UNIVERSITY OF CALIFORNIA, SANTA CRUZ**

Dr. BATALHA. Thank you. Good morning, Chairman Beyer, Ranking Member Babin, and Members of the Subcommittee. It is such a joy to be here to share the wonder of scientific discovery and the success of this new space telescope. Webb is performing at or even better than our expectations and has already achieved groundbreaking discoveries in our field. This is truly the beginning of a new era of exoplanet exploration, the hallmark of which will be the study of exoplanet atmospheres enabled by JWST.

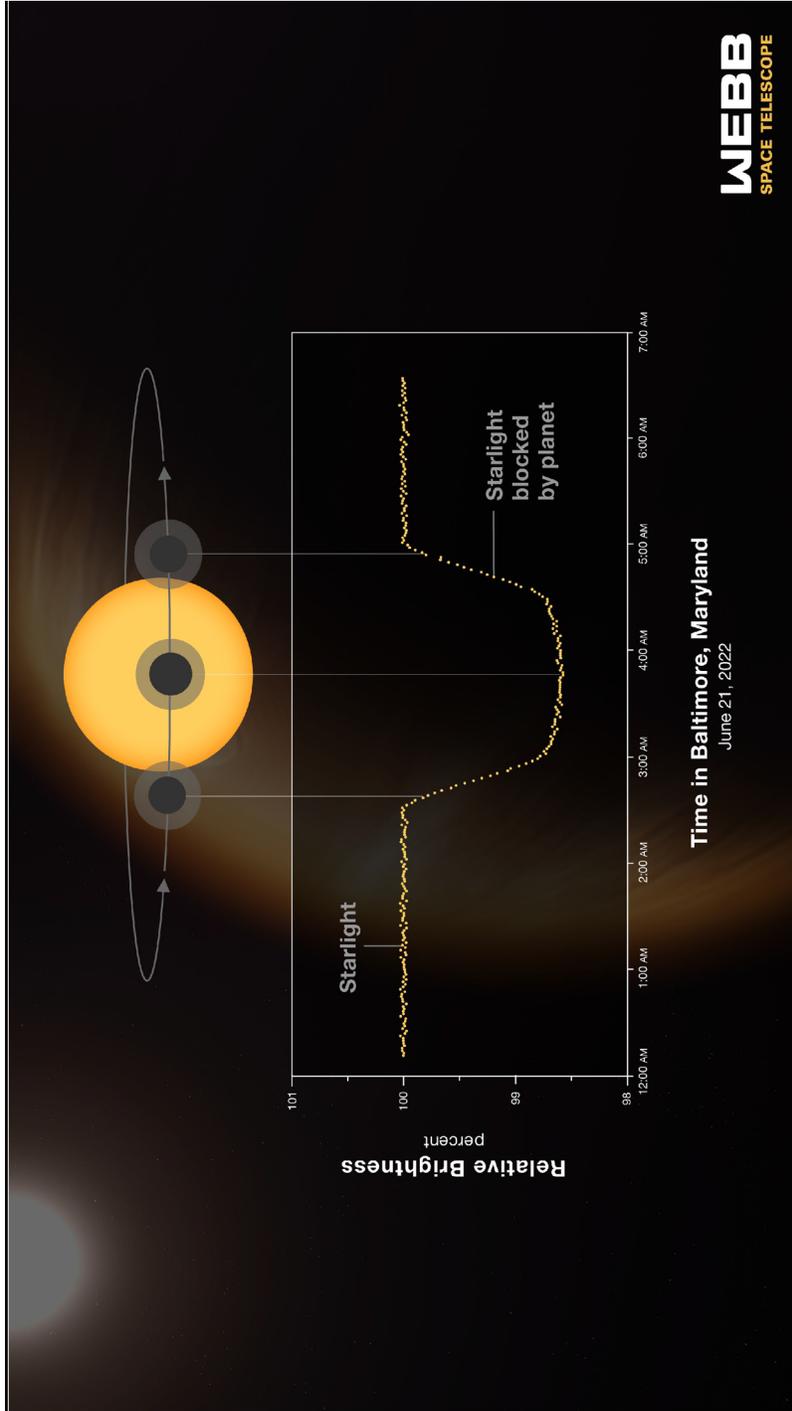
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Transiting Exoplanet Science with JWST

Dr. BATALHA. To date, over 5,000 planets have—orbiting other stars in the galaxy have been identified. Most were discovered using the transit method, which involves the precise monitoring of brightnesses of stars to search for the dimming of light that occurs if a planet eclipses or transits in front of its star. The bottom panel here shows how the brightness changes with time. This is the method employed by NASA space missions like Kepler and TESS. Those missions taught us that planets are common in the galaxy. On average, every sunlike star has at least one planet, and we estimate that more than 10 billion are potentially habitable in our galaxy alone.

[Slide.]



Dr. BATALHA. But these missions also taught us that the diversity of planets in the galaxy far exceeds the diversity of planets in our solar system. We need to better understand the physical processes that give rise to that diversity and their impact on planetary habitability if we are to find evidence of living worlds in the future. And that's where JWST enters the scene.

Like Kepler and TESS, JWST observes transits, but Kepler and TESS observe them in white light, colors scrambled together. JWST can measure the dimming of light in hundreds of infrared colors simultaneously. Why do we care? Well, when exoplanets eclipse their host star, some of the starlight passes through the atmosphere on its way to our telescope. And the atmosphere imprints a chemical fingerprint on the light because each atomic and molecular species absorbs a unique pattern of colors. The net effect is that the planet blocks more or less light in each color depending on which molecules are present.

These in the next slide are measured transits from a planet named WASP-39b, observed as part of our Early Release Science program and shown here stacked vertically in 25 different infrared colors. The host star is similar to our sun. Its transiting exoplanet is a little bit larger than Jupiter but about the mass of Saturn, and it orbits its star 8 times closer than Mercury is to our Sun.

[Slide.]

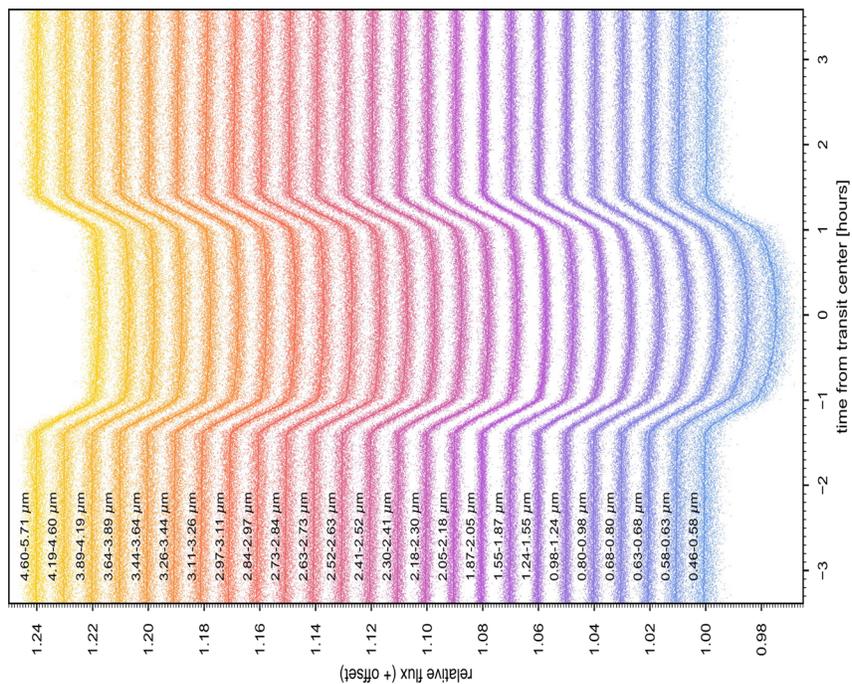


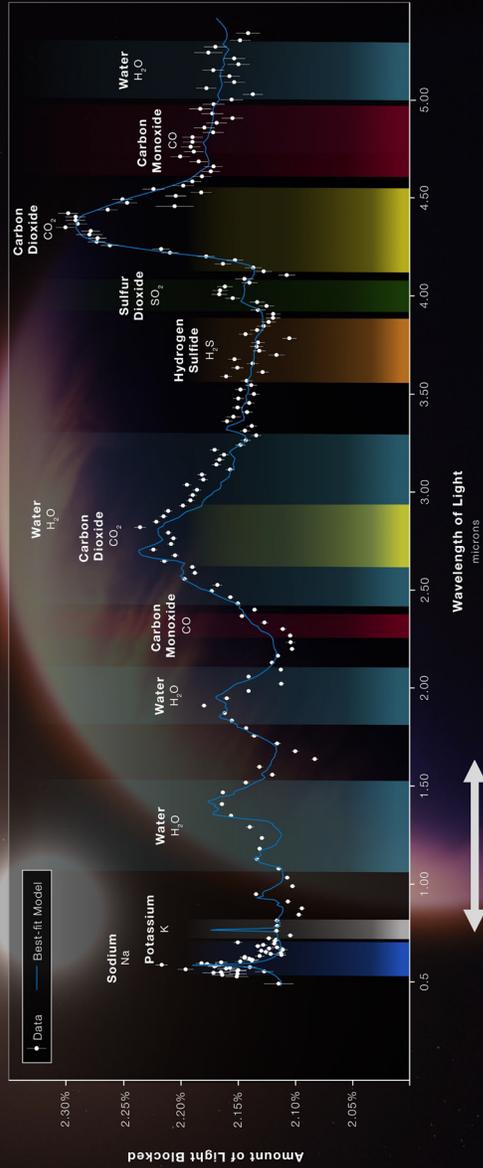
Image Credit: Z. Rustamkulov, JHU

Dr. BATALHA. Now, these transits may all look the same, but there are subtle differences that JWST can measure. We can calculate the amount of starlight blocked by the planet in each observed color. And we plot that versus wavelength, as shown by the white points in the next graphic. This is the graphical representation of a planetary spectrum, the amount of light blocked on the Y axis versus wavelength or color on the X axis. And it might not have the aesthetic appeal as Maisie's Galaxy or the Stephan's Quintet but I would argue that it is just as profound regarding the mysteries it reveals.

[Slide.]

HOT GAS GIANT EXOPLANET WASP-39 b ATMOSPHERE COMPOSITION

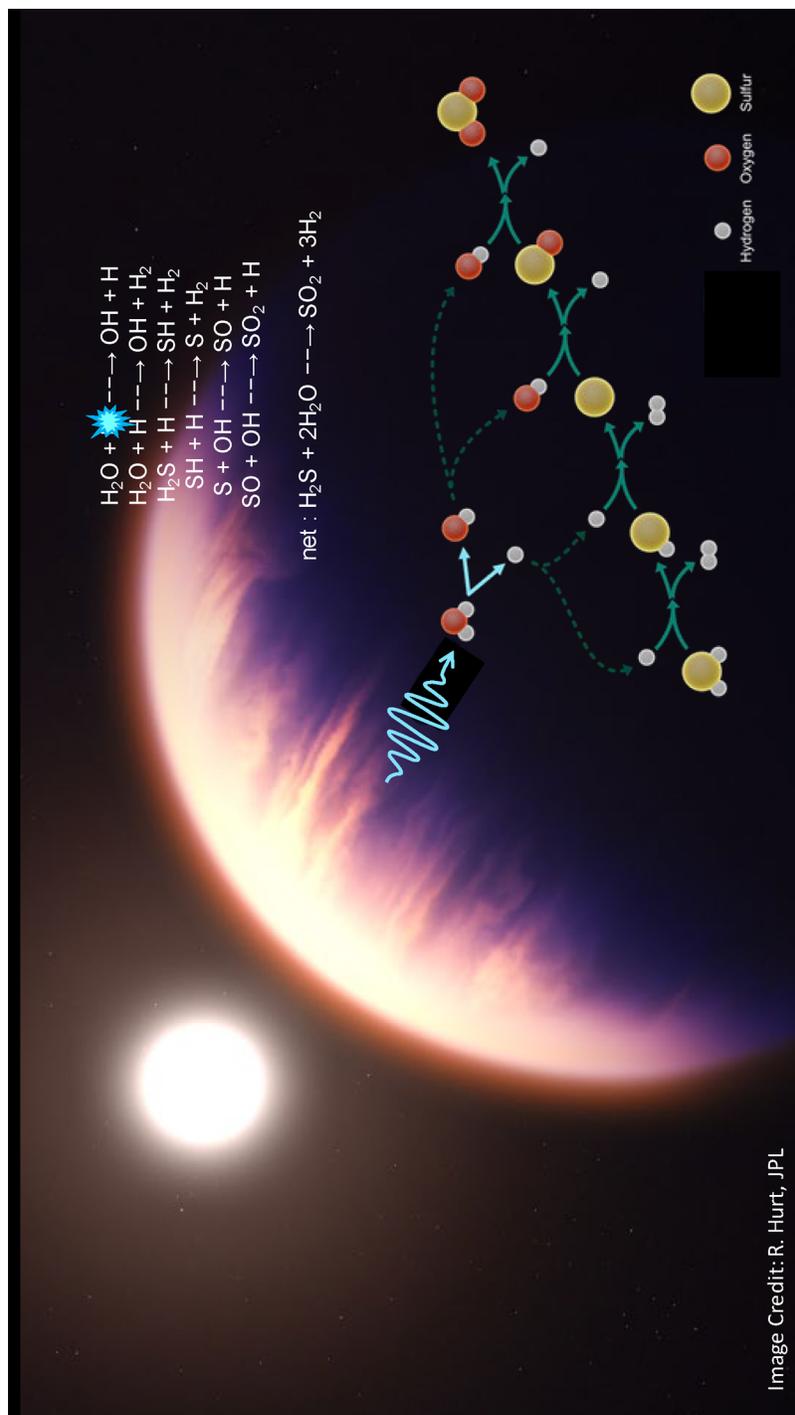
NIRSpec PRISM | Bright Object Time-Series Spectroscopy



WEBB
SPACE TELESCOPE

Dr. BATALHA. And from this spectrum we see a panoply of atomic and molecular species that we could not see before. The tallest bump or hill in this spectrum is due to the absorption of carbon dioxide molecules. We also see evidence of sodium, potassium, water, carbon monoxide, sulfur dioxide. The spectrum tells us so much more. It tells us there are patchy clouds. We learned that the atmosphere is enriched by heavy elements, suggesting that the planet was bombarded by planetesimals early in its life. And we even see evidence of photochemistry.

[Slide.]



Dr. BATALHA. The presence of sulfur dioxide cannot be explained without invoking starlight as a catalyst for the chemical reactions. High-energy photons from the star rain down on top of the atmosphere and break apart water molecules, triggering a cascade of chemical reactions leading to the production of sulfur dioxide. Photochemistry is fundamental for life on Earth to thrive. This is the first evidence of photochemistry of a molecule that requires photochemistry for its existence.

Over 70 transiting exoplanets will be observed by JWST just in cycle 1, hundreds over its lifetime. We now have a new lens on exoplanet diversity. From these data, we will gain insights into planet formation and evolution processes, and we will lay the groundwork for identifying habitable environments and living worlds in the future.

Thank you so much for your attention, and I'm happy to answer any questions that you might have.

[The prepared statement of Dr. Batalha follows:]

Early Science Results for Transiting Exoplanets Observed by JWST

Natalie M. Batalha, Professor of Astronomy & Astrophysics, UC Santa Cruz

JWST is ushering in a new epoch of exoplanet science that will rewrite textbooks. Progress will stem largely from the characterization of exoplanet atmospheres enabled by JWST technology. Herein, I will focus on the method of transmission spectroscopy. I note that coronagraphic observations from JWST will also provide significant contributions to our understanding of planet formation and evolution.

Background

To date, thousands of planets orbiting other stars in the Galaxy have been identified. Most were discovered using the Transit Method which involves precise monitoring of the brightness of stars to search for the dimming of light that occurs when a planet eclipses (or “transits” in front of) its star, blotting out a fraction of the light as seen from the telescope’s vantage point (Figure 1). The dimming repeats like clockwork, once every orbit. The amount of dimming tells us the radius of the star and the time between dimming events tells us the orbital period. Johannes Kepler taught us in the 1600’s that the orbital period is related to the distance between the star and the planet which is how we know if a planet is orbiting in the star’s Habitable Zone.

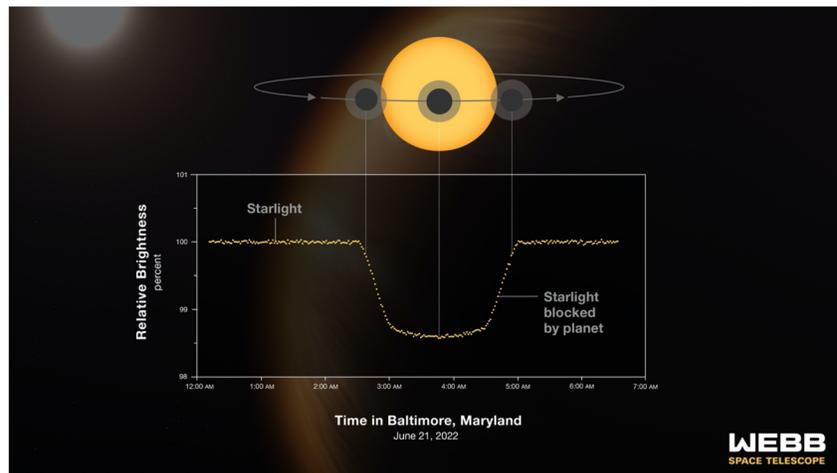


Figure 1. The Transit Method for detecting exoplanets is based on precise measurements of stellar brightness. Planets with edge-on orbits relative to our line of sight eclipse their star producing a dimming of the starlight that repeats once each orbit. During the planet’s transit across the face of the star, some light will pass through the planet’s atmosphere (here exaggerated by the gray annulus). Atoms and molecules in the atmosphere will imprint a chemical fingerprint on the light. (Credit: L. Hustak, STScI)

This is the method employed by NASA space missions like Kepler (2009 – 2017) and TESS (2018 – present). Kepler taught us that planets are common in the Galaxy. On average, every

sun-like star has at least one planet and more than 10 billion planets are terrestrial-sized and orbit in the Habitable Zone where liquid water could pool on the surface under the right conditions.

Kepler also taught us that the diversity of planets in the Galaxy far exceeds the diversity of planets in our Solar System. We know of worlds with lava oceans, two rising suns, lock-step orbits, and even comet-like tails. We also know of planets intermediate in size to the terrestrials and gas giants in our own Solar System. Dubbed “super-earths” or “mini-neptunes” (occasionally even “water worlds”), these are the most common types of planets known to us and yet we have no equal in our solar system. It behooves us to understand the physical processes that lead to such diversity in the Galaxy and how those processes impact planetary habitability.

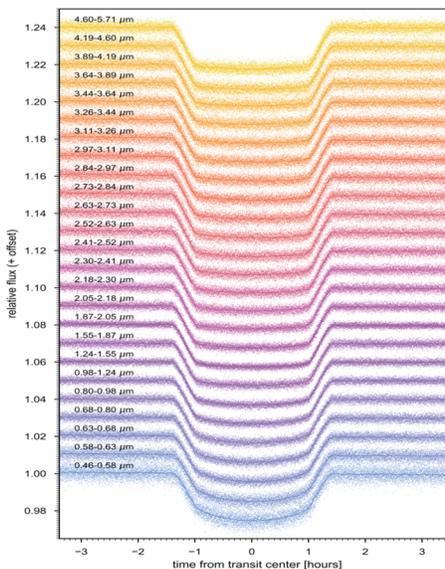
The study of demographics has been limited to the examination of bulk planet properties – properties like the total mass and radius gleaned from detection surveys. Applying the method of “transmission spectroscopy” to hundreds of exoplanets will yield a new lens on planetary diversity. JWST is uniquely suited to this task for nearby exoplanets (like those identified by NASA’s TESS Mission). From JWST data collected over the next decade, we will gain a much deeper understanding of how planets form and evolve, and we will be better equipped to identify the most likely abodes of life with future missions.

Transmission Spectroscopy

Transiting planets are especially valuable for scientific studies. Kepler and TESS observe transits in, effectively, “white light” whereby many colors are combined together. JWST is observing exoplanet transits too. But thanks to ultra-stable spectrometers, JWST observes transits in hundreds of infrared colors simultaneously (Figure 2).

Figure 2. JWST observes planetary transits in hundreds of infrared colors (wavelengths) simultaneously. Shown here are 25 transits, stacked vertically, each representing a different wavelength. The Carbon Dioxide (CO₂) molecule, for example, absorbs light preferentially at 4.3 μm (second transit from the top). A transiting planet with CO₂ molecules in its atmosphere will block out more starlight at 4.3 μm than at other colors. (Image Credit: Zafar Rustamkulov, JHU)

When planets eclipse their host star, some of the starlight passes through the planet’s thin atmosphere on its way to Earth’s telescopes. The atmosphere imprints a chemical fingerprint on the light since atoms and molecules absorb starlight at distinct colors. In effect, the planet blocks a slightly different fraction of light depending on the color and depending on which molecules



are present in the atmosphere. The spectrometers aboard JWST allow us to measure the amount of light blocked at each color thereby building up an atmospheric “spectrum.”

This method of studying planetary atmospheres is called “transmission spectroscopy,” and it has been employed by the Hubble Space Telescope and large ground-based telescopes on a small number of (mostly giant) planets. JWST is extending the capability and increasing sensitivity by collecting more photons in a stable environment across a broader range of infrared wavelengths where a variety of molecules generate strong absorption features.

Pre-launch simulations predicted that JWST data will enable atomic and molecular abundance measurements, atmospheric temperature and pressure determinations, an understanding of heavy element enrichment in planetary systems, investigation of cloud dynamics and haze production, and studies of photoevaporation and photochemistry for hundreds of planets down to super-earth and sub-neptune sizes. Pre-launch simulations also predicted that JWST will be able to detect the presence of atmospheres on terrestrial-size planets orbiting M-type stars, including a number of planets that orbit in the Habitable Zone (e.g. those orbiting TRAPPIST-1).

Early Science with JWST

In 2016, the exoplanet science community started an open-science initiative to discuss strategies for the first exoplanet observations with JWST. This effort resulted in Early Release Science Program ERS-1366. It has grown to include over 300 scientists working collaboratively. The program aims to test all of the JWST observing modes capable of performing transmission spectroscopy by observing three giant planets in short-period orbits (i.e. “hot jupiters”): WASP-39b, WASP-18b, and WASP-43b. Each planet had previously been observed by the Hubble Space Telescope, and each showed some evidence of atmospheric absorption. The goal of the program is to provide representative data to the community together with analysis tools and best practices.

Herein, I report on early science results for WASP-39b. WASP-39 is a sun-like star approximately 700 light-years away toward the constellation Virgo. The transiting exoplanet is 30% larger than Jupiter with a mass comparable to that of Saturn. It orbits the star once every four days at a distance that’s 8 times closer than Mercury is to our Sun. Four transits of the exoplanet have been observed, each with a different instrument mode.

A transmission spectrum is constructed by measuring the amount of light blocked during eclipse at each infrared color. Figure 3 shows the spectrum from NIRSpec PRISM. The most prominent feature near 4.3 microns is due to the absorption of starlight by Carbon Dioxide (CO₂) molecules – the first robust detection of CO₂ in an exoplanet atmosphere [1]. CO₂ is present in all solar system planets that have atmospheres. It’s also the primary background gas that we expect to detect in terrestrial-size exoplanets. Moreover, it’s a very sensitive tracer of the overall heavy element enrichment in a planetary atmosphere.

Other science discoveries gleaned from the transmission spectra of WASP-39 b include:

- The identification of multiple chemical species in the atmosphere, including sodium (Na), potassium (K), four independent water (H₂O) features, carbon dioxide (CO₂), and carbon monoxide (CO).
- Evidence of clouds. The data suggest that the cloud deck is not one uniform blanket. To fit the spectral features, higher complexity in the cloud deck is required as seen on solar system giant planets.
- The first detection of sulfur dioxide (SO₂), a molecule produced from chemical reactions triggered by high-energy light from the planet's parent star. On Earth, the protective ozone layer in the upper atmosphere is created in a similar way (Figure 4).

More than a dozen scientific studies using these data are in progress. We will be able to quantify chemical abundances, study disequilibrium processes, vertical mixing and photochemistry, search for additional molecules, and constrain the temperature and pressure structure of the atmosphere.

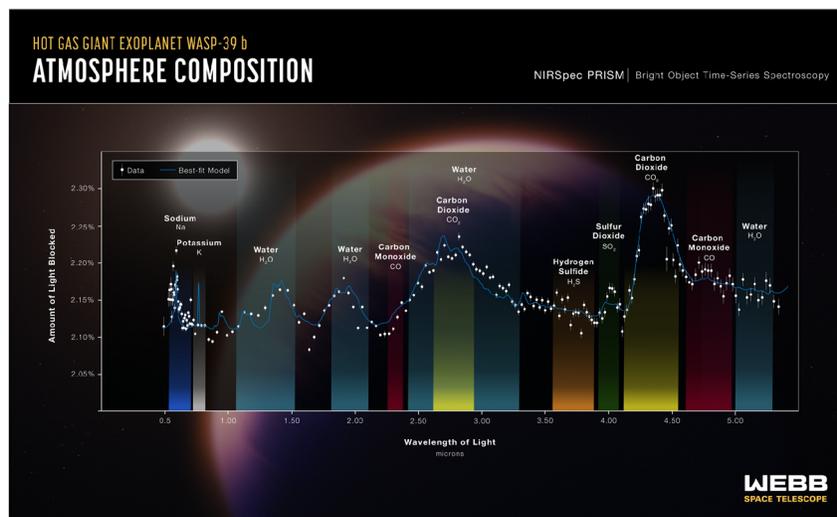


Figure 3. The atmospheric spectrum of the exoplanet WASP-39b from JWST's NIRSpec PRISM instrument is generated by measuring the amount of starlight blocked by the planet (y-axis) at each wavelength (x-axis). The measurements are shown here as white circles. The shaded regions in the background mark wavelengths impacted by a variety of atoms and molecules. The rise and fall of the data points align with these regions. JWST data reveal the presence of Sodium, Potassium, Water, Carbon Dioxide, Sulfur Dioxide, and Carbon Monoxide in the atmosphere of WASP-39b. (Image Credit: STScI)

Instrument Performance:

The WASP-39 b observations allow us to independently investigate the performance of the JWST instruments. The open-science nature of the Transiting Exoplanet Early Release Science Team allows us to apply independent analysis pipelines to the data for robust intercomparison of

performance benchmarks. Observing the same exoplanet with multiple instruments at overlapping wavelengths allows us to perform consistency checks. We find:

- The telescope and its instruments are performing at or better than pre-launch expectations. This finding is in agreement with the commissioning test on the exoplanet HAT-P-14 b. [2]
- JWST yields unprecedented precision and stability in spectroscopic timeseries data.
- There are no obvious and/or unexpected systematic errors that limit the interpretation of the data. We have not yet identified a noise floor for JWST timeseries data. As we average more data together, the precision continues to improve.
- Data from different instruments are consistent in the overlap regions.

These findings have profound implications. For example, several pre-launch studies were conducted to predict JWST capabilities for transiting exoplanet science. Among those were studies of the seven terrestrial-size planets orbiting the nearby M-type star, TRAPPIST-1. Three of its planets orbit in the Habitable Zone. Those studies predicted that JWST would be capable of detecting the presence of an atmosphere should one exist and identify the dominant background gas assuming enough transits are observed. Pre-launch predictions were based on models of how we thought the telescope would perform. Now we have ground-truth observations that confirm the models and confirm that we can achieve our science goals with JWST even for these challenging exoplanets.

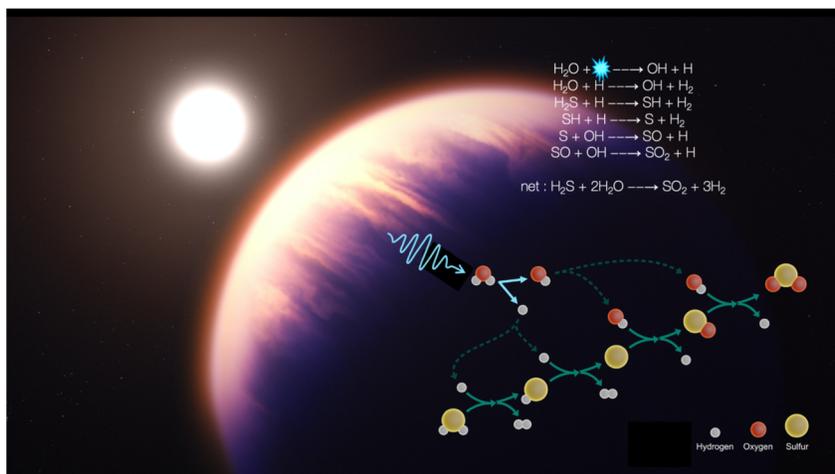


Figure 4. Detailed modeling reveals that SO_2 in the WASP-39b atmosphere is produced by photochemistry – chemical reactions catalyzed by high-energy starlight (light blue symbols). Photochemistry is fundamental for life on Earth to thrive, from the production of ozone in the upper atmosphere to photosynthesis in plants and algae to the production of Vitamin D in our skin. (Credit: R. Hurt, JPL)

Looking Forward:

With its unprecedented precision, stability, and infrared wavelength coverage, JWST will catalyze a new epoch of exoplanet exploration characterized by atmospheric studies. Over 70 transiting exoplanets will be observed by JWST in Cycle 1 alone. Over its lifetime, hundreds could be studied providing a new lens on exoplanet diversity and a new survey data for demographic studies. From these data, we gain deep insights into planet formation and evolution processes. We will learn about the nature of the mysterious but common super-earths/mini-neptunes. We will know if terrestrial-size planets orbiting M dwarfs have atmospheres, and we will lay the groundwork for identifying habitable environments and living worlds in the future.

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Current position:

2018- Professor of Astronomy & Director of Astrobiology, University of California, Santa Cruz

Previous positions:

2012-2018 Research Astrophysicist, NASA Ames Research Center, Moffett Field, California
 2008-2012 Associate Professor of Physics and Astronomy, San Jose State University, California
 2002-2008 Assistant Professor of Physics and Astronomy, San Jose State University, California
 2000-2002 National Research Council Post-doctoral Fellow, NASA Ames Research Center
 1998-2000 Postdoctoral Fellow, Observatório Nacional, Rio de Janeiro, Brazil

Education and degrees:

1997 PhD, Astrophysics, University of California, Santa Cruz, CA
 1992 MSc, Astrophysics, Observatório Nacional, Rio de Janeiro, Brazil
 1989 B.S., Physics and Astronomy, University of California, Berkeley, CA

Synergistic Activities:**NASA's Kepler Mission**

2016-2017: Kepler Project Scientist, Mission Closeout Phase, NASA Ames Research Center
 Duties include advocating for decisions that ensure the mission meets its science goals, advising the project manager on science matters, participating in scientific analyses, reviewing technical documents, interfacing with NASA headquarters and the Exoplanet Program Office, communicating science results to the public and the scientific community.
 2012- 2016: Kepler Mission Scientist, Extended Mission Phase, NASA Ames Research Center
 Lead scientist for exoplanet occurrence rates; responsible for ensuring that the Kepler mission meets its science goals; interface between external science community and Kepler project office; member of Kepler's Science Leadership team; science liaison to Kepler Public Affairs;.
 2010-2012: Kepler Science Team Lead, Prime Mission Phase, NASA Ames Research Center
 Responsible for coordinating a 50+ member science team, devising strategies to achieve the science goals of the mission, organizing working groups to accomplish scientific goals, allocating resources, constructing budgets, interfacing with Kepler Education and Public Outreach team, working closely with NASA Public Affairs, and serving as chairperson of the Science Council.

NASA's Nexus for Exoplanet System Science

2014-2018: co-Lead for NASA's Nexus for Exoplanet Systems Science (NExSS)
 NExSS is a cross divisional (Astrophysics, Planetary Sciences & Astrobiology, Earth Sciences, Heliophysics) research coordination network (17 teams, ~250 scientists) working to advance the field of planetary habitability and the search for life on exoplanets.

James Webb Space Telescope

2017 - 2021: James Webb Space Telescope Users Committee (JSTUC)
 Committee serves as a conduit of information between STScI and the science community
 2015-2017: James Webb Space Telescope Advisory Committee (JSTAC)
 Advises the STScI on the Institute's readiness to support science operations with JWST, the implementation of NASA's science policies, and matters related to the general observer program.

Selected Recent Grants & Contracts:

NASA Interdisciplinary Consortia for Astrobiology Research (ICAR), PI
Follow the Volatiles, 2021 - 2026
 Multi-Institutional, UCSC lead, \$5M

NASA Keck Key Strategic Mission Support FY20 - FY22, co-PI
The TESS-Keck Survey, FY20 - FY22
 Space Telescope Science Institute, Early Release Science Program for JWST, PI
 78.1 hours awarded, ~\$400k (FY21-22) + ~\$500k (FY22-23)
 NASA Keck Key Strategic Mission Support 2018 A&B, co-PI
 A Spectroscopic Catalog of Kepler Planets Orbiting Cool Stars: Probing the Physics of
 Photo-Evaporation, 10 nights awarded
 NASA's Nexus for Exoplanet System Science, PI, 2015-2020
 Management contract, NASA Astrobiology, ~\$100k per year

Individual Awards & Honors:

2020 Legacy Fellow of the American Astronomical Society
 2019 Elected to American Academy of Arts & Sciences
 2018 Honorary Doctorate, University of Uppsala, Sweden
 2018 Alumni Achievement Award, UCSC
 2017 Smithsonian Ingenuity Award in Physical Sciences
 For scientific leadership of NASA's Kepler Mission.
 2017 Time Magazine's List of the 100 Most Influential People of the World for 2017
 2017 Lecar Prize, Harvard-Smithsonian Center for Astrophysics
 For exceptional contributions to the study of extrasolar planets
 2011 NASA Exceptional Public Service Medal
 For outstanding leadership of the Kepler Science Team

Selected Recent Publications:

TESS-Keck Survey. V. Twin Sub-Neptunes Transiting the Nearby G Star HD 63935
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*Characteristics of Planetary Candidates Observed by Kepler. II. Analysis of the First Four Months of
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Chairman BEYER. Thank you, Dr. Batalha, and thank all of you for fascinating testimony.

And Dr. Clampin, I believe one of the images you showed us was the first time the public has seen that.

Dr. BATALHA. Yes.

Dr. CLAMPIN. That's correct, yes. It was unveiled this morning.

Chairman BEYER. Thank you for sharing that.

Dr. CLAMPIN. You got to see it first.

Chairman BEYER. Great. By the way, if there are Members who wish to submit additional opening statements, your statements will be added to the record at this point.

[The prepared statement of Chairwoman Johnson follows:]

Good morning.

Thank you, Chairman Beyer, for holding this hearing on such an exciting topic, and welcome to our distinguished witnesses.

This Committee has held multiple hearings throughout the development of the James Webb Space Telescope, or JWST. But today we are finally here to discuss the science that is starting to flow from this amazing observatory.

I want to express my deep appreciation to the thousands of scientists, engineers, and stakeholders who made JWST possible, including those at NASA, in industry, at our universities, and our international partners. Without their work, we would not be here today.

From the release of the first JWST images this past summer, we've gotten breathtaking glimpses of some of the first galaxies in the universe, new and dying stars, and the rings of Neptune.

JWST has even given us visual indications of the DART asteroid impact event.

I look forward to hearing from our esteemed witnesses about JWST's science results so far on the formation of the first stars and galaxies and their evolution over time. I also look forward to hearing more about how JWST's instruments are being leveraged to characterize planets in our own Solar System as well as distant exoplanets.

NASA's Great Observatories have not only expanded our frontiers into the universe, but they have also inspired students and people across the world.

That's a topic about which I'm equally passionate because inspiration is a catalyst for innovation. Our future lies in the next generation of Americans, and I hope JWST will inspire them to continue our leadership and global collaboration in space science and exploration.

I want to thank our witnesses again for taking the time to share what they have learned so far from JWST, and for pointing us to the exciting science that lies ahead.

Finally, before I close, I would like to congratulate NASA and its contractor team on the successful launch of the Space Launch System early this morning. It is a stunning achievement, and I am looking forward to following the progress of the Artemis 1 mission to the moon over the coming days.

Thank you, and I yield back.

Chairman BEYER. Let me begin our first round of questioning. Dr. Batalha, you talked about the photochemistry being necessary for life on Earth, and so we've made the leap of faith that photochemistry is necessary for life in general. Can we really say that? Do—is it not possible to imagine non-water-based life on other planets?

Dr. BATALHA. We only have one example of life, so we're going on what we know. But the rise of complexity in the universe takes a certain form. I mean, the very elements that are required for life are the very elements that the universe creates in most abundance. It's also the case that life harnesses energy to do work, to maintain itself, to evolve to grow, and so it needs an energy source. So the way that the host star interacts with the planet is a synergy. It's a symbiosis that is probably very common to the rise of complexity and to the rise of life.

Could it be—is it certain that that’s the only pathway for creating life? No. But it is true that whatever pathway that is, it’s going to require energy. It’s going to harness energy to do work to maintain itself. That’s a fundamental law of physics that we can’t escape.

Chairman BEYER. Great. Great. Thank you very much. That’s the best explanation yet that I’ve heard.

Dr. Finkelstein, those stars you showed us that are so old, bright, don’t have the dense materials, is it safe to assume they’re long since dead?

Dr. FINKELSTEIN. Yes, absolutely. That’s correct. The most massive stars burn through their fuel so quickly, they live only a few million years at most. So we sort of caught them at a glimpse in time when they were shining very brightly.

Chairman BEYER. On the whole issue of inflation—matter, anti-matter coming into being—this rapid expansion, are we understanding that? And are there any insights on inflation that have come from JWST so far?

Dr. FINKELSTEIN. Not yet at this point. Inflation is happening at a very, very, very early epoch, the—essentially, the instant right after the Big Bang. One of the things we can learn from studying the galaxies that come a while later, a few 100 million years later, is whether the abundance of galaxies, the masses of galaxies are consistent with our idea of what we call a cold dark matter cosmology. So is there anything that we have seen yet to break that idea? And so far, it seems like you can explain what we see with ideas that we’ve had in the past. You don’t need to actually fundamentally change cosmology, but again, we’ve only had a few months with these data, and a small amount of of data has come in, so I would say stay tuned.

Chairman BEYER. Very cool. Thank you.

Dr. Clampin, what is reionization, and why is that important? Microphone, Dr. Clampin.

Dr. CLAMPIN. Sorry. So reionization is when the first stars started to form in the universe and essentially ionize the intergalactic medium or, you know, the medium that was present at that time. So it’s a very important stage because it’s the epoch when the first stars and galaxies started to form and change the nature of the universe.

Chairman BEYER. Cool. Very cool. Dr. Finkelstein, you mentioned dark matter. I know it’s been in a lot of the popular science recently that maybe that dark matter has been hiding inside the many more black holes that are out there than we thought. Is there anything that we’re seeing in JWST that would give credence to that thought?

Dr. FINKELSTEIN. Not so far, but one of the most exciting things to come with the spectroscopy that we’ll be obtaining in the next months to several years is it will give us our first chance to look at the formation of the earliest black holes in the universe. We know that, today, all galaxies have supermassive black holes at their center, but it’s really challenging to grow black holes that large. And so we should, we think, see evidence of them growing in these very early galaxies. And that’s hard to see in the images alone, but you can see it with the spectroscopy.

Chairman BEYER. Dr. Batalha, you're an astrobiology expert. I've heard tell that if you ask a roomful of scientists how many believe that there is other life in the universe, every hand would go up. Is this something that you have to—is that the leap of faith you make before you commit yourself to astrobiology?

Dr. BATALHA. I think that's true. I myself believe that life has to be out there because, I mean, complexity arises in the universe. It should arise everywhere. I think the fundamental question is how frequent is life and is intelligent life common? That's a very different question. If I had to posit a guess, which scientists don't like to do because we'd like to have evidence, but if I had to posit a guess, I would guess that living worlds are common. And by that I mean microbial life. Whether or not it evolves into intelligent life is another question. And I'm not so sure if intelligent life is going to be common or rare, but we know how to find out.

Chairman BEYER. Great, great. Thank you very much. I appreciate all of it.

And let me introduce the Ranking Member of the Committee, Dr. Babin.

Mr. BABIN. Thank you. Very, very, very fascinating information.

Dr. Clampin, JWST was apparently hit by some micrometeorites after deployment. I also noticed this morning that NASA announced a new strategy to minimize future damage to the spacecraft. What impact did those strikes have? Can it be quantified at this point? What—were the impacts greater than planned? Is JWST more susceptible than expected? And is there anything that can be done from an operational standpoint that can mitigate the risk of these micrometeorite impacts? And would those modified operations impact the planned science? I know—and I can repeat this. But if you could answer some of those, I'm very curious to hear—to see what what you all had planned before and what you have planned in the future.

Dr. CLAMPIN. So to date, we've seen I think 14 micrometeorite impacts, and the majority of them are what we call very low energy. We've seen one which has significantly higher energy, and I'll come back to that in a minute. But when we design the telescope, we designed all the science requirements to what we call the end of life, assuming that in that environment there would be micrometeorite strikes. And we have a very detailed model that's provided by the Marshall Space Flight Center for the environment at second Lagrangian Point where the telescope's operating. So we knew that we were going to see micrometeorite strikes and built that expectation into the performance for the end of life so that we will get to the end of 5 years, which is the nominal lifetime, with an operational telescope that was still producing the science requirements.

As I said, you know, we've seen 14. One of them was a little bit of a surprise in that it seemed to happen—it was higher energy than expected based on the model, and we think that that may have actually hit a piece of the mirror, which produced a more significant effect than the rest of them. That said, because the telescope is comprised of 18 individual segments with each of them having 6 degrees of freedom and an additional degree that allows us to change focus, we've been able to compensate for the impact

that that particular micrometeorite had. And so—but we are still returning image quality that's much better than we originally expected from the requirements.

In order to make sure that we are playing it as safe as possible, we are looking at operational changes for the second cycle science where we avoid pointing the telescope in the direction where micrometeorites would have a sort of direct, normal impact on the mirror. And this is really just going to affect when in the year people's science gets done. So you can look at objects, you know, twice a year, and it just depends on how you schedule the science. So we're not expecting any major scientific impacts. And for very special targets that we may need to point into the RAM, we will, you know, make—you know, provide a waiver to do that.

So I think the answer to your question is we expected this, and we're being very conservative and making some operational changes to make sure that we minimize any future impacts.

Mr. BABIN. OK, thank you very much. And a question for all. JWST is arguably the most powerful and advanced space telescope in operation. China, however, is planning to launch a space telescope next year that will co-orbit with their space station in low-Earth orbit. How does this telescope compare to Hubble, JWST, Roman, or other great observatories? And what are the advantages and disadvantages of a co-orbiting observatory in low-Earth orbit?

Dr. CLAMPIN. I can take that one. So I don't know a lot about that particular telescope, but I can say a couple of things. First of all, you always worry about the contamination environment around a space station, which can, you know, result in residue or volatiles getting onto the primary mirror, that it potentially impacts your ability to do science in the far ultraviolet. That said, otherwise I think, you know, potentially the performance is likely to be similar to that of Hubble in the visible, you know, imaging bands—

Mr. BABIN. OK.

Dr. CLAMPIN [continuing]. Given that it's in low-Earth orbit,

Mr. BABIN. Dr. Finkelstein or Dr. Batalha?

Dr. BATALHA. Congressman Babin, I don't really know a lot about the platform, so I can't do—I can't offer in detail—

Mr. BABIN. OK.

Dr. BATALHA [continuing]. Detailed comments about the comparison. Sorry.

Mr. BABIN. Thank you.

Dr. FINKELSTEIN. Same for me.

Mr. BABIN. OK. Thank you, and I'll just yield back. My time's up. Chairman BEYER. Thank you, Dr. Babin.

And we now recognize the gentleman from New Jersey, Mr. Norcross.

Mr. NORCROSS. Thank you, Chairman. And I'd like to thank the witnesses for being here and keeping my curiosity of the world alive. It's why I enjoy so much this Subcommittee.

So not to be a buzzkill on this, but the issue comes to the mechanics. We're seeing where and—the potential of where we're going. Are all the systems, Dr. Clampin, up and operating as expected today?

Dr. CLAMPIN. Yes, JW is operating exactly as we expected it to operate. And as we have said, it's exceeding many of the requirements—science requirements that we built it to.

Mr. NORCROSS. Are there items that are on schedule to be looked at further or newer in the operational life of this that you want to get done now, that because of what might happen will not be as effective in five years?

Dr. CLAMPIN. No, I think we're going to take the approach of—as we have done with Hubble in the past, having a competition every year called the proposal cycle. And a peer review panel will select the very best ideas, and we will basically do those programs with the telescope, making sure that we get the best possible ideas each year done and those science programs completed.

Mr. NORCROSS. OK. So being first, other than to answer those questions, is not a mechanical issue of something that will be done? Great.

Dr. CLAMPIN. No.

Mr. NORCROSS. So what are the potential issues or, as I say, what keeps you up at night on this telescope?

Dr. CLAMPIN. So we built this telescope and tested it extensively on the ground. And most—I'll be honest, most of the issues that kept me up at night were the initial deployments and the whole process of commissioning the telescope and getting it to the point it is today. Right now, I'm very comfortable with the way the telescope's operating, and I think, as you've seen from the science results that have been presented, that we're really very happy with the way it's operating.

You also may be aware that the initial launch was extremely precise and put us into an orbit that allowed us to minimize the expenditure of propellant, so we are anticipating something like a 20-year lifetime based on what we call the consumables, which is the propellant that are needed to, first of all, keep it in its orbit at L-2, and second, just to do what we call desaturate the momentum wheels every few days. So right now, we're very comfortable with the way the telescope's operating.

Mr. NORCROSS. Would you be comfortable saying that you had exceeded all the the expected outcomes that this telescope is going to do?

Dr. CLAMPIN. I would certainly be comfortable. And I'll give you one example. I mean, our image quality, which is defined in terms of what's called a wavefront error, was—when we've got the commissioning done, we were basically at half the wavefront error that we expected to be at. And what that means is sharper images, better sensitivity. And you combine that with the pointing, which came in at 1 milliard second versus the requirement of 7, and you have a telescope that's more sensitive with sharper images than we had anticipated.

Mr. NORCROSS. One of the core obligations we have is oversight. And we quite often hear in government how things don't work. I just want to say thank you for exceeding our expectations, and let's continue on. With that, I yield back.

Chairman BEYER. OK. Thank you, Mr. Norcross, very much.

I'd now like to introduce the Congressman who last night had the most important congressional district in the country, Mr. Posey.

Mr. POSEY. Thank you, Chairman Beyer, for holding yet another exciting Committee meeting, and thank you to the panelists for your fascinating testimony. This has got to be the most enjoyable Committee in Congress.

Dr. Clampin, I represent, as Chairman said, the Space Coast Kennedy Space Center. So James Webb was launched last year from Kourou in French Guiana aboard an Ariane 5 launch vehicle and fantastic launch. I applaud the accomplishment. But just—I'm wondering going forward, are we going to launch any future observations on foreign soil or are we going to use U.S. soil?

Dr. CLAMPIN. So let me start by just congratulating you on a great launch from the Kennedy Space Center last night, and it's really thrilling to see Artemis finally get off the ground and roaring into life. In answer to your question, we live in a very different world now where there are lots of different U.S. commercial launch opportunities, including a number which provide us with new capabilities that we're definitely thinking of as we look at the Astro2020 decadal survey. But just to give you a couple of examples, the Roman Space Telescope will launch on a Falcon Heavy and many of our SMD missions are now launching on U.S. launches. So my expectation is we will take advantage of the new U.S. launch capabilities that have been provided to us.

Mr. POSEY. Thank you very much. Dr. Batalha, I hope I didn't mess it up too badly. Can you walk us through the process of gaining observation time for James Webb, you know, how its organized? Is it any different than other observatories, or do you have any thoughts on how it's working so far?

Dr. BATALHA. Yes, absolutely. It follows the same model that was used by the Hubble Space Telescope and actually many ground-based observatories as well. It's highly competitive, as you can imagine. The scientific community writes proposals, submits them. There are experts who agree to serve on a committee to review those proposals. It's a blind review, so you don't see the person who's leading that team. You don't see their name, and that's meant to mitigate biases that the review committee might have.

I've served on both the Telescope Allocation Committee and on the Executive Committee of that process, and I can say that it's very thoughtful with regards to technical feasibility and the impact of the science and balancing the portfolio of the telescope.

Mr. POSEY. All of you comment on this if you would, how the James Webb will contribute to our understanding of the supermassive black holes compared to what we learned from Hubble.

Dr. FINKELSTEIN. Absolutely, so as I mentioned, you know, we have reason to believe that these black holes are forming and growing in the early universe. And black holes can be tricky to see. They don't emit light themselves, so you have to find black holes that are either interacting gravitationally so you can see motions, which is also very difficult, or that are actively accreting gas. And as that gas spirals into the black hole and the black hole gobbles it up and grows in mass, it gets quite hot, and that light can escape. And that process is very energetic, and so there are unique

signatures that you could see in a spectrum. And so this is, I think, one of the most exciting things I'm looking forward to in the next month is some of those are going to be very obvious signatures, and we'll know right away, yes or no, there are black holes growing in these galaxies.

If we don't see those signatures, that might be even more exciting because you still have to make these big black holes by today. And if our best idea is that they kind of slowly grow throughout the universe is sort of disproven, then there are more exotic scenarios such as maybe the early universe makes modest-sized black holes in what we would call a direct collapse black hole scenario. You can make a black hole out of a pocket of gas that's a million times the mass of the sun, so you're already kind of making baby supermassive black holes early on. And maybe—if that's the case, maybe there are ideas about how we might be able to see those in some of the deepest imaging that's upcoming with JWST. And so no answers yet, but I think in the very near future we'll have either either good answers or good additional questions.

Mr. POSEY. You mentioned the universe being 13.9 billion years old. What was before that?

Dr. FINKELSTEIN. My favorite answer to that is your guess is as good as mine. A more technical answer which I don't like is that the concept of time only exists as long as the universe exists, so there was no before. We can measure very precisely the evolution of the universe as long as the universe has been around. We can measure very precisely the age of 13.82 billion years. Why the universe began, what came before if there is even a concept as before, that we don't know. And it's very hard to test because to do science, we need to make observations to test our theories, and we only have the universe that we live in right now.

Mr. POSEY. And beyond the universe?

Dr. FINKELSTEIN. The universe is infinite as best we can tell, and so there is no beyond the universe.

Mr. POSEY. Thank you, Mr. Chairman. I yield back.

Chairman BEYER. Thank you, Mr. Posey, very much.

Now let me recognize Congress' greatest champion for travel to Mars, the gentleman from Colorado, Mr. Perlmutter.

Mr. PERLMUTTER. Thanks, Mr. Chair. And I want to thank the panel and all your colleagues for your persistence and your perseverance with this project because it had a few ups and downs over the course of its life. And I want to thank this Committee for its patience because the scientific product—products that have come from this, are just remarkable.

So, Dr. Batalha, I want to start with you. How do you choose what exoplanets you're going to study? I mean, there's—you've said there's a whole bunch of them, but you picked 70. And then I'm going to talk to you, Dr. Finkelstein. How do you choose what galaxies you want to look at?

Dr. BATALHA. Great question. There are over 5,000 exoplanets that we know of, but not all of them are bright enough for us to study their atmospheres, even with Webb. So there is a NASA mission called TESS, which is doing an all-sky survey to find transiting exoplanets that are near the solar system. Those are the ones for which we can get really good precision, part-per-million

precision, to see these bumps and wiggles in the spectrum that are telling us about the presence of molecules. So the list gets whittled down. There are still hundreds even after that, many hundreds. And so you look at the kind of science questions that you want to answer.

There is an exoplanet or a star called TRAPPIST-1 that is very close to us that harbors seven exoplanets orbiting it, three of which are in the habitable zone, orbit in the habitable zone. So you can imagine that we are spending a good deal of time observing those planets. That's going to be a high priority target.

Mr. PERLMUTTER. So how do you and your colleagues choose who's going to study what planet? How do you share information—

Dr. BATALHA. Yes.

Mr. PERLMUTTER [continuing]. Among all of this? I mean, how—is it open? Is it closed? Is it, you know, I got planet X, you got planet Y, we don't talk to each other?

Dr. BATALHA. Yes, it's a little of both. For the Early Release Science program back in 2016 I started an open committee. It was open to everybody who wanted to participate. We have over 300 scientists who participated in that process in order to create a truly grassroots strategic plan for what the very first exoplanets we would observe should be. So that was an open process. The data is nonproprietary. Anybody who wants to participate can. It's truly open science. And that's been a very valuable exercise for how we do science.

Mr. PERLMUTTER. Great. Dr. Finkelstein?

Dr. FINKELSTEIN. Yes, thank you. So first, I also want to acknowledge the large number of people that made this possible, including the CEERS team, not quite 300. We have about 200 scientists in our team and of course the engineers that made this telescope possible and the people doing the work, which is usually the junior scientists, the graduate students and postdocs.

So how did we decide what galaxies to see? Well, we didn't know these galaxies. We're discovering them. So we're doing what we call blank field astronomy, which was a wild idea first tested out in the mid-1990's with the Hubble Deep Field. The Hubble Deep Field was kind of a bold idea to point at what we thought was an empty place in the sky, spend a couple hundred hours observing, and see what you find. And I think many people thought you would find nothing, and it turns out you see the universe is filled with galaxies. And that's become a very useful strategy. Now we know that there are galaxies pretty much no matter where you look.

So then the next question is, why did we look at this particular place in the sky known as the extended growth strip, and the reason why is that Hubble had looked at it before. And the Hubble data is very, very useful for the JWST data. Hubble has the visible wavelength data that is crucial to combine with our infrared data.

And finally, one key part of our Early Release Science program in particular is we're using multiple instruments with JWST, and we want them all to overlap the same place on the sky. And it turns out with a sort of fate of geometry, this extended growth strip field is kind of a strip in the sky, and JWST can look at that

strip at just the right angle to allow the instruments to overlap. So it's a nice combination of things that allow us to point here.

Mr. PERLMUTTER. Thank you. And, Dr. Clampin, last question. As you built the telescope—and, you know, there were a few hiccups along the way—what would you do differently today if you were going to build another telescope like this?

Dr. CLAMPIN. So I can spend hours talking about this, but I helped chair a NASA study called the Large Mission Study, and I was the person who put together the plans for how we would formulate the next mission differently. So the first and most important one, I think, is you need to focus on schedule from the beginning. You also need to get the technologies to—fully matured before you start actually designing the mission. And I don't just mean, you know, six or seven individual miracles. You have to remember that those miracles have to work together. So the biggest challenge on these very large missions is the system, not the individual technologies. So think about that, and make sure you don't overdo the science requirements and you keep focus on the key science that you want to do, and I think that's the path to success.

Mr. PERLMUTTER. All right. Thank you. I yield back to the Chair. Thank you.

Chairman BEYER. Thank you, Mr. Perlmutter, very much.

I will recognize the gentlelady from California, Ms. Kim.

Ms. KIM. Thank you, Chairman. And I want to thank all of our witnesses for joining us today.

Gosh, I also want to echo my colleagues in congratulating NASA for the launch of Artemis 1 and how exciting it was. I was there the first time when we thought we were launching it. Fourth time is a great charm.

This launch truly marks the new era of space exploration for the United States and its international partners, and I'm looking forward to the future Artemis and NASA eventually landing astronauts on the Moon.

The James Webb Space Telescope was years in the making, as we all know, and it's really exciting to see, you know, how, despite all the, you know, challenges that we faced in the development, we saw last Christmas a wonderful gift that, you know, as we watched the James Webb Space Telescope finally launching ESA's Ariane 5 rocket. And early this year, the world watched as NASA released James Webb's first fully developed image of Cosmic Cliffs in the Carina Nebula, so exciting.

So I want to congratulate NASA, ESA, and CSA, and their many partners for the success of your mission. And while there are many lessons still to be learned from telescopes development, I'm pleased that we're taking this opportunity to examine and celebrate the scientific achievements of the James Webb Space Telescope and to hear more about the telescope's future observations.

And I want to start with Dr. Clampin. I want you to know that much of my key focus on this Committee is STEM (science, technology, engineering, and mathematics) engagement. So can you speak to the STEM engagement opportunities that this JWST has provided NASA with, and can you specifically talk about NASA's K through 12 engagement?

Dr. CLAMPIN. So we have had a very active and vigorous STEM program from the very beginning of JWST. And you can see from the engagement of the public, you know, there's this, you know, iconic image of somebody standing in Times Square taking a picture of a JWST image as it comes up on the display. So we are heavily invested in every stage of STEM education. And the great thing about astronomy and astrophysics is it's a very accessible science for all ages, and so it's really good for bringing in young people into STEM careers and getting them engaged. We also at NASA have a very vigorous, you know, education support program, and I'd be happy to get you more information on that.

Ms. KIM. Great. You know, why much of the mission of JWST is to examine what is beyond our solar system, we were amazed by the clearest image of Jupiter that we've ever taken. So can you describe JWST's observation of Jupiter, what it has taught us and—about our own solar system? Yes.

Dr. CLAMPIN. So the—for me, the observation of Jupiter was amazing because we spent a large amount of time trying to figure out how we would observe something as bright as Jupiter without completely saturating the—all the sensors. In fact—point of fact, it turned out that our calculations had really been, you know, spot on and we were able to take images of Jupiter.

So it's—most of the science that JWST will do in this field is more in the form of long-term monitoring, you know, understanding what's going on in the atmosphere of Jupiter and tracking it over time. So the first image is just the first step in a long program of tracking what's going on with the atmosphere of Jupiter.

The other part that's also very interesting, and there are a number of programs approaching this, to study the moons of Jupiter and also the other gas giant Saturn. And it's the infrared opportunities and the ability to do infrared spectroscopy of their atmospheres that, you know, present really interesting opportunities. And those observations are still to come.

Ms. KIM. Valuable, valuable lessons and observations. Thank you so much. It looks like I'm running out of time, so I'll yield back.

Chairman BEYER. Great.

Ms. KIM. Thank you.

Chairman BEYER. Thank you very much. Let me recognize the gentleman from Florida, Mr. Webster, for his questions.

Mr. WEBSTER. Yes, I got here a little late, but—and maybe it's been asked, but how do you determine within vast amount of space and what—how do you determine the initial direction that you're going to point the telescope and take a picture, and how deep do you go? How do you determine that? Anybody?

Dr. FINKELSTEIN. Yes, so for distant galaxies, it sort of really doesn't matter where we point. There's a variety of factors. You want a place that has the longest observability window. As Dr. Clampin said, you can't look everywhere at all times. Sometimes the Sun is in the way, things like that. And you want places that are sort of pointing out of the plane of the solar system and out of the plane of the galaxy because you don't want a lot of dust that's in our solar system in the way called zodiacal light. And you don't want light from stars. We don't, for our galaxy surveys.

And then for how long you observe, that's always critical. When we write these proposals that Dr. Batalha was talking about, it's crucial to have a very good estimate of how much time. You can't just sort of say, oh, we think we need 10 or 20 hours. You need to say we know. And so NASA has developed tools to estimate the sensitivity before launch of the telescope, and we have some idea of the faintness of the galaxies we want to see. And this calculation tells us here's how long you think—we think you should observe. And then we take it one step further now. NASA has also helped develop excellent data simulation tools. And so you can say, OK, let's say this exposure time tool said you need 2 hours. Let's actually simulate the data. Do we actually see the galaxies in those 2 hours? And we did that process for our Early Release Science proposal to show that, yes, we can actually do it. And then—so it turns out that the telescope was working even better than expected so we can see a little bit fainter than we thought we were going to.

Mr. WEBSTER. So do you—so you have a—is it mapped out already in where you're headed and what you're doing and where you're staying and how long you're going to look and all of that? Is that something that's mapped out ahead of time?

Dr. FINKELSTEIN. So it's a year-by-year process, and so the telescope is currently executing at cycle 1 observations, and proposals for the next year called cycle 2 are going to be due at the end of January, and so sort of a year-by-year process.

Mr. WEBSTER. Well, that's very, very interesting. So once you—but how far ahead are you? I mean, what are you—are you just a year ahead in that you've done one year, you've done another year, and you won't do it the next year until you finish this second year?

Dr. FINKELSTEIN. Yes, we're sort of close to the midway point of that first year of observations, not quite there, and so there is some amount of multiyear planning. Eventually, the Hubble Space Telescope got to a mode where they did accept multiyear proposals, and JWST may eventually get to that point. But right now, there is so much exciting science to do, we want to try and get as many, you know, observations in covering as many targets as possible, and then we can start to think here are some maybe longer-term ideas that you might want to do.

Mr. WEBSTER. So if you find something that's interesting, do you still just move on or do you stay?

Dr. FINKELSTEIN. Usually, you have to propose for the next year. There—I will say—I mentioned we're getting spectroscopy next month. Part of that is a particular type of observation called a director's discretionary time proposal, where if you find something exciting, you can kind of appeal to the director of the Space Telescope Science Institute, and they have an amount of time they can give out for—I like to call it emergency time, really exciting observations. Often, it's exploding objects like supernovae that are fading. You really need to get to them. In this case, it's a really exciting distant galaxy. We'd like to know if it truly is the distance we think it is.

Mr. WEBSTER. I have other questions, but I don't know what they are. Thank you so much.

Chairman BEYER. Thank you, Mr. Webster. We will do a second round if it occurs to you after Ms. Bonamici.

Ms. Bonamici, you're recognized.

Ms. BONAMICI. Thank you, Chair Beyer, Ranking Member Babin, and thank you to our witnesses for your expertise and your testimony.

I'll join my colleagues in congratulating NASA on the successful Artemis launch.

This has been a very exciting and certainly thought-provoking hearing this morning. We know that space exploration has played such a pivotal role in uniting our country and our world but also in broadening our understanding of our place in the universe, inspiring future generations of scientists. And I think back to July when the first images came out. And I know you've mentioned a couple of times the Times Square display and really how stellar those—I guess, pun intended—photographs were and continue to be.

And I want to, of course, acknowledge not only the Federal investment but the more than I think 300 universities and all the participation and partnerships that made this happen. We've—I've discovered certainly over the years on this Committee that we've had many discussions about how do we increase the appreciation among our constituents and people in the country and around the globe of the work, of the science. How do we get—pique interest in further studies? And how do we make sure that our communication with with the public gets across the importance of what's happening?

And so I know Representative Kim asked about education. I wanted to first ask our professors Dr. Finkelstein and Dr. Batalha. You're both professors. What have been your experiences since the successful photographs started coming out in July? How has this changed among your students, among prospective students? Has it changed their views? And what programs should we engage in to make sure that—invest in to make sure we're engaging students to further their careers in science?

Dr. BATALHA. Great question. The data, the images, the scientific discovery is so inherently alluring. It's very easy to talk about it with our youngsters. I've spoken to elementary school students, to Girl Scouts and high school students and people in community colleges and the public. And everybody is just, you know, eyes like saucers.

I think that science, you know, you need to communicate the wonder of it and how it maps to meaning, what it means to be a human. For me, I got a late start in science because I couldn't map the science to scientific discovery. It's hard to understand that feeling of scientific discovery and how absolutely joyful it is. Carl Sagan called it a kind of ecstasy when you have that deep understanding.

So taking these images out into the public, you know, I showed the deep field and I told the public when I look at that image, I marvel at how much life might—must be captured in all those galaxies, you know, thousands of galaxies and billions of billions of stars.

So I think that's what we need to do. Of course, you also need the rigor of the classes, the coursework to go along with it—

Ms. BONAMICI. Sure.

Dr. BATALHA [continuing]. And mathematics showing the joy and fun of mathematics and science curriculum is also extremely important.

Ms. BONAMICI. I'm going to ask Dr. Finkelstein to go into a related direction. If we want to maximize—and I'll ask this to Dr. Clampin as well. If we want to maximize the scientific return from James Webb, what types of skill sets and educational background do we need? And right now, do we have the—is the research community well-positioned for working with all the data that's coming in?

Dr. FINKELSTEIN. Yes, that's a great question. So I think space sells itself. It's really easy to get anyone interested in it because it's so amazing. For me, it's really about trying to chase our origins, the ultimate origins of where the Milky Way galaxy came from.

We need students in the STEM sector, and space really inspires students to go that route. Some of those students choose to go into astrophysics, and that's fantastic. And then we get to work with them at universities. And something that has become more and more common over the last decade or so is more undergraduates participating in research. And so we have a number of undergraduates that are working with us on these data, and I know that's true around the country and around the world. And that gets them the real experience of what it's like to be an astronomer and to make discoveries and have those aha moments and really say, oh, this is something that I could actually do for a living.

Ms. BONAMICI. That's great. And I—it looks like I'm just about out of time, but, Dr. Clampin, if you have just a sentence, it'd be helpful.

Dr. CLAMPIN. I would just say one of the things I find really inspirational is a lot of my students that—when I was at the Goddard Space Flight Center were inspired to join NASA because of what we did with Hubble. And we will do the same with James Webb.

Ms. BONAMICI. Terrific. Thank you. And as I yield back, Mr. Chairman, because I can't stay for a second round, I just want to mention the importance of diversifying the work force and making sure that the opportunity to work in this field is available, especially to those historically left behind. And I yield back. Thank you, Mr. Chairman.

Chairman BEYER. Thank you, Ms. Bonamici, very much.

I now ask unanimous consent on the Committee to wave on Ms. Stansbury for—without objection. Let me now recognize online Ms. Stansbury for her questions.

Ms. STANSBURY. Thank you so much, Mr. Chairman, and thank you to the Committee for letting me participate today. As folks have noted already on this hearing this morning, we're not only celebrating the findings of the Webb Telescope, but also the successful launch of Artemis 1. And as a woman in STEM, I want to just note that it's being led by an amazing group of women, including Charlie Blackwell-Thompson, who is the first woman ever in American history to oversee a NASA countdown and launch. And

so this is long overdue in history-making, along with all of the scientific discoveries that we're talking about this morning. And I do want to add to the chorus of everyone who's been working on the Webb Telescope and the science that's coming out of it.

After three decades of bipartisan work, dedicated collaboration by our extraordinary scientists and engineers at NASA, our space industries, and of course scientists across the world, this amazing telescope launched last December. And I want to say on a personal note, I was among the millions of people who stayed up late through the night and into the morning on Christmas morning to watch the launch of this telescope and had the extraordinary opportunity when I was working on space policy at OMB (Office of Management and Budget) as a staffer to actually see the assembly of the telescope at Goddard. And so it's really been an exciting journey to see the telescope launch and everything that's coming out of it.

In my home State of New Mexico, which is a powerhouse in science, technology, and aerospace, we could not be more excited about the Webb Telescope and what it's teaching us about the origins of the universe and our place in it, but also helping to inspire the next generation of scientists and researchers who are not only engaged in this work, but also the students who we've been talking about this morning who are inspired by what we're finding from this project.

In particular, Professor Tony Hull, who's a Professor at the University of New Mexico, was part of the team that helped to polish the telescope's mirrors, which are bringing these extraordinary images back to us, and other scientists at our major flagship university, including Professor Dragomir, who's working as part of a team to explore exoplanets and unique phenomenon outside of our solar system.

As we've been discussing this morning, the discoveries of this telescope not only will tell us more about the universe and our place in it but are helping to excite and energize a whole new generation of aerospace engineers and scientists and thinkers about the universe. And so I want to use the remainder of my time to ask each of our three panelists two questions. The first is what are you personally most excited about and surprised about what we're learning from the telescope? And the second is what is the next chapter of exploration? What is the—what are we learning from the Webb project that is telling us where we need to extend the frontiers of science and knowledge? So starting with Dr. Clampin, maybe could you share your thoughts on what are you personally most excited and surprised about and what the next chapter is?

Dr. CLAMPIN. So I've been most excited by the transmission spectra from exoplanets that Dr. Batalha showed. I think they're really exciting, and I'm looking forward to seeing observations that the TRAPPIST-1 system come in.

As far as where we go next, I think the next big challenge is the search for life. And I talked briefly in my initial remarks about how we will address the decadal survey, the National Academies Decadal Survey, by trying to build a 6 meter or more space telescope that will look for habitable exoplanets around solar-type

stars and then characterize them to look for evidence of life. So that's kind of where I think we're going next.

Ms. STANSBURY. Thank you. And Dr. Finkelstein?

Dr. FINKELSTEIN. So I think for the near future what I'm most excited about is to look even deeper. The Early Release Science images I've shown you, they're very shallow. They're less than an hour of exposure time. And in cycle 1, there are a number of deeper programs, including a public deep field called NGDEEP (Next Generation Deep Extragalactic Exploratory Public) that will be observed at the beginning of February. And so soon we will have the JWST equivalent of the Hubble Ultra Deep Field.

Into the future, in the not-too-distant future I'm extremely excited about the potential of the Nancy Grace Roman Space Telescope. One of the exciting things we're finding is that the early universe has big, bright galaxies, and that telescope, although it has a smaller mirror than JWST, has a much larger camera. It's optimized for finding these massive, rare beasts in the early universe, and it's going to be fantastic to have that capability very soon.

Ms. STANSBURY. Amazing. And Dr. Batalha?

Dr. BATALHA. Yes, I will echo what Dr. Clampin said, but I wanted to add one thing about the exoplanets. The most common type of planet known to humanity right now is a kind of planet we don't even have in our own solar system. It's intermediate to the rocky terrestrials and the big gas giants. We call them super Earths or sub-Neptunes, but actually, we don't really understand their nature. Is this more real estate for life? That's a big question on our mind. And this is a class of planets that JWST will be able to characterize and shed light on exactly their nature. I'm very excited to see that happen.

Ms. STANSBURY. Amazing. Well, thank you all. And again, congratulations to NASA and to all of the teams who worked on this amazing project and for all of the exciting scientific discoveries yet to come. Thank you, Mr. Chairman. I yield back.

Chairman BEYER. Congresswoman Stansbury, thank you very much.

We'll now begin a second round of questions with Dr. Babin. And I—at least, me.

Dr. Batalha, if you'll forgive me wandering a little bit, I think one of the most interesting questions in politics is does history have a direction? And I know it's sort of a metaphysical question, but I was really intrigued by your comments about increasing complexity and the universe coming together to continue to form the elements. You know, back at the beginning, I guess there's only hydrogen or—and now we have this incredible—and then combining that with Shannon's second law of information, that there is always more information in the universe in this instant than there was the instant before, along with the second law of thermodynamics, which talks about everything moving to the lowest energy state. How do you put that together—can you put that together in a way that suggests that the universe has a direction and that direction is complexity?

Dr. BATALHA. That's a very good question. We grapple with these questions. I think that they're fundamentally tied to how we see our place in the universe and how we find meaning. We observe

this complexity arising. It seems very logical, like it's going to proceed the same way everywhere. The building blocks of life are in the galaxy. We see carbon dioxide, we see water molecules, we see this rise of complexity, even more complex molecules that reside in protoplanetary discs and in star formation clouds. So it seems very logical that life is just another step in that process.

But you're asking a bigger question, which is what happens to life? What really is going to happen to us? Are we going to survive into the future? What does it look like if humans become spacefaring creatures? How does that affect our evolution, both cultural and biological? And those are questions that I can't answer. I don't even know if we will survive to the future or if that's a given. I don't know if the universe evolves toward goodness. These are all questions that I think are up to us.

What I know is that we have the ability to affect that outcome, whether or not we survive to the future. And when we study planets and we understand the limits of habitability, we learn something about the sustainability of life right here on planet Earth. And that's one of the main motivators, I think, for studying exoplanets with JWST.

Chairman BEYER. Thank you for answering a difficult question. And thanks, too, for pointing out that there's a difference between the question is there life in the universe versus the question is there a consciousness, other consciousness in the universe? Very, very different potential answers.

Dr. BATALHA. Yes.

Chairman BEYER. Dr. Finkelstein, you talked about—you showed the incredible picture of all those different galaxies across the bottom. They look like six or seven different varieties right there. Can you talk about the structure of galaxies? I mean, you know, we were used to thinking the Milky Way and the spiral galaxy, but it looks like there's more going on.

Dr. FINKELSTEIN. Yes, absolutely. So there are a wide range of morphological differences in galaxies, and I have a bias. I think the spiral ones are the most beautiful. And one of the amazing things about some of those small panels is you can actually pick out the star clusters, those tiny little knots or pearls in those galaxies. Those are clusters that have hundreds of thousands of stars just forming. And I didn't show you comparison, but if you look at the Hubble images of those galaxies, a lot of that detail is lost.

And so one of the results I showed you in the written remarks I didn't have time in my statement was what we are already learning about the morphology of galaxies. And in fact, when we first made that big image, we actually put it on a huge 30-foot television screen we have at the Texas Advanced Computing Center. And one of the things we realized is when you look at the small galaxies, you see some spirals. And because they look really small, they must be really far away. And with the Hubble Space Telescope, the limits of Hubble, we thought that once you get about 10 billion years or so into the past, you don't really see spiral galaxies anymore. Everything is kind of an irregular clump.

But now with JWST we have the resolution. It turns out the spirals were there; we just could not see them. And so you see them out to redshifts of 2 and 3. You see barred spirals, these elongated

features in the center similar to our own Milky Way Galaxy. We found the highest redshift barred spiral at a redshift of greater than 2, so that's over 10 billion years into the past. And we see evidence that galaxies have these ordered discs, these ordered rotational motions out to maybe even a billion years after the Big Bang. And if you ask some of the theoretical astrophysicists, they would say, oh, we knew that was there, you just couldn't see it before. But you never know until you look. And now we finally have the observations to prove it.

Chairman BEYER. That's very cool. You're making me jealous talking about the 30-foot TV.

One more question. I think maybe to—a question from Mr. Posey or one of my Republican friends, that what's beyond the universe? Typically, with thinking that the definition of the universe was as far as light has expanded, rather than being infinite, that it's still expanding into whatever is beyond it or nothing that's beyond it.

Dr. FINKELSTEIN. Yes, I just taught this earlier this week in my class. So that's the difference between the observable universe and the entire universe. So the universe has been around for a finite time, only 13.8 billion years, and so we can only see objects that were close enough that their light has been able to reach us in that period of time. But to our best understanding, that is not all there is. There is more universe out there that is inaccessible to us right now because the universe has not been around long enough for that light to travel to us.

Chairman BEYER. Great. Thank you very much.

I now recognize Mr. Babin for his questions.

Mr. BABIN. Absolutely fascinating. Thank you. I'm going to bring us back down to Earth for congressional oversight here, OK?

Dr. Clampin, the Government Accountability Office, the NASA Inspector General, the National Academies of Science, and this Committee conducted a significant amount of oversight on the JWST program over the past 20 years. We've learned a lot about what to do and actually what not to do. As NASA continues with the development of the Roman telescope and begins to consider other follow-on observatories, what are the top three lessons learned from JWST that came out of all these reports, these audits, these investigations and independent reviews? If you could, I know that's digging deep, but if you could tell us some of the fruits of our labors up here.

Dr. CLAMPIN. So I think a lot of it comes down to how you formulate these missions at the very beginning, the phasing of how the different pieces get put together. One of the things we did on JWST, for instance, and, you know, some other programs is basically get too far along with the spacecraft or the—you know, the absolute mission design before we completed the instruments. So then, you know, we need to sort of make adjustments to accommodate the instruments. So the first thing for me is you make sure that all the technologies are at the required maturity level and that you understand how they're going to work in the architecture that you're formulating, so you really have to think about systems rather than individual boxes of technology.

I also think the schedule is very important and trying to, you know, formulate and execute a mission to the schedule from the

very beginning. And, you know, that's something that I'm very focused on doing for the next response—you know, as we respond to the National Academy, thinking about the next big, large mission, which is this—what I call habitable worlds observatory, you know, getting all the technologies mature and at the point where we understand how they work together as a system before we start formulating the design for the observatory. And then once we build—start building the observatory, we're really focused on building it to a schedule. So those are the two main things for me. You know, the the larger missions really require a systems-level focus, and making sure you understand everything before you sort of launch into it is very important.

I'm now, as I'm sure you're aware, responsible for making sure that Roman comes in on schedule, and Roman's already well along. And one of the things that I'm doing there right now is just making sure that we're addressing, you know, issues that have arisen as we've come out of the pandemic, you know, work force issues and supply chain issues. And we've been working to put in place with our industry partners innovative approaches to addressing some of these so that we stay on schedule.

Mr. BABIN. Yes. Thank you for your service, too.

A second question for you if you don't mind, Dr. Clampin. NASA paused JWST science observations using the MIRI (Mid-Infrared Instrument) medium-resolution spectrometry (MRS) mode on August the 24th because of increased friction in one of its grating wheels. NASA concluded the issue was likely caused by increased contact forces between subcomponents of the wheeled central bearing assembly under certain conditions. NASA announced that it had developed and successfully tested a plan on November the 2nd and that it would resume MIRI MRS science observations on November the 12th starting with a unique opportunity to observe Saturn's polar regions just before they become unobservable by Webb for the next 20 years. Was NASA successful in implementing this plan? And how is MIRI MRS mode functioning now? And what level of confidence do you place on the issue being resolved and that it will not be an issue in the future?

Dr. CLAMPIN. So let me just assure you that, yes, we did get the observations of Saturn done, so I actually got an email late yesterday saying that they've been completed. We have a plan of incremental steps to bring the—this particular mode instrument—it is a mode, it's not the whole instrument—

Mr. BABIN. Yes.

Dr. CLAMPIN [continuing]. So we're bringing that back, you know, step by step, exercising the wheel, tracking all of the engineering telemetry, making sure we understand how it's performing as we return it to, you know, what I'll call normal service.

Mr. BABIN. OK, good. Thank you very much. And I'll yield back, Mr. Chairman.

Chairman BEYER. Thank you. And I now recognize the gentleman from Florida, Mr. Webster, if you have any additional questions.

Mr. WEBSTER. I think I do.

Chairman BEYER. The floor is yours, sir.

Mr. WEBSTER. This is to anybody. There's one picture in here southern Ring Nebula? How wide—or what's the dimensions of that nebula?

Dr. CLAMPIN. I have to say I think we'd have to get back to you on that. Off the top of my head I do not recall—

Mr. WEBSTER. So would you know the dimensions of any of these photos as far as millions of miles, billions of miles, or maybe you don't even measure them in miles. I don't know.

Dr. CLAMPIN. I think most of them have that information in the comments that go with the plate. I mean, they're also very different ones. You know, a planetary nebula in our galaxy and others are very deep image of the sky. But we can get you that information.

Mr. WEBSTER. Great. So have you, among yourselves or among just the people that work on this, is there—do you take a poll and see what's the most fantastic display that's been or people have their own ideas or is there one that sticks out as just the most phenomenal discovery you've made?

Dr. CLAMPIN. So let me just come back to your last question. I'm told it's about .4 lightyears across, so that gives you some idea of the size.

And in answer to your second question, I think it really depends who you ask. I'm sure Dr. Finkelstein and Dr. Batalha would have very different answers, and I probably would be closer to Dr. Batalha. So it really depends on what field you work in. Everybody's sort of waiting for their particular observation to get done or to work on the data that's been taken in their particular area of interest. And I think part of the, you know, happiness of the science community right now is that, you know, they're just getting to see what these observations look like and how this telescope's going to change their particular branch of astrophysics that they work in.

Mr. WEBSTER. So do you have a favorite?

Dr. CLAMPIN. My favorite, I think, is still on the calendar to be observed over the next 6 months, which is the TRAPPIST-1 exoplanet system.

Mr. WEBSTER. How about anyone else?

Dr. BATALHA. Can I make one point that I alluded to earlier? You know, you're asking about the images, these beautiful images. Everything we know about the—well, almost everything we know about the universe is from the light we collect in our telescopes. And the great power of JWST is that it can take that light and spread it out into a rainbow. And in that rainbow, embedded inside of that are these chemical fingerprints, evidence of motion, dynamics, all kinds of information embedded in that spectrum. So I would contend that the most profound images if you will are actually these plots of these graphical representations of the spectra because they contain so many clues about the nature of the universe. So I love the images. I'm very inspired by the deep fields showing tens of thousands of galaxies, each with hundreds of billions of stars. And I look at that image and I wonder how much life is represented in that tiny little speck of, you know, grain of sand that's been imaged. But the spectra, I think, are extremely compelling, and I'm really looking forward to seeing more spectra so we can understand the diversity of all of the worlds that are out there.

Mr. WEBSTER. So do you filter out all of the extraneous spectra and just get down to one particular wavelength or how do you how do you do that?

Dr. BATALHA. No, the power is in looking at all of the colors. JWST is focusing on the infrared but a very broad region of the infrared. And every single color tells us something different because the molecules that are out there and the atoms, they absorb each one with a unique chemical fingerprint. And each molecule tells you something different. In an exoplanet atmosphere, for example, each molecule's absorption happens in a different layer of the atmosphere. So if you look at many molecules together, you can buildup the whole temperature pressure profile of that atmosphere. You can start to understand things like climate and dynamics and really the history of that exoplanet, how it lived and how it has evolved.

Mr. WEBSTER. Awesome. OK. I yield back.

Chairman BEYER. Thank you very much. We're coming to a close. Dr. Babin and I would love to continue to talk about the infinite number of universes and the metaverse and dark energy and all that, but it sort of wanders away from our oversight responsibility perhaps. I do have one more question though. Who is Stephan in Stephan's Quintet? Is that one of your children, too?

Dr. FINKELSTEIN. No, no. My other child is Kieran, who I think might be a future lawmaker, so you may see him here at some point.

Chairman BEYER. That's great. Great. In the meantime, I'd have to say that of the eight years that Dr. Babin and I have been on this Committee, this is maybe tied with the gravitational waves hearing as the most fascinating that we've had. So you've been terrific witnesses. I'm really impressed with the depth of your knowledge and your excitement and your ability to transmit that to us and to the world, so thank you very, very much.

So before—the record will remain open for two weeks for additional statements from the Members or additional comments on the direction of history in the universe and for any additional questions the Committee may ask of the witnesses. The witnesses are excused, and the hearing is now adjourned.

[Whereupon, at 12:04 p.m., the Subcommittee was adjourned.]

