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From his home in Maryland, John Mather's thoughts are often a million miles away — or more precisely, 1.5 million kilometers away at the second Lagrange point. From this gravitational position, the James Webb Space Telescope will look off into the cold of space with the Earth and the sun at its back, so that it can sense the weak infrared light from features of the early universe. If all goes as planned, Webb will be launched to this point next year to begin a $9.6 billion mission that Mather, a cosmologist and the project's top scientist, has been helping to plan for 25 years. I spoke to him via video call about why Webb has been worth waiting for. Here is our conversation, compressed and lightly edited. — *Cat Hofacker*

JOHN MATHER

POSITIONS: Astrophysicist at NASA Goddard Space Flight Center, since 1974; senior project scientist for the James Webb Space Telescope, since 1995; led the scientific proposals for the Cosmic Background Explorer, or COBE, satellite, 1974-1976; COBE study scientist and then project scientist, 1976-1998.

NOTABLE: 2006 recipient of the Nobel Prize in physics with George Smoot for his measurements of cosmic microwave background radiation via the Cosmic Background Explorer satellite, which confirmed the Big Bang theory. Led the team that defined the Webb telescope's science objectives and chose the instruments that will receive light from its mirrors.

AGE: 74

RESIDENCE: Hyattsville, Maryland

EDUCATION: Bachelor's degree in physics from Swarthmore College in Pennsylvania, 1968; doctorate in physics, University of California at Berkeley, 1974.

Q: If launch holds for Oct. 31, 2021, it is now one year and 29 days from the day we're speaking. Does that feel surreal?

A: Well, I just don't worry about it. You cannot worry about these things for 25 years. I'm just looking forward to having it up there, so we'll go onto the next thing to do.

Q: Have you started making your launch day plans?

A: We actually haven't all figured out where everyone will be, but it's pretty likely that I will be here in the Washington area, because shortly after launch scientists will be saying, "Is everything OK? What do we do now?" I don't want to be 24 hours by airplane from home when something like that might happen, so I think I probably have to give up watching the rocket go up. Soon after launch, scientists will be sitting there in control rooms with engineers and computer wizards to make sure that we're doing the right thing for the commissioning process: first unfolding the telescope and then focusing it and then setting up all the instruments. We are already doing rehearsals and detailed reviews of exactly what we are going to do at each minute of every day for the first six months after launch. We have a digital simulator of the observatory and send it commands to pretend that you're doing the real thing, pretend that something bad happens, and do you know how to respond?

Q: What's the big mystery we're trying to solve?

A: There's more than one mystery. They all fall into the category, for me anyway, of how did we get here from the Big Bang? What is the sequence of events that led from an expanding universe full of hot stuff to the expansion and turning around in places? With Webb, we will be seeing farther out into space and farther back in time. So we'll be able to see the first galaxies growing out of whatever was there. We will see the first stars turning on and the first stars blowing up. We will see some signs, we hope, of the first black holes forming and growing. After you see the first stars and galaxies growing and becoming more like modern ones, then we say, "Well, locally stars are being born today too, right? How is that working?" Over in the Orion Nebula, where you see Orion's sword has a big blob in the middle, that's a place where stars are being born today.

> Mather got back to me later and noted that, actually, we see the nebula as it was about 1,300 years ago, the time it takes for light to reach us from Orion. — *C.H.*

You can't see them grow because they're inside dusty clouds that are opaque. Webb's infrared detectors will look inside those dusty clouds, around the dust rings to see stars and galaxies growing. We will also be looking at some places where we have signs of planets. We know there are planets around most stars, and some of them we can see already. Most of them are hard to see, but we will look where we know them to be. We know a pretty large catalog of stars that have planets that go in front of the star, causing the star to blink a little bit. We'll be looking especially at those because you can analyze the star light and say, "Well, some of it went through the planetary atmosphere on its way to our telescope. What's the chemistry of it?"

Q: You often phrase these science objectives as existential queries: Where do we come from and are we alone? So how do you boil these philosophical questions into the technical specifications of a telescope?

A: We go at it from both ends. You say, "Hey, scientists want the most observing capability you could possibly have because everything is unknown." And then we talked to our friends in engineering and they say, "Well, you can't have that. That's too hard for us." So we all agree about what we could build that would still be spectacular enough to be worth all this trouble. It's a kind of instinct; at first we think we can build it this big and this powerful, and then you try and maybe realize this isn't really going to fit after all. For a long time, we thought our telescope would be 8 meters across, and then we said, "That's too hard; how about 6.5 meters?" And now that we've got it just about finished, I think we must've been crazy to think we could get 8 meters in there. It's a very tight fit to get the 6.5-meter telescope into the top of the Ariane 5 rocket. It's folded up and it's still a snug fit. So you start off with a plan and engineers have to say, "I can't do that," and then we go back and say, "OK, scientists, are you still interested? Is this still the best thing that we could possibly build and is this still what you want?" And they of course said even if it's a little smaller, it's still super spectacular and they want it for sure.

Big science, but late

The main role of the James Webb Space Telescope will be to peer back 200 million years after the Big Bang at what scientists expect will be beautiful, hot swirling masses of gases in the process of becoming stars, planets and galaxies. Because the universe is flying apart, light from these features has been stretched to infrared wavelengths, which means Webb must be chilled to nearly absolute zero to image them.

By now, Webb should have been deep into this and other scientific work. But during construction, leaks were discovered in the valves that would pump propellant to the spacecraft's thrusters; its tennis-court-sized sunshield ripped during testing; engineers needed longer than expected to devise a way to fit the 6.5-meter primary mirror inside its launch vehicle's payload shroud and erect the mirror in space to the required precision. At best, Webb will reach space about 10 years later than planned, and its cost has increased to $9.6 billion, a figure that includes its first five years of operations.

— *Cat Hofacker*

Q: Was that reduction from an 8-meter to a 6.5-meter primary mirror disappointing? That translates to a decent amount of surface area you now don't have for capturing light.

A: Of course it's disappointing, but it's kind of obvious you have no choice. You just can't fit stuff in the rocket that's bigger than the payload fairing. You also contemplate how much is it going to cost us to build the mirrors and how long is it going to take us. We know what we're going to do and you can't possibly do the original plan, so do what you can with what you have and make it work.

Q: Even with the slightly smaller mirror, there's an awful lot to accomplish for what's estimated to be a five-year science mission. Can you achieve all you want to achieve with this telescope in five years, or do you think it'll end up going on longer?

A: We will run it as long as we have fuel to run it. It does need fuel for a couple of purposes: to stay where it's supposed to be in the Lagrange 2 orbit and also to point in the right direction. The sunshine actually pushes on the telescope and wants to turn it over, so we have to push back occasionally. We'll run it until we run out of fuel or something disastrous happens. What would be a catastrophic failure? There's nothing obvious we know. Other observatories have gyros that wear out or wheels that wear out. The gyros that we're using to measure the speed the spacecraft is turning are different from what they have on the Hubble, which had to be replaced. We're planning to keep on running Webb until we can't. We've got fuel for 10 years, at least, and if we're lucky, a lot more. So I'm not too worried about the five-year life; it's just that you can't promise something that you could never possibly test. We don't have a way that we know of to use it after the fuel is gone, so what we have to do is make sure it doesn't come back and hit the Earth.

▲ **The Orion Nebula** in an image from the Hubble Space Telescope. The James Webb Space Telescope's infrared detectors will "look inside those dusty clouds, around the dust rings to see stars and galaxies growing," Mather says.

NASA

Q: Along with the change to the mirror, a coronagraph instrument was later added to detect distant planets. What drove that decision?

A: When we first conceived of the observatory, we didn't really know there were planets around other stars. It tells you how far back in time we started; in 1995 was our first conversation. That's when they were just beginning to find planets with the radial velocity technique from the ground. So as time went on we said, "Well, it would be really great if you have a coronagraph or something that would block the light of a star so you can see the little planets orbiting nearby, and so what should you do to have one?" You wouldn't want a telescope with a very different design, so very small changes were made at the instrument package just to say, "OK, well, look, we'll do what we can, but they're not allowed to make anything more difficult." When we get to designing a next observatory that's specially built to look for those planets, then they'll make some different choices.

"We calculated that if you were a bumblebee hovering at the distance of the moon, we could see the sunlight that you would reflect and the heat that you would radiate."

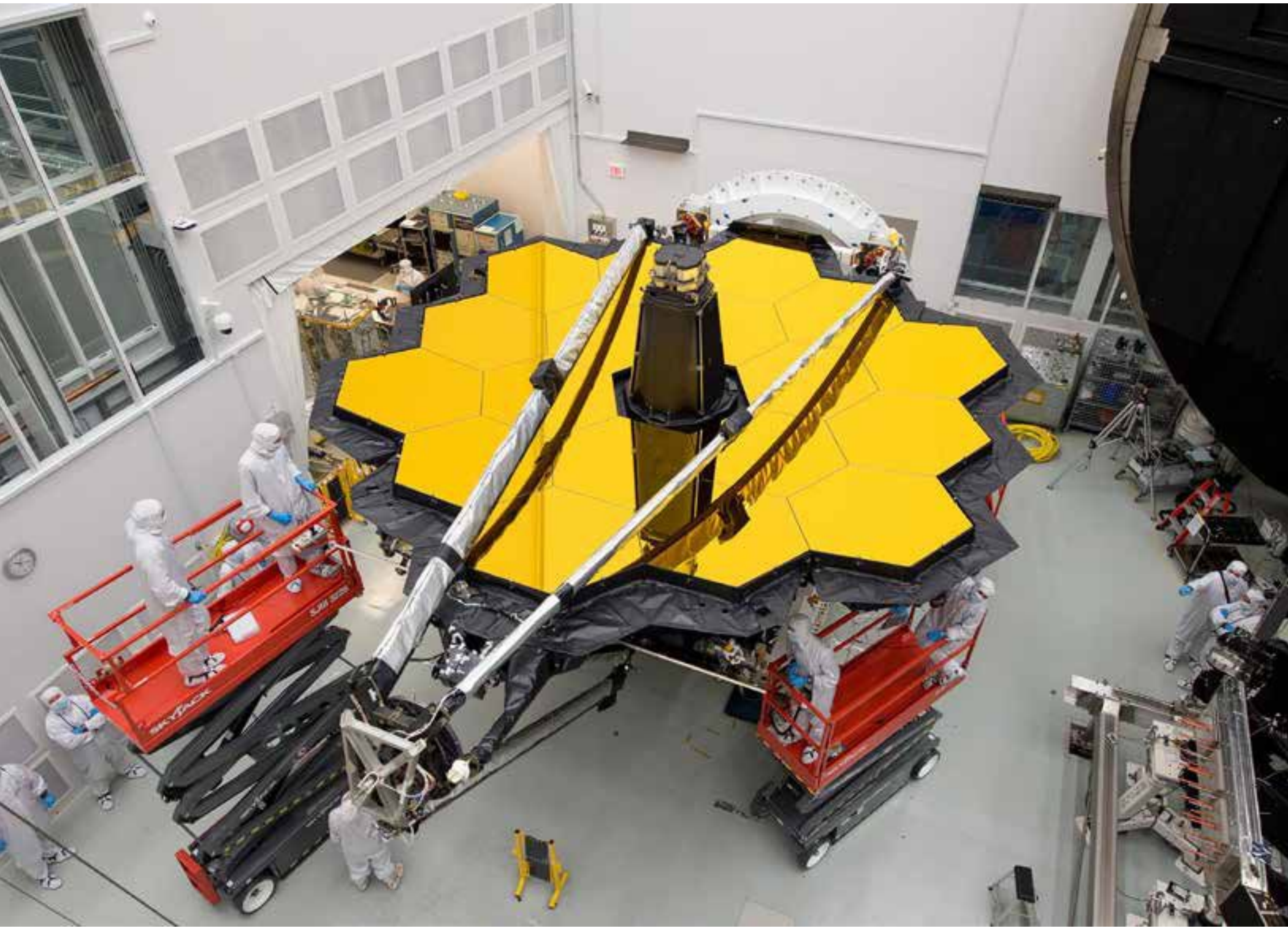
Q: So because Webb was conceived more than 25 years ago, how have the questions driving the science goals changed over time? And how do you make sure this design can answer not only those questions but the surprises that might await us?

A: What we know is certainly going to improve with time, so we had to ask, "What are you going to do with this observatory that nobody could ever do without it?" I ended up working with science teams to define, "What do you really want? What are the science objectives? Why are they so exciting that you should spend all this time and money on answering those questions?" In other words, what makes the Webb telescope special and unique? And it is two things: One is that it is very large, and one is that it can pick up the infrared light very well. Nobody had any plans to do anything like that with any other tool. Even if we've learned more about the subjects that we're looking at, we're still never going to get the information that the Webb telescope will. We said, "Well, suppose this doesn't work out. What else could you do?" And the answer is there's no way to get that information without that telescope.

Q: After 25 years of concepts and studies and construction, if someone came to you today and asked for an infrared telescope with the same objectives, would you do it differently?

A: It's certainly been a little bit longer trip than we were all planning. When we all started, we were very ambitious and very optimistic. We had a very optimistic boss at the time, former NASA Administrator Dan Goldin, who said, "Well, why didn't you just do it quicker?" It didn't turn out to be that you could. You're going to draw the sketches really quick, but you can't actually go through the process of building something that you're sure is going to work. If you want it to work, you really have to do it through every single test. It is sort of my lesson from life: If you do not test it, it will not work. And there's no such thing as taking a chance when there are hundreds and thousands of different ways that something could go wrong. If you don't check them all, one of them will get you. The test program that we do is 100% essential and it takes them forever. We've learned a few things about how to do the engineering, but there is actually no other way to get that information besides a big telescope that's cold in space. So you might do a different design. You might say, "Well, I have different mirror materials, a different way of unfolding it, a different way of cooling it down,

▼ **The honeycomb** primary mirror of the James Webb Space Telescope at NASA's Johnson Space Center in 2018, where the mirror and the science instruments (not pictured) were placed inside a cryovacuum chamber that replicated the freezing temperatures the telescope will operate in.
NASA



▲ **JWST in its launch** configuration at the Northrop Grumman clean room in California, where engineers in October completed the acoustic and vibration testing that replicated the forces the observatory will experience during launch. Plans call for enclosing the observatory in a protective container early next year and shipping it on a barge to French Guiana for fitting inside the payload fairing of an Ariane 5 rocket.
NASA

different design for the instrument package." All the details would be different if you started fresh, but the general idea has to be about the same.

Q: So paint me a picture of a future in which Webb has launched, the Nancy Grace Roman Space Telescope [formerly the Wide Field Infrared Space Telescope] has launched and Hubble is still operating. How do these telescopes work together?

A: What usually happens is somebody that's using one telescope says, "Look what I found; this is really important, and can I have some observing time on your telescope?" That's pretty likely. The Hubble has been running a long time, so I don't expect to get a lot of new surprises from it. The Roman telescope is pretty likely to show us a surprise because it takes pictures of huge areas of the sky all at once. It has a hundred times as much "bite" — meaning it can see 100 times as much sky at one time — as the Hubble can get or the Webb, so if there's anything special and unusual, it's likely to find it. We are expecting to get phone calls from astronomers to say, "Look what I found, please follow it up right now." Webb is bigger, collects more photons, is more sensitive at most of the wavelengths that we cover, but we would still get beautiful pictures. They will be different. Infrared sky really does look different from the ordinary visible sky, spectacular pictures we get with Hubble. We will be able to do those, and we'll be able to do them much more quickly, but we'll also get other pictures that you never could have seen.

Q: I remember hearing the first pictures of Hubble caused such a frenzy, they broke the internet. As a scientist, what's most exciting, these spectacular images or something else?

A: For me as a scientist, the exciting part is the discovery, the things that we didn't ever know were there before. Hubble certainly surprised us. The one that I really fastened on is that every galaxy has a black hole in the middle and nobody had ever guessed that. Nobody had any reason to expect it. Nobody had ever seen it; the Hubble had just enough power to see them. And so, oh golly, that changes everything. Then we certainly did not expect that it'd be able to image planets around other stars or start getting chemical

"We're planning to keep on running Webb until we can't. We've got fuel for 10 years, at least, and if we're lucky, a lot more."

analysis of those planets when they transit in front of their stars, but the Hubble did those things with the tools that were designed with something else in mind. It's my hope that we're going to get a similar number of surprises out of the Webb telescope, that something is going to be there nobody dreamed about.

Q: Given that it's taken much longer than planned to begin operations, what impact do you think Webb will have on future observatories?

A: We hope they're all positive, that the telescope works as planned and it does indeed discover things people are hoping to find, and then it opens up questions that we didn't even have before because we couldn't even ask them before. If we don't find a big surprise, I'll be disappointed, but you know, one way I think about this is this telescope is so incredibly powerful that it's hard to imagine how the universe has no surprises for us. We calculated that if you were a bumblebee hovering at the distance of the moon, we could see the sunlight that you would reflect and the heat that you would radiate.

Q: Do you worry at all that because Webb's costs have increased so much over time — to nearly $10 billion from the $1 billion originally estimated — that future observatories will be more limited in cost and maybe scope?

A: Yeah. People have up and down feelings about these things. When you're a graduate student, you can't possibly imagine how anyone would spend so much money on one thing, then you just get into the middle of it and you say, "Now I understand how that takes all that money and all that time." Really, it's actually people's time that we're getting; how many engineers and technicians does it take to build something that really will work? It's a lot. So I'm hoping that our next generation will be equally ambitious and say, "That is so important that it's worth money." I think it's important, and it is worth all that money, and I think the next generations will be as well. Our number one thing we have to do is prove that it can be done and that this amazingly difficult and complex thing will work. We do that, then I think people will be ambitious.

Q: It sounds similar to how the impact of the Apollo era is described. How did you feel that impact, personally?

A: I still feel it. I look around and so much of what we have today is because of the national push for excellence in science and engineering in the Apollo days. Apollo was the sort of visible piece of the Cold War, and it was the way that the nation could say we're going to invest in science and engineering. And so now we are the world leaders in so many areas that were sponsored by those people. So it affected my future. I got to go to school to be a scientist because we got to beat the Soviet Union. It's hard to remember my early childhood very well because I didn't keep a lab notebook, a diary; I wasn't a real scientist yet. But even when I was 8 years old, I would have heard about Darwin and Galileo, and I saw the planetarium show with the museum. "Oh, this is so exciting." And then there were television programs about the beginnings of knowledge. I didn't know how I was going to fit into that. I just thought quantum mechanics, relativity, that is the coolest thing; I just have to understand that. It still is strange and mysterious, and people do not have intuition about it. I thought if I can do anything like work on those topics, that will be cool.

Q: Webb is in some ways the continuation of your Nobel Prize-winning work with the Cosmic Background Explorer satellite. Webb is peering back 200 million years after the Big Bang; can we go even further?

A: We certainly can learn more about the Big Bang because we're already working on it. The cosmic microwave radiation that we've measured with a COBE satellite and got to go to Stockholm for has still one big territory that's unmeasured. It's called the polarization. A piece of the polarization of that radiation should come from the Big Bang itself. So that's as far as you can get in that direction, and if you ever understand that, you'll get as close as you can ever get to observing what the physicists called the unification of the forces. This is one of their holy grails: to see how the forces of physics connect. Quantum gravity is the basis of that. And we don't know what it is. So that's one big mystery. Then all the steps about how we turn the early universe into life. That's fascinating, too, and astronomers will work on their part. We can tell you when and how the atoms got to make a little planet like Earth with the right conditions. Then we'll hand over the job to biologists and other people to say, "The chemicals could have done this, and maybe that would have become alive." So I think eventually we'll have a story about that. That's not impossible that we'll have an understanding of it, even though the evidence has mostly disappeared. ★