NASA HEADQUARTERS SCIENCE MISSION DIRECTORATE
ORAL HISTORY PROJECT
EDITED ORAL HISTORY TRANSCRIPT

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INTERVIEWED BY REBECCA WRIGHT
GREENBELT, MARYLAND – JUNE 8, 2017

WRIGHT: Today is June 8, 2017. This oral history session is being conducted with Dr. John Mather for the NASA Headquarters Science Mission Directorate Oral History Project at Goddard Space Flight Center in Greenbelt, Maryland. Interviewer is Rebecca Wright, assisted by Sandra Johnson. We thank you so much again.

MATHER: Well, thank you for asking.

WRIGHT: We appreciate your time. We know you are a very busy man. Especially today, we would like for you to share information with us about your role as the Senior Project Scientist with the James Webb Space Telescope. It's exciting times for all of us as we look forward to the launch, but we would like you for you to go back a number of years and tell us how you first became involved, and then what your duties are, and how they evolved as they came through those years.

MATHER: Starting back more or less at the beginning, or before the beginning, in 1989 we launched the COBE [Cosmic Background Explorer] satellite, which was my first project here at Goddard. It took us about four years to finish off the operations of that mission, and some more years to finish the analysis. That gets me up to mid-90s. What was I doing then? I was writing a book about it called *The Very First Light [The True Inside Story of the Scientific Journey Back to the Dawn of the Universe]* with a coauthor John [I.] Boslough and thinking about, "Well, what do I do next?"

My friends say, "We're building the Spitzer Space Telescope"—but it didn't have that name yet—"and it's not going to be big enough. Can we maybe think about another way to get a bigger telescope up there without spending too much money?" So we started sketching telescopes that would unfold, but not be nearly as hard as the Webb Telescope turned out to be. I presented this at a seminar here, and people laughed at me and said, "We'll never do anything like that, that's too hard."

However, I think the day before Halloween of '95, I got this phone message from Ed [Edward J.] Weiler that said, "We are doing a study. We want to get rolling on what's the new telescope going to be, so call up John [H.] Campbell. He knows what this is about, and we need a proposal tomorrow. It only needs to be one page." It turned out Ed had just received the authorization to spend some money on something, and this is what he wanted to do.

What I hadn't appreciated at the time was that my friends were involved in writing a report calling for this telescope to exist. You have probably seen it. It's the "HST & Beyond [Exploration and the Search for Origins: A Vision for Ultraviolet-Optical-Infrared Space Astronomy" (1996)] report from Alan Dressler and committee. It was brilliant. It hadn't happened quite yet then, but Alan Dressler went down to meet [NASA Administrator] Dan [Daniel S.] Goldin. They got acquainted, and they liked each other. Within a few months of that, Dan Goldin went to the [American] Astronomical Society and announced that what the committee asked for was much too small, and we were going to build a bigger one. He got a standing ovation, which is not exactly common for NASA Administrators. In fact, hardly any of them ever go to the Astronomical Society, but he did. He liked it. So that was our first peer review, as I like to say, a standing ovation for the idea.

Dan knew something that we didn't all know. He had worked in TRW [Inc.], which had already been working on segmented telescopes. He didn't think they were impossible the way other people would naturally assume, so "Of course we can build a bigger telescope. How big do you want?" He announced this, and it was very clear from that minute that the idea was a good one, and that NASA was going to support it, so we almost didn't have to recruit any interest. People came to us and said, "Can I help do that?"

Pretty soon we recruited a study manager, Bernie [Bernard D.] Seery. He is a really brilliant engineer and manager, and conducted the studies necessary to figure out what are all the technologies you have to have, and make sure that we got them all invented. He was our study manager for a long, long time.

So what did we have to do? Well, we had to put out contracts to people who promised that they could develop our new technologies. We had a list of 10 new things we had to have, and we managed that from here. We also started negotiating the international partnership, because Headquarters said, "We need to make this international deal. It's good for us, it's good for them. If we are going to let other people use the telescope, they should help build it. And, by the way, pay something for it."

It turns out to have many other advantages too, but the difficulty of arranging international partnerships is not so small. It took us a long time and a lot of changes of the plan, but we did it. I guess you know the upshot was the European Space Agency contributes the launch vehicle, and one instrument, and a half of another instrument. The Canadian Space

Agency contributes the fine guidance sensor, which makes sure we can lock onto a guide star and keep a sharp image, as well as a research instrument.

All of them get to participate, and their scientists are guaranteed a certain fraction of observing time. That's what they get for this effort. As well, of course, their local industry gets to have work, so that's another advantage that people have for supporting the space business in each country. It keeps people busy, and helps them be creative and invent things that they never had before, and develop new products that they can sell.

Clearly, they have been important for our contractors. As you know, we have got Northrop Grumman [Corporation] as our prime contractor. They were chosen in 2002. They were still called TRW at the time. It didn't take them very long to say, "We are going to build you a big model." You have probably seen the pictures of it, right?

WRIGHT: Yes, I have.

MATHER: They built that on their nickel, because that enables them to prove to the entire planet that they can build a bigger telescope than you can. Of course, they have other customers that would be interested in telescopes.

Jumping back a little bit in time before that, of course Bernie Seery had connections, and we made a connection to the DoD [Department of Defense]. We did do jointly-funded technology development for the mirrors with the DoD. At a certain point, we decided that we didn't have to cooperate anymore, because they needed different things than what we needed, but it was a good help to get started.

That was the hardest one of all the technologies that we had. We had to get I think 12 different contracts to different companies, and they all said, "We can do that for you." One of them was correct. That's why we do it our way with competitions and a "prove it to me" kind of process, because you can never actually take claims of future product on faith. And also why it's really good to have multiple choices, because if you really, really have to have something by a certain date, you can't just take "yes" for an answer. You have to have two yes's at least. That's a reminder. That's how we got to the Moon as well. James [E.] Webb, the man [former NASA Administrator], made sure we had multiple ways to make sure we could get there.

WRIGHT: A sound business decision that has proven itself many times. Since we are talking about the technology, when you mentioned the jointly developed DoD technology, did you do that for efficiency and time, or for funding?

MATHER: Some of both. When two funding sources come together and say, "We all need this," it attracts a lot more attention from the people who think they are going to develop a product they can sell. A lot more people want to come forward and say, "We'll do that for you." So that's good to stimulate the creative force of industry. It also makes some more money available, too. You can get farther if it's not your only nickel.

WRIGHT: And it develops that partnership or relationship. You mentioned there were 10 new technologies. Were there some of those technologies that were harder through the years, to get to the level that you wanted?

MATHER: Yes, some of them turned out to be harder than we thought they would be. We have a cryocooler requirement. You have one detector system that has to run at 7 [degrees] Kelvin. We thought at the beginning, we would just use a block of solid hydrogen, protected and well-insulated, in a thing called a “cryostat” to keep our detectors cold. That turned out to be difficult, expensive, and not having a long lifetime. So, okay. The other alternative is make yourself a refrigerator. We have got compressors, like you have in the kitchen, that compress a gas that can go expand at the other end, and absorb heat and provide cooling at the other end. The principle of that has been known for a century. The practice of it to get it ready to go into space is pretty hard. So that one was harder than we thought.

Something else that was harder than I thought it would be was the big plastic sunshield. We’ve got a sunshield that’s as big as a tennis court. You can’t buy a roll of plastic that big, so how are you going to do that? The technology was developed for us special. It involves ways to stick the small pieces of plastic together to make the big piece. Also, what was harder than people thought it would be was to get the right shape. We needed the edges of the sunshield to be pretty much straight, as you see in the model there [demonstrates]. Otherwise, there may be pathways where the cold parts can see the warm parts directly, so we had to make sure that couldn’t happen. That means the edges have to be straight. But when you stretch out a stretchy thing, it’s pretty normal for it to come out with a curved edge, so you have to work at that. A lot harder than we thought.

The price of that sunshield is more than the price of a lot of satellites we have put up, just because it’s all custom, it’s all handwork, it’s all new ideas. We use a software called NASTRAN [NASA Structure Analysis] for analyzing the mechanical properties of solid things, but it’s not ready yet for something stretchy. A big, stretchy piece of plastic that has the right shape after launch, at another temperature, and made out of little pieces? One heck of a hard problem. That turned out to be much more interesting than I thought it would be.

Another one that was obvious from the very beginning was learning how to focus the telescope after launch. I don't remember if we talked about that one before.

WRIGHT: No, we haven't.

MATHER: We knew we had to do something different, because Hubble [Space Telescope] was launched and it was out of focus. We did learn from experience how to do that, again by running a competition by the way. We had different teams around the country compete to say, "Well, we know how to calculate this, and we'll show you how to do it." Then we found out which one was the best, and we followed it up, and it worked.

It turns out to be the essence of the idea we are using for the Webb as well. It's done by taking pictures of a star in focus and out of focus by known amounts. Then you get all these funny-looking patterns, but the computer knows what they mean. You can back up from the fuzzy pictures to say, "Move all those motors that control all those mirror segments just so, and it'll be fine." That's a huge accomplishment, and we had to demonstrate it, because, as I like to say, "John Mather thinks it'll work is not the same as the hardware does work." The hardware doesn't care what I think.

Anyway, we had many, many rehearsals. We made a small-scale model test telescope to demonstrate that. But at the end we say, "Yes, we are confident that will work." We are about to demonstrate it by test in the vacuum tank in Texas, at your place [NASA Johnson Space Center, Houston].

The other technologies, the hard ones included improving the detectors. We already had detectors that would work at the right wavelengths, but they were not as large as we wanted, and they weren't as sensitive as we wanted, so all of those had to be improved. The way I describe it, there are the manufacturers that have their secret recipes with special mouse milk, and they know how to do it, but even when they do know how to do it, it's not 100 percent reliable. You do it the same way the next time, and it doesn't work that time, and you say, "What did I do different?" And you don't know. So we had a lot of trouble with them. But they are brilliant.

In the end, these detectors are so incredibly good that it's hard to express how good they are. Just to give you a little bit about that, we measure how good a detector is by how many extra electrons we get out of a pixel per hour. We get a few extra electrons per hour per pixel, which means you can take time exposures for a really long time and build up the light turning into a signal, and see something incredibly faint. So, we are now able to say to the public, "You know, if you were a bumblebee hovering at the distance of the Moon, we'd be able to see you." And you are nodding as though you have heard this story.

WRIGHT: I was interested, yes, when I have seen that. It's an interesting statement. It's very, very descriptive for people.

MATHER: Yes. One of the main reasons is the telescope is cold and big, but the other one is the detectors are miraculously good. We didn't have them before. We had to pay good money for them. Then we had a surprise with them too, because there was a period where we discovered that we bought the good ones and we put them on the shelf, and they went bad just sitting on the shelf. So, we had to figure that out. And of course they did, they figured it out. There are places where you just have to have time and money to go do it over.

WRIGHT: I think someone referred to it as it has a "long development history." That was a kind way of saying that things were put in place, and hopefully exactly as you want it.

MATHER: Yes. But this of course is also the result of a lesson we learned from Hubble. Hubble was really difficult as well, and it was scarier in the sense that they counted on inventions to be completed on a schedule that was not realistic. So we said, "No, we are not going to do that. We are going to complete the inventions, and then we are going to make the schedule." It was still hard, but it wasn't so chaotic.

WRIGHT: There's so much that you've put together, but you started out at some point with a blank piece of paper. Then you pull in these lessons from here, and this information from there. Can you share some of the discussions that you had, of the ideas that maybe didn't make it, or that whole process?

MATHER: We can talk about the very, very beginning. The number one question is where are you going to put the telescope? Because that controls everything else. The first question was "Is there any possibility of building one that you can keep near Earth, like Hubble is?" We worked at it for a while, and the upshot was no, you can't do it. You would need a gigantic refrigerator that you can't buy to keep the whole telescope cold enough.

Where is the other place you can go? Well, this is called a Lagrange point two [L_2]. It's a million miles away from Earth, and the telescope will get cold all by itself if you can put up the umbrella. So that was our plan, and it's a different difficulty, but at least it's a possible mechanical engineering job to do. Put it a million miles away and put up your big umbrella. That makes the telescope cold. That implies a whole lot of other things. Number one, you are not going to go there to fix it, at least not yet. It'll be possible in the future, but isn't yet. That implies everything about the reliability process.

A lot of technology that we already know has to be polished up a little bit to work out there, but we tried to not invent anything that we would have to invent. People said, "Well, can't you use optical laser communications?" And the answer was yes, you could, but you don't need to, so we won't. No need to ask for extra miracles. Nowadays, you could do that. It would be just as easy now, but you don't need it for this particular observatory. Future ones yes, because they will produce 10, or 100, or 1,000 times as many bits per day, and so they need different stuff.

We were on the story of how did we all get started. The first discussion was where do you put it, and we answered that one right away. Then, how are you going to keep it cold? What sort of umbrella do you need? So we drew various shapes that you could have. Finally, I think it was very early 1996, we had a meeting up at the Space Telescope Science Institute [Johns Hopkins University, Baltimore, Maryland]. We had a draftsman from Goddard, some engineers, some scientists, and the people up there at the institute that had been thinking about this for years. We all got together, and we started sketching. We sketched something, and it's turned out about like what we built. The main features were obvious from the first day, practically.

Now I should back up and say what had been people thinking about before even I got onto the project. There was a conference in 1988, even before the Hubble was launched, and they had a big book that was published about what do we want next, and how much would it cost, and what would it look like, and what would it do? They were pretty close. At least some of the articles in that book said, “We want a big infrared telescope, and this is why, and this is how much it would cost.” They were closer to it than our team was for a while.

The sort of short answer is, why do you want an infrared telescope? Because it’s the next big opportunity. You can’t do it from the ground. A telescope gets very bright at infrared wavelengths, and the air is opaque at many wavelengths, so gosh, it gets pretty hard to do astronomy that way. Obviously, we don’t know much yet. That was even before the Spitzer Space Telescope had been launched, so we hardly knew anything. But we knew it was going to be the next opportunity.

WRIGHT: Were you able to apply a lot of lessons that you’ve learned from Spitzer? You mentioned that you have used the lessons from Hubble.

MATHER: Yes, some. The detectors they developed for that, we sort of went farther than they did, but similar ideas. Got personal experience in the end. We recruited several scientists that worked directly on the Spitzer to be on our team, so they had personal experience to make sure we didn’t forget what they knew. Of course, we also recruited locally here many people who worked on the Hubble Telescope. Their offices are all up and down the hall here, of people who worked on the Hubble before they worked on the Webb. That’s another way to not forget what you know, is to get the same people.

So that was the very early ideas. We also started right away with scientific teams discussing "What do you want to see?" The book had already established the basic idea, so then we needed to get a little more specific and say, "Well, if you want to see the first galaxies the way the book says, what were they like? How faint are they, how far away they are, and what color are they? What wavelengths are they bright?" And then you have to build your telescope to see that, if that's your objective. We pretty quickly concluded that we could build a really big telescope—an eight-meter was possible—and it would be enough to see what we thought the first galaxies would be. So, by golly, that tells us what to do. It's really hard, but that tells us what to try.

Then, after that, we had a day where NASA and the Space Telescope Science Institute staff invited industry people to come together. We said, "This is what we are thinking of doing, and we want you to understand it, because we are going to draw it and ask you to build it." Industry people told us, "Please go away for a little while. We want you to listen to our idea. Give us an hour, and we'll come back to you with our idea."

And their answer was, "No, don't do that. Don't draw the telescope yourself and ask us to build it. Let us compete with each other to show you our best ideas. We'll draw the telescope, and you'll choose, but we'll build. So let's start with a competition." They called it a Cooperative Agreement Notice, which is something NASA does to sort of share the effort with our proposers.

So we said, "Oh, we'll do that. We'll take the entire summer that year to do really quick, intense study, and we'll report out at the end of the summer on the various ideas." We had three teams, actually. Two contractor teams with their university friends, and the government teamed with the Space Telescope Science Institute team. We made these three gigantic [Microsoft]

PowerPoint presentations and documents, and we all presented them to each other at the end of the summer. Of course, the companies didn't present to each other. They wanted their secrets. But they presented to NASA.

So now we had three teams all saying, "Yes, we could do what you need," and we could afford the budget. Now, we had been commanded by Dan Goldin to please find a way to do this project for half a billion dollars. I see you winking at that. We actually didn't know if it was possible, but we said we should try. We should look. And we couldn't do it in the end. Half a billion, even accounting for inflation and the changes to the rules, was nowhere close to the right answer. Eventually, as you know, it cost $8 billion to get to launch, plus operations, and that's just the U.S. piece. I don't know what the dollar equivalent of the Canadian and European parts are, but overall the total mission is over $10 billion.

So Dan Goldin's vision was a little too ambitious, to say the least. But it wasn't a command. It didn't say, "Do it." It said, "Try to do it," so we tried. We had to go through a lot of ideas about how you might possibly do it that way, but there are two major reasons why it can't be done.

One is that we are not organized to do it in that fashion. To be organized to do it in that fashion you would basically say, "Okay, bring everybody together in one building, bring everything you need, and go like crazy." That's the model that SpaceX [Space Exploration Technologies Corporation] does, aluminum in one end and rockets out the other.

There was no way we were going to do that. Our project is much too big to do that, the expertise is too dispersed around the world, and just not going to happen. Legally, it also doesn't happen, because we are run by procurement regulations, and you just can't do that. So there wasn't a chance that it could ever have been done that way.

Also, SpaceX has the advantage that they do it over and over, so they learn each time to do it better next time, and we don't get to do it over and over. We get to do it once. It's like having to do it 10 times, but only fly it once. Since you don't get to fly it 10 times, you have to rehearse and rehearse, and practice and practice, and design and fail and design and fail, and then fly. That's basically why it takes a lot more work than people like to admit. So if we were going to do 10 of them, we could indeed do them a lot cheaper than doing one, but we are not doing 10. By the time we get around to wanting the next telescope, somebody will say, "Well, that's not where the next opportunity is. We want something different." We are not going to build another one of these that I can imagine. So we'll see.

WRIGHT: What did you learn that summer from the industry? You said you had those three presentations.

MATHER: We learned that basically we all had very similar ideas about how to do it. We realized that it was really hard, but we all had pretty much agreement about the technologies we would have to finish off also. The list of 10 things we had to invent was pretty similar in 1996 as it is later on, with the one exception that we had to shift from a solid hydrogen tank to an active refrigerator.

So that's how we got rolling. We also started having science team meetings. Now, this is before there was an official science team, so I called it the "volunteer science team." People that wanted to work on it, they came together, and we talked about what would be the coolest science to do, and how to calculate everything that was mentioned in the book. "How hard is this? What do you want to do?"

Then we decided, "Well, it's time to get official about this." So we said, "Okay, Headquarters will now solicit nominations and proposals to be on our official science team." We called it the Ad Hoc Science Working Group. I chaired that group, and our job was to say, "This is top priority for the project. If you could build it, this is what we would use it for."

This was important because we now have to decide exactly what are those instruments going to be—how big, how good. And now we are going to divvy up the project between the United States, Europe, and Canada, to say, "Okay, who's doing what part? The instruments are something that different groups could produce, so we'll definitely have to decide how good they have to be, and who is going to make them."

We went through that for a long time. We voted on what are the top priorities, and we wrote a book about what we thought was the best and most important stuff, and we called it *[Next-Generation Telescope] Design Reference Mission* [1998]. This is a sort of computer file saying, "Observe this for so long, and with these colors and so forth, and that'll open up science for us."

WRIGHT: What were you looking for when you were reviewing the nominations and proposals? And how many people did you end up bringing in on?

MATHER: I don't remember. I didn't do the selecting, that was Headquarters that did that. But we would certainly be looking for people who had convincing expertise on the subject, that had been through the trials and tribulations of doing other space projects, and that were respected in the community and everybody knew that those people could do the job.

We ended up choosing a fairly young crowd. They are not so young now, but they were young then. We even had a little worry for a while that these people are too young, but that didn't last. We did have external advice from more senior groups from time to time on various different kinds of things.

Finally, we basically said, "These are the instruments we are going to build," and we negotiated our international partnership. We got ready to choose, ""People have been working on this a long time by now." Because the members of that original group might actually become competitors for the proposals that we are going to solicit, we have to let them go and create a new group. So we created a new thing called the Interim Science Working Group, and I chaired that one as well. At this point, our job was more to advise the project management and Headquarters about what do we think is going on and what's important? While that group was advising us, we were at that point also preparing to choose the prime contractor, the big contractor.

That ran along until we actually had the formal solicitation—and Headquarters did this also—to choose the instrument providers. The instrument providers included European, Canadian, and Americans. The American one is the near-infrared camera [NIRCam], and that's Marcia [J.] Rieke at [University of] Arizona [Tucson].

The members of all of these teams became members of the new science team, the current Science Working Group. They have been with us ever since 2002, when they were chosen. At that time of course people didn't think it would take this long, so these people are no longer the youngsters that would be considered too much of lightweights to have community respect. They are the community-respected people, and they have all stuck with us, which is a remarkable endurance feat considering how hard the job's turned out to be.

So that's what I have been doing all this time with science teams. I have been organizing meetings, conducting the meetings, making people agree on things, conducting votes, keeping track of things.

WRIGHT: How often do you meet a year?

MATHER: Usually two or three times a year. And of course as the project grew, I no longer do it by myself. We now have I think 12 other young scientists—slightly younger scientists—here at Goddard, and they do almost all of that. In particular, my Deputy [Senior Project Scientist], Jon [Jonathan P.] Gardner, runs all these meetings now and he is really good at that.

All of the other areas also have individually-assigned scientists here at Goddard to make sure that some scientists are following the engineering work in detail. We don't do the engineering, but we need to make sure that we understand it and do a cross-check. Because once in a while, scientists think differently about things than engineers do, and it's a good thing. Now we could check each other.

The engineers say, quite rightly, "Well, if it's not broke, why, don't fix it. Don't improve it, it's good enough already." And the scientist once in a while has to say, "Well, it is not really good. We really should do better about that." We have had pretty darn good luck about that. We wrote specifications that we have not had to relax in most areas.

The engineers said, "We understand why that's important. We'll do that." And they worked really, really hard to make it happen. There are only a few things where we had to say, "Well, that's too hard. We are going to back off." The places we did back off were places that didn't actually matter that much. It means that we have an engineering marvel to match the incredible scientific demand. And you could say, "Well, that's also why it's expensive," but to tell the truth, there is no gradual thing in this stuff. If you said, "Well, why don't we just leave off all the instruments?" We'll get no science and it would still cost almost as much. Which is shocking, because there are so many large pieces of a big project like this, five or six different pieces. You have to have all of them, and they are all expensive. So they say, "Well, why don't we cut way back on that?" Well, it'll still have most of the rest.

WRIGHT: Did you find that you were making sacrifices?

MATHER: We did have one really important change to make at a certain time. Shortly after we chose our prime contractor they said, "Okay, the budget has to go up a lot." And it became immediately obvious that we couldn't afford everything we had been asking for. Even before we selected them, we said, "Well, we can't afford the eight-meter design. We are going to make a 6.5-meter telescope, please."

We got far enough with the technology development for the mirrors to say, "We could never afford the time and the money to build all the big mirror that you said. And besides, it won't fit anyway. The rocket's only so big, and it's a really snug fit." Maybe we could have made it fit, but it sure is snug. Another thing about the mirror technology—it turns out to be heavier than we thought. If the mirrors are heavier, you can't have as many.

Anyway, that's all the process we had to go through. The science team was deeply involved in all of these discussions about "What's the real requirement?" But ever since 2002, where we said what the real requirement was and who the players are, we basically haven't had to change anything.

WRIGHT: That's an achievement in itself.

MATHER: It's a major achievement. It means that what we said we would do, we could do. But the flipside of it is, it was a whole lot more expensive than we expected.

WRIGHT: Anywhere along that path that you thought you might lose the project because of the expense or the budget?

MATHER: Yes, it was obvious that you could lose it, but I thought, "I am not going to think about that part. I am just going to do my best." That's what we all did. You just can't focus on the bad part. You have to focus on the opportunity.

WRIGHT: You seem to have had the support, though, from the NASA Administrator.

MATHER: Yes, we have had. It fluctuated. Some people were more interested than others. By about 2011, we knew we were in big trouble. We had been asking each year for more money, and the curious process in the federal government is you don't actually ask Congress directly. There are so many people between the project manager and the Congress that it's like a game of telephone. Each level above you says, "Well, I don't think I can ask for that much. I am going to ask for less." By the time it gets around to Congress, people are basically asserting that we can do fine with a small budget, and that's not true.

By 2011, it was embarrassing to everyone. NASA was embarrassed, [Maryland] Senator [Barbara A.] Mikulski—who was a really strong backer of science—was embarrassed. She wrote us a letter and said, "Please come back with a plan we can believe. And please get an external committee to review it, too." So we did that [James Webb Space Telescope (JWST) Independent Comprehensive Review Panel (ICRP)].

That was chaired by John [R.] Casani at [NASA] JPL [Jet Propulsion Laboratory, Pasadena, California], a very famous project manager of great honor in his own world. We felt the committee was kind of hostile, but in the end they wrote a [2010] report that basically said this: "Did great work, didn't ask for enough money." That's about the best words you could hear. That's my version of what they said. They had a lot of detailed recommendations, but I thought you couldn't ask for better.

Congress actually heard these words. I don't know the process at Congress—I didn't have anything to do with that—but somebody said the right things and Congress said, "Okay, we'll send the money." And they kept that plan. NASA put that into the budget every year, and Congress said yes every year since then.

So for six years now, we have had a do-plan which we have stuck to. The Congress sent the money, and we do the plan. Knock on wood, because it isn't a guarantee of future performance, but we have done awfully well. I do not know exactly how we accomplished that. I know Bill [William R.] Ochs and the project managers made that happen. For every technical problem that comes up, you have to find a work-around that you can afford, and they did. That's another miracle.

WRIGHT: While we're talking about management and connections, you are the project scientist, and you just talked about the project manager. Can you talk about your responsibilities and how they fit in with the other parts of the management, and how you have ended up communicating the necessary things to each other to have it work?

MATHER: At the beginning we said, "Well, these are the general scientific objectives, and this is what we want to look at." Then we calculated some more and we said, "Now, this is how big the telescope has to be, and how long you have to look, and how good the detectors have to be. And if you can do that, that would be great."

We wrote that all down in a book called the Science Requirements Document, and that got translated into detailed engineering requirements by engineers. We worked together to make sure that the translation was correct. And then after that, it's pretty much been engineering. Engineers understood perfectly—well, we met and once in a while they said, "That's too hard. Can you back off?" And we said, "Yes, maybe we could." Mostly, they understood no, you can't back that off, because we know why that was important to us.

So they struggled and struggled, but they solved the tough problems. And that's actually good. It's astonishing how much effort you can waste saying, "Why don't we cut back on something? Are you sure you need that? Maybe 1.5 sandwiches is enough for lunch instead of two?" You could spend a year figuring that out. In that time, you are wasting your time. It's much better to say, "This is the requirement. Let's go fix it, let's go make that happen." So, people did.

In the early days that was not quite the case. In the early days we had people arguing, "Well, I would like to redesign your observatory, and it'll be so much cheaper my way." That was kind of confusing. People knew it would be expensive, and they were afraid, for a good reason. What if you go do all this work and people say no? But I guess my observation is stick to your plan, and be inspired and inspirational about it, and people will eventually see that. So they did.

WRIGHT: The engineering task—you are the project scientist, is there a project engineer specifically?

MATHER: Yes. We have many project engineers, but my nearest counterpart is the systems engineer. His office is right next door, Mike [Michael P.] Menzel, and he is brilliant. He is just a wonderful guy to work with. He understands what you say and why you mean it, and he knows how to accomplish what you want. And he knows how to exert himself in the team to make good things happen.

Of course there is not just one systems engineer, there are many. Each subsystem has its own systems engineer and managers. A typical engineering team has a manager and a systems engineer at the top, then they make sure all of the people that report to them have done the right technical work, and have gotten it done on budget and schedule. That's what that team does.

Our job as scientists is to hand our science job on to their manager and the systems engineer, and say, "Please build this, please." When they fully understand the job, that's what they do. We like to participate in their discussions to make sure that they do understand, but they understand. It's very rare for a scientist to come up and say, "Well, I have a better idea about how to do your engineering job." The engineers are really good at what they do, and very rare for a scientist to have a better idea. Once in a while, we have something to contribute, which is something nobody has ever done before, and I'm happy when we can do that. But mostly, it's scientists cheering on the engineers and checking that their work is what we meant.

WRIGHT: And then you have a project manager that oversees it all?

MATHER: Yes.

WRIGHT: And relays to Center management, and then on to Headquarters as well?

MATHER: Yes. Bill Ochs, his office is down the hall. Have you interviewed him?

WRIGHT: No, I have not.

MATHER: Then you will want to do that sometime. Right now, he is really busy. In fact, I think that's true until we're done, because he is the focal point for everything about success. So I am cautious about asking for his time. I don't want to take his time. I don't need my hand held, I just want to know that he has got what he needs.

WRIGHT: And you are going to be pretty busy. Are you shifting gears now as you are getting closer to launch?

MATHER: Yes. As time has passed, I have accumulated so many young people to work with me that I don't do technical work much. Most of my work now is communications, and making sure our general public is aware of what we are doing and why we are doing it, and looking at big-picture items.

But in general, what our scientists are doing now is getting ready for flight. We have got the Space Telescope Science Institute in Baltimore, and they are going to do the scientific operations there. The control center is there too, with NASA participation. So we say, "Okay, these are the commands we are going to send every day, and this is okay or it's not okay." I think we have an intricate, interlocking process between the NASA engineering team and the people we hire up there. Their job at the institute is to make sure we know where to point the telescope and why. So they are going to complete a process of soliciting proposals, reviewing them, putting the selected ones in order, and making the observations according to a schedule. That's a hugely difficult challenge. It's a big team up there that is required.

After we take the data, then it all has to be processed through the computer and made available to the users and say, "Your star is so-and-so bright at each wavelength," or "Here is a picture of the thing you wanted us to take the picture of for you." And it's all been processed. Everything that we know of that represents the instrument has been removed, so now you can say, "This is in standard units, and you can trust what we are giving you." So we do that part.

Those scientists that are chosen, by the way, are all around the world—American ones, some European ones, some Canadian ones, and who knows where else. That's being figured out now. Me personally, I don't have any particular observing plan at the moment. I will have to write a proposal too, if I want to observe something. I have some ideas, but they are not particular radical or interesting, so I don't know what I am going to do at that point personally. I could say, "I really want to do something else, because this is a big notch on my accomplishment list, but I want to do something else." Or I could say, "Well, now I have a really great idea of something I want to observe." So I don't know what I am going to do.

WRIGHT: If you could tell me some more about the science team that you have been working with. As you mentioned, they have been on since the early 2000s, and hung in there. I guess that's a compliment to their institutions, that they have allowed them to stay on this project. Each one has their own separate duties, but yet you will all work together to talk about things. Kind of give us an idea of what happens with that.

MATHER: Right. We have got several categories of these people on the science team. The first category are people who are in charge of an instrument, who make sure that it is built and provided to NASA. Those are called "principal investigators" or "team leaders." In the U.S. we pay them, because we are going to send them whatever it takes to buy that hardware. And of course their institution is happy for that.

In Europe, they have different arrangements. They have to pay their own scientists. In Canada, ditto, they have their own fund sources. But their fund sources have been happy with them. I think everybody recognizes this particular project is really the big thing that we would be proud to work on, so everybody has managed to come through with their support.

That's the first category, and those people all have guarantees of some observing time. They have already been required to submit their list of targets, so they get dibs on things that they say, because they are guaranteed-time observers. And they get a total of about 4,000 hours altogether for all these teams.

There is a second category who are called "interdisciplinary scientists." Those are people who observe but do not build. They also get a share of that several-thousand hours, so they also have submitted their list of proposed targets to look at. There is a third category of people that are more like me, who are in the job because of a position in our agency. So I am working for the government, for the taxpayer, to do the right thing. A lot of us are on the committee for that reason, representing our countries or our agencies. So it is the mix of these three categories. None of those ex-officio people have any guaranteed time, so we all get to propose if we want to use the telescope.

WRIGHT: Do you find that the people from each of those categories have different inputs or feedback depending on what your conversations are about?

MATHER: Yes. Yes, we have very different perspectives, and useful.

WRIGHT: Can you give me an example of maybe a topic or two or something that you all discussed that it was good that you have that type of a mix of people? That it seemed like it advanced the discussion, maybe kept from a failure? Just an example that you take different type of scientists and how it works well. Because sometimes we think that we should all have people that think like us to get anything advanced.

MATHER: Okay. So diversity of opinion, if not of appearance.

WRIGHT: There we go.

MATHER: Clearly, the instrument builders know the requirements of their hardware totally, and they are responsible for delivering stuff. So if we want to know "Is this going to work?" we ask those people. This is hugely important. If you ask me "Is it going to work?" I don't know, because I don't know the details.

On the other hand, I have the job of trying to make sure the entire planet knows how good this is, and why they should be building it and supporting it. We also have a little bit of difference of priority, too. I work for the public, so my job is to make sure we get the best science for the entire observatory, and the individuals that have guaranteed time, they do not. They have a job to make the best of what they have been given, but that's not the same as the general public. This is not exactly the same interest. It's a little bit different job.

It gets to be interesting when you say, "Well, what are we going to look at first?" Is it the people who have guaranteed time? The guaranteed-time observers get to keep their information private for a year, but that's not necessarily the best for the world, particularly if there is some chance that the observatory doesn't last forever. Similarly, if you find something really exciting, we all want to follow it up, so please don't keep that secret forever. Those are competing interests, so that's a thing we currently think about, is how do we resolve that? We have a process, and basically it is a combination of ask politely if you will please let the data out sooner, and also provide some motivations.

We also developed, based on input from advisory committee, something we call the "early release science." This is different from what the guaranteed time investigators have. We said, "Okay, we are going to ask our entire world community for ideas about what we should look at first. This particular small amount of time—a few hundred hours of observing time—is going to be whatever you all say, and it will all become public right away. So it's great that you are going to volunteer to help us do this, but you don't get to keep it to yourself."

That's an answer to the question of "What if you see something really cool but you keep it to yourself?" That's part of what we do. Again, our project is so large that I don't do any of this personally, though we have a process. So that's how it goes.

WRIGHT: Interesting statement that you made, that the answers or the discoveries belong to the whole planet. Which is different from when SpaceX might launch. They are doing it for their company, and for their customer, but science belongs to those who have an interest in it.

MATHER: Yes, yes. There are different kinds of reasons for people to do stuff, but a great nation does this. We give stuff away. We get credit for it, but we give it away, and that demonstrates who we are. So we encourage people to do that a lot, as much as we can.

But the people who don't want to give it away right away have their own reasons, and fair enough. Particularly, university professors have graduate students, and the graduate students need a shot at getting their degrees from analyzing this information, so they don't really want to be competing with the people who could write a paper tomorrow about the same picture. And there are people who can do that.

When we published the COBE maps a long time ago, the next day there were published papers about them. People had been waiting for that to come out. They said, "We already know what we are going to say if it's this way, and we already know what it's going to say if it's that way, so the whole paper is written. We just have to plug in some numbers." I know some people are like that. No graduate student can compete with that, so the university people have multiple reasons for wanting to do it their way. We'll see, it'll be fun.

WRIGHT: You mentioned earlier about some of the lessons that you learned that you applied from the Hubble, and of course one was the fact of trying to get everything exact as possible, because you won't be able to repair anytime soon. How much of an impact was that? I read something about how everything was measured twice, and I am not sure if that was a statement that you made?

MATHER: I would have said something like that. The carpenters say, "Measure twice, cut once," and they are right. Here, our version of it is if you really, really require something to work, you better measure it twice independently. The error that was made on the Hubble mirror was about a ruler. In the end, it was a ruler. It's a reminder that if your two tests use the same ruler, they could both be wrong because the ruler is wrong. Do not use the same equipment to test the thing as you use to build it with. So we made sure. The Webb Telescope mirrors are measured differently when we accept them than they were when they were built, and we have multiple ways to do that. That matters a lot to us. Everything that matters, you've got to be sure.

It's a general lesson for life. If you really care about something, better make sure more than one way. You can't just ask John Mather if it's okay. If you need an opinion, you have to at least ask two people. If you need a measurement, you better have two independent measurements. If it's a theory or a calculation, you better have two different people do it, with two different tools.

We found, for instance, that the tools were incorrect in places. You buy a computer code that's supposed to calculate how much stray light is going to get in because starlight is bouncing off the mirror in a certain way. We had several different computer codes we were using, and they were all incorrect in some different ways, so we were able to find it. When it matters, you have got to really push. And who'd have known that one? You would never suspect that the computer code is incorrect, now would you?

WRIGHT: No, no.

MATHER: But it can be, it can be. And of course, the reason that we would find it and other people didn't is we are applying it in extreme circumstances. Our telescope is cold, it's dark. Everything is different about our computer simulations than it is about anybody else's. They are enormous, too. Our computer simulation of that hardware has got millions of nodes in it. You know about nodes and simulations?

WRIGHT: Some, but not as much as you.

MATHER: Basically, it says, "We are going to divide our physical object into little bits." The computer will know how they all connect to each other. The more little bits you do, the better it could be, but then also the harder it is to do it. So in our case, the hard part was things like the joints between carbon fiber structures.

Carbon fiber is inhomogeneous material. It's carbon cloth made with glue. You come to a joint and you say, "Well, neither of those is the mix that I've gotten in the joint. It's a different kind of glue." So you have to make a computer model of the joint of two pieces of carbon fiber stuffed together that goes down to tiny, tiny pieces to account for the fact that it's a variation of properties from place to place.

That's one heck of a hard thing to do, but we had to master that one, because that big structure is enormously complicated, and we didn't want it to twist, bend, warp, and other things as it cooled down. And even if it does, after it's cold you don't want it to be changing. It has to just sit there. So a huge investment of that was required by our engineering teams. A hundred years from now you would say, "Well, why was that so hard?" But today, it's hard.

WRIGHT: Yes, it definitely is that. October 2018 is the current launch date. You will be busy until then, I am sure.

MATHER: Yes, for sure.

WRIGHT: We talked about the user community and getting those things ready. I think another term that you have used—whereas Curiosity [Mars rover] might have had the "seven minutes of terror," you said you were going to have six months of terror. Talk about that. The launch is just the beginning of the wait.

MATHER: Yes. It's actually not that bad, but the launch is the beginning of a checkout period that lasts six months.

But ours is different from the Mars lander. The Mars lander had to do it all by itself. There was no possibility of us noticing a problem and fixing it on the way down, because the landing, seven minutes long—it takes longer than that just to get the information back. That little guy had to do it all by himself, all alone, so everything that could have gone wrong they had to fix it in advance. That was hard. It took imagination, it took skill, and it took a lot of computer code checking.

We have a different plan. We do it step-by-step, under individual commands, and at every step you say, “Did I get the right answer?” And if I didn’t, this is what we know we have to do about that problem. Our system is redundant. Every motor has two sets of electrical winding on it, and two sets of controllers, so if it doesn’t work we can switch to the other. And so we will be doing that.

Ideally, we don’t have to do any of that switching to the backup, but there is always a backup. And we have time. We have got quite a long time allowed for focusing the telescope. We have about 10 steps that it takes, each of which has many sub-steps. When you first unfold the telescope, it is nowhere near correct. The mirrors, none of them are in place. We know about where they are supposed to be, but they will have just survived a launch—a heck of a lot of vibration—so nothing will be exactly right. A lot of time allocated to figure that out, yes.

WRIGHT: And you get to enjoy the moment.

MATHER: Yes. But as long as it’s not dead, we have just routine engineering. That’s the plan. That is something we are ready to do. We already have rehearsed all this stuff. A year and a half before launch, we know how to focus that telescope. We have got simulations, we have got the scripts written.

A vast amount of stuff has already been done so that you would get pretty close to the right answer if you did what we have ready today. We will have plenty of opportunity to check. The tests that we are about to do at Johnson, many of those scripts will be tested. We'll focus the mirror in the big vacuum tank there to make sure that works.

WRIGHT: From what I understand, it's going to be behind closed doors for about 100 days. Is that correct?

MATHER: Yes. It will be in the vacuum [JSC Chamber A], so really closed door, yes.

WRIGHT: It's amazing that it's going in there. Talk some about why it went to Johnson, and the work that Johnson had to do to prepare for it.

MATHER: Okay. Well, I only know the top-level version of it. A long time ago, when we were just beginning this project, we thought, "Oh, they have a really gigantic vacuum tank at [NASA] Glenn [Research Center], out in [Cleveland] Ohio." So people imagined that was the place to go. Then when we got down to it, it turned out no, that's not a good place after all. Without going into details, it would have been really hard and expensive to do that. So what are we going to do? Well, we had better look around. Then we found Johnson is the place to go. They have a big tank, it's leftover from Apollo. It's a good tank. It hasn't been much used, but it's available.

But then, what we had to do was pretty big. We had to really scrub it and clean it, because we are going to put something in there that cannot be contaminated. And we had to cool it down. This is something they didn't need for Apollo. We have to make sure it is going to be so cold that it'll be simulating the temperature the telescope will have out there. We had to buy a gigantic refrigerator. It's huge. I have seen the warm part. It's a gigantic red thing, about 30 or 40 feet long, and uses a megawatt of power to cool the insides. There is also just the precooling, and we take truckloads of liquid nitrogen to cool the outer shells.

So this is a huge engineering project just to get it cold. We spent quite a long time getting it ready, cleaning it up, making sure there are no sandwich bags at the bottom, all that stuff that could have been in there. It's hard, but they did it, and so it's ready.

Then, after we got the chamber pretty much ready, we have to get the equipment ready. You can't say just, "Well, I'll push the telescope in and make it go." You have to test the test equipment. So build all the test equipment, build a simulator for the telescope so you can test the test equipment on a simulated telescope. We did all that. It takes a long time to do this, but you can't avoid it, you have to do it.

WRIGHT: And they modified the building itself to build an actual cleanroom to protect it, correct?

MATHER: Right. Since the telescope has to be clean, you open it up in a cleanroom, which we didn't have. So around the front door of the tank, we put a room with clean air, and the process for doing that.

WRIGHT: Have you been down there? I know that you are going in a couple of weeks, but have you been down there already to see it so far?

MATHER: Just briefly, I was there last week. We had a visitor, [Congressmen] Brian Babin and Randy [Randall K.] Weber, whose districts are right there [in southeast Texas]. So yes, I went for that, and I have a phone message about "Brian Babin just came in this afternoon," so he is interested. He is clearly very interested in the Webb Telescope, and in NASA. Glad to see that.

WRIGHT: Yes. It's always good to have a champion somewhere on the [Capitol] Hill to keep it going. When you were developing those new technologies, we always use the expression that they are "state of the art." As you have been working on these, do you feel like the technologies that you developed and designed so many years ago are still the ones that you need to go where you are going?

MATHER: Yes.

WRIGHT: Or you always have that fear that something better is going to come along?

MATHER: That happens in other parts of the world, where there's other customers—if you want a better computer processor, somebody else always wants one too. So if you wait, one is going to happen. In our world, there is nobody else that wants what we want, so there is no other, better one anywhere.

There is one small area where better ones—or bigger ones anyway—are coming along, and that's the infrared detectors. There is a new generation currently in progress that's got a larger format, more megapixels. I don't think it's more sensitive, so we really didn't have to have it. We are getting just about as good a result as we would have gotten if we could have had the new generation. That's the only one that I am aware of where progress has continued after we stopped developing.

WRIGHT: Is the project living up to the expectations you wanted it to when you started 20 years ago?

MATHER: Yes, it really is. I had no idea how hard this was going to be, nobody really did. But it was really clear to me that this was the next great opportunity, so it didn't take me five seconds to say yes, that's what I wanted to work on when I was given the shot. So yes, it's what I want. And I am sure we're going to discover something amazing. I just don't know what it is yet.

WRIGHT: Well, that was going to be my next question. A lot of people have lots of speculation of what you feel like it's going to be able to do, but I was curious if there is something you really want it to do?

MATHER: Yes. I'll just give a few guesses about things that might turn up that we can be sure about. I think we are going to get a big surprise about the first galaxies. They are unknown to us, so we don't know how the black holes were formed that are in the middles of big galaxies. We don't even know how the little ones are formed that are making gravitational wave bursts, now that we have seen three of those.

Black holes are still a very big mystery. I have a speculation that there is some form of small early galaxy that came and went, that was formed and then disappeared. That would be an explanation for why don't we have any of them locally. So I am guessing there is something like that out there.

We have something we didn't expect in the beginning, the ability to study planets around other stars, exoplanets. I think we are going to get a surprise there, because everything we know has been a surprise. The laws of physics are not changing, but what nature does with them is always a surprise. I have a friend who works on the exoplanet subject, and he says we are still waiting for our first successful prediction of anything about the exoplanets. Everything has been a surprise. That's cool. So whatever we find, it'll be a surprise as well.

We could get a surprise about something ordinary—quote, "ordinary"—like how do stars form? They do it in places that are invisible, mostly. You have seen our beautiful pictures like the Eagle Nebula [Messier 16/NGC 6611], and they are beautiful to look at because you can't see inside. So gosh, what is going on inside? Well, I'd like to know. We'll make some progress with that.

Here is a weird example. What if there is a little class of sub-stars that are just zooming around and filling the local space, and the nearest-by luminous object is nothing like that we ever saw? What if little Jupiter-sized objects are zooming around in-between the stars? Well, I think it's pretty likely. We are beginning to think so, have found a few. There is even a star out there that I call a "chilly star." It's called a brown dwarf star. It's a real star, but it's cooler than the Earth.

WRIGHT: What kind of impact do you want the Webb Telescope to have across the planet? What are you hoping it'll do?

MATHER: Well, I would like us to be able to put newer, better pictures in every astronomy book, and new stories about how things actually happened. Our general idea is we wanted to look at everything from the Big Bang until now, so the first things we hope to see are the first stars and galaxies, and black holes. We want to see the galaxies grow.

We have a story, we've got lots of computer movies we didn't used to have, and they might be right, but they might not. We would like to see the stars and planets being formed, and we are just getting a hint about how to do that. And we'd like to see everything about planets and how they form, and might even turn into life-supporting planets. We don't think we are going to see life on another planet with Webb, but we are certainly going to look and see what we can see. It is thought maybe we could see an Earth-like planet having enough water to have an ocean. On the other hand, we have no idea whether to expect that or not. We know of a few really nearby planets. The nearest star has a planet, Proxima Centauri. You saw that, right? There is no particular reason to think it's like home.

I think the most likely thing about planets around weird stars like that one is that they are round rocks, that they are just lifeless, bare things. Some of them will have atmosphere, and some of them will be roasting hot. I don't think very many of them will be home. But we have got to go look.

The idea that you could find the TRAPPIST-1 system of planets starting with a telescope on the ground? That telescope on the ground is about this big [demonstrates], and they were able to detect three of the planets with that. So then they said, "Well NASA, can we follow that up with your telescopes in space?" And yes, now we have got seven [planets]. So we have got surprises coming to us from a lot of directions.

Did you see a week or two ago, they announced they had found a disappearing star?

WRIGHT: Yes.

MATHER: You saw that? I think I believe it, and what can happen to a star that disappears? Well, it could turn into a black hole. That's the first explanation, and a popular explanation. Now, what else? I don't know. Maybe it surrounded itself by dust, but I think they have already argued against that.

WRIGHT: You'll have the next 20 years to enjoy all of the discoveries at the lab. So what are you planning to do after this? Not that you'll have a lot of free time.

MATHER: Well, a lot of possibilities. I could go retire and go to the beach, but I don't think I will. I could write a book, I have some ideas. I could observe with the Webb, I could actually help contribute to the new observatories we are working on. NASA is currently studying four really wonderful observatories to be considered in our next decadal survey. Have you seen that stuff? Paul [L.] Hertz, our Director of Astrophysics at Headquarters, has decided to study them all so we can have a serious discussion in 2020.

They have also selected a handful—maybe six or eight—probe-class missions for further study. These are smaller, and you could do more of them. All those are interesting, too. I got to contribute to at least two of them to help them win, so I was really pleased with that. Those are smaller, quicker, could be opening up new territories.

One that I am fond of is an X-ray telescope that would look for X-ray flashes. If you could see the X-ray flash associated with some event like a gravitational wave burst, that would be exciting. Then we would be able to say, "Okay, point the Webb Telescope"—or any other one—"over there today, see what that was."

There is so much happening. It's all I can do just to keep up with the popular stories about it, much less contribute to details. I could imagine going back to school. I wish I was a graduate student again. The kids coming out of school now, they know so much.

WRIGHT: When we came in, you had a group of them. You were commenting about projects, that these are never done alone.

MATHER: Yes.

WRIGHT: Talk about what it takes to put one of these projects together, the dedicated people, and all these new—as you mentioned—young people that are excited about learning more, and giving their time for discovery.

MATHER: Yes. I think everything we know is community knowledge, in a way. I came across a really lovely article that pointed this out. People are concerned these days that kids don't know how to understand evidence. And nobody really understands I think in a way because we are all embedded in a context. I know to trust science because I have grown up with science.

Other people know to trust their neighbors. You know, where do I get the best tamales? Well, ask your friends. They say, "Oh, go over there. That's where they are." We all have our local sources of knowledge, and that's a universal phenomenon of people. Our science community is a real community, but it's spread out, it's dispersed. We have got scientists in every country. If you want to know about your neighborhood, then your neighbors are your community.

That's sort of an aside from this, but it's a reminder that we can only do what we do because of the communities, and our communities in technical and scientific things are dispersed. If I need a widget that does something, I may have to go to Kansas or California, or Azerbaijan, or wherever they are made to find them. That is changing quickly, since everything can be posted on the internet in a flash, for good or bad. The community is also spread out in a way that it never was, so when you say, "Well, I think I am going to invent something," the first thing you do is Google it, see if it already has been invented. Then you say, "Oh, oh no! Somebody already invented it. I'll just buy it. So now what? What am I going to invent next? What else do we need that we don't have? Oh! I'll Google that." Or, "Nobody has invented that. Who could help me?"

This has changed so dramatically, and our technology has changed so dramatically, too. When I came here to Goddard in 1976, people were designing satellites with pieces of paper and sharp pencils. And they were good at it, but it was really hard work, because it's really hard to visualize something that you've drawn on a piece of paper. If you have gotten a computer design now, say, you can rotate it in front of your eyes, you can put the other parts together with it, you can see when that will all fit together. In the old days with pieces of paper, you had to build it and see if it would fit, because you couldn't visualize well enough.

So things have changed a lot. We can 3D-print parts you could never possibly construct before. So whatever it is you want, we'll be able to do it. I heard the futurist of Microsoft [Corporation] talk once and he said, "If you can imagine it, you can build it." It's almost true. If you want a thing that's made out of an atom here, and another atom over there, and another atom over there, if you really want it, we can make it.

I used to think, well, travel to the stars is obviously impossible, but one of the members of the COBE team was behind this idea of the Starshot. Have you read about the Starshot?

WRIGHT: No.

MATHER: It's now being supported by private funding, as well as some by NASA. It's called the Breakthrough Starshot. The idea is you get one heck of a powerful laser, and one heck of a tiny projectile that's large and very lightweight. It reflects the light back, and you can push on the thing with the laser beam, and can accelerate it to a quarter of the speed of light. It'll get to Alpha Centauri in 20 years. It is impossible today, but it's not impossible under the laws of physics. This is my sort of motto for things. If it's not impossible according to the laws of nature, try it and see how far you can get. They are trying it, they are already working on it. And you can draw what you need. You can't build it yet, but you can draw what you need. I like to think about things that are really hard and really impossibly difficult, then see if we can do them.

WRIGHT: When you were talking about the design of the technology, and then you were also talking about how the engineering and mechanical and the scientific all came together—when someone looks at the model of the JWST, it's very simple, but yet it's very complex. It also, when it's standing there with its glorious mirrors, reminds you so much of artwork. I've actually thought of it being more of a "space-art-craft" instead just a spacecraft.

MATHER: Yes, yes.

WRIGHT: Then you shared with us too, when we were walking in about how Goddard had an art day. I'm looking at an art piece on your desk, but explain how this other piece of artwork came out to typify what's going on with the telescope. It's very unique.

MATHER: We had an art day that was dreamed up by one of our public outreach specialists, Maggie [Margaret E.] Masetti here. She organized a day for artists to come and look at the telescope through the cleanroom window. They looked, and they thought, and they imagined, and they drew. They wrote poetry, they painted pictures, they sketched, composed music—all kinds of things happened.

And one artist had the idea to make this thing that I'm showing you [demonstrates]. This is the small version. She has got a Webb Telescope mirror made out of 18 hexagons, as the real one is, but she's got arms coming out of it. These are arms. One of them, this is me. This is Amber, I guess, I think that's Amber [N.] Straughn [Deputy Project Scientist]. I think this is the artist herself [Ashley Zelinskie].

She does a 3D scan with a portable scanner of each person's arm. I just held my arm here like this, and she walked around my arm. So there it is. It's made small, and coated with real gold. Made with a 3D printer. All of this is something you could only have dreamed of a long time ago, and it's done by high-tech [technology] stuff now. If you said, "Michelangelo [Renaissance artist], can you make me one of those?" he could have, but it would have been a very different process.

WRIGHT: I have my ideas of what the artist is saying, but what do you think she is saying with that? Or what did she tell you she was saying?

MATHER: She didn't say what the story was that it was telling, really. I have a piece of paper that summarizes how it was made, but it doesn't tell the meaning of it. So the meaning is whatever you give it, I think.

WRIGHT: I think so, too. I think that's how art works, right?

MATHER: Yes.

WRIGHT: It's an amazing spacecraft, because that's what it is. When you take all the different types of arts and sciences and put them together to create, and of course to bring back what it's going to bring back.

MATHER: Well, I like to say that science is about imagination. A scientist has to imagine something that you cannot see—and not only imagine it, but imagine it so well that he or she can say, "And this is how it works." And if you are really good at it, then you can say, "And here are the equations that describe it." Or maybe you can't do that. Maybe you just have a story, but you say, "This is how chromosomes work." Well, I've never seen a chromosome, but I know how they work, sort of. I have seen movies about how the chromosomes are ripped apart by little chromosome readers in the cell, and then put back together after they've been copied. We have got a movie of the Xerox machine that runs inside the cell to duplicate a chromosome. Isn't that astonishing? It was all done by imagination.

Similarly, our engineers have to say, "Well, we are going to build you something that was never built before. We are going to imagine it, and then we are going to build it." They have to imagine also all the ways that it might go wrong, and make sure that doesn't happen.

People might think differently about us. I think science has been so badly taught in so many places that people don't know what we do. Some people think, "Well, scientists are just those people who know so much." My picture of it is we are the people who know the least. We are always thinking about the stuff we don't know. That's kind of the opposite. We are up against the crossword puzzle of the universe. How does it all fit together, and can you tell a story about how it really works? If you understand that, can you build something you want that's based on that?

That's what we have been up to while the public thinks we are trying to make them learn things they didn't want to learn in physics class. We are imagining the world as you cannot see it, and trying to make it go the way we want it. And that's really different.

WRIGHT: It is, it is that. Is there anything else you have you thought about you'd like to add about your project?

MATHER: I always think it's important to mention that individual human beings made this project possible. Our first team leader was Bernie Seery, and I guess you know his name right, already?

WRIGHT: Yes, yes.

MATHER: Then we had Phil [Phillip A.] Sabelhaus, and he died a few months ago. He had retired from NASA. He was having a good time, he was going to go off on travel to go to the beach and see all kinds of things, and he died unexpectedly soon. Our current Project Manager is Bill Ochs, who you know, right?

WRIGHT: I know the name, yes.

MATHER: Yes. And he was just down the hall, you'll want to talk with him.

I think, personally, that the art of project management is much more difficult than the art of science. You can get a building full of managers, but only a few of them would be able to pull off a project like this one. We have one, so I am totally, eternally appreciative of what they do. I don't think I could possibly do it myself. I could study and learn, but I'd never be able to do what they do. That's how I feel. It's like when you watch Roger Federer [tennis player] play, you say, "Well, I'm glad he can do that, but I can't do that."

I am so appreciative of the individual human beings, and also of the system that we have built up here at NASA. We struggled at the beginning, we couldn't beat the Russians at first, and now what we can do is astonishing. I am just amazed at what we can do. The people who built the system that we are in, we don't even know who they were. But they built the system.

There was a system that enabled NASA to recruit me. There was a system that enabled NASA to recruit all these people that enabled us to build the hardware, and the buildings, and the tanks. And Congress, who has decided they like us and they will send us money. And there was the Soviet Union that forced us to do it. Yes. Who'd have thought that was an important part of our system? But it was. They scared the bejesus out of us here in this country. I don't know where you were in 1957, but people were scared.

Even before that, they were teaching little kids to hide under the desk in case of nuclear attack. Even when you are seven years old, you think that's stupid. But it just showed us we were scared. And then they said, "Oh, that must be the fault of the educational system that we didn't do the right thing over there, so we are going to make sure the kids have science." So I got to benefit from that. The country spent a fortune, but look what we got.

WRIGHT: And are still getting. Or you wouldn't be having those students in your office ready to work hour after hour, and write word after word.

MATHER: Yes. We are discovering stuff, and this is an extraordinary part of history. We are right at the beginning of a new era, and I don't know what it's going to be. It's going to be different. But it's very exciting.

WRIGHT: It is exciting, and I wish you the best of luck in the next 18 months, and then after that.

MATHER: Well, thank you. We are working hard to earn our luck. We do the test, we argue and think. And that's what it takes to earn our luck.

WRIGHT: Well, we look forward to exciting times and reading more things.

MATHER: Okay, Rebecca. Thank you for coming to ask.

WRIGHT: Oh, thank you so much for your time. We appreciate it.

[End of interview]