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INTERVIEWED BY SANDRA JOHNSON
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JOHNSON: Today is June 7th, 2017. This interview with Dr. Paul Mahaffy is being conducted for the NASA Headquarters Science Mission Directorate Oral History Project at Goddard Space Flight Center in Greenbelt, Maryland. The interviewer is Sandra Johnson, assisted by Rebecca Wright.

I want to thank you again for agreeing to talk to us. I want to talk about your educational background, your early life, and how you first became interested in working for NASA. I know you had a little different upbringing because you lived in Eritrea. You were actually born there.

MAHAFFY: Correct.

JOHNSON: Talk about those early years, and what made you interested in chemistry and then led to NASA.

MAHAFFY: Yes. My parents were with a mission, and I was born over in Eritrea along with all my many siblings. Seven children in our family. I was right in the middle, the happy spot there in the middle. My mother, who in her early days was a country schoolteacher, taught us all.

There was some English in the little village that we lived because Eritrea had been a British protectorate at one time. So in addition to the multiple languages that people spoke, there was also some English there. But it had also been occupied by the Italians, so a lot of the folks spoke Italian. I think when I was kid I probably spoke Italian as well as English. It was a beautiful spot in nature. We were up in the mountains, 7,000 feet or more above sea level, and in a very small village. Education was relaxed, I would say. We were taught by our mother, but the time constraints you have in a normal school—with school opening at a certain hour and closing at a certain hour—weren't necessarily there. We could take a day or an afternoon off and go hiking in the mountains.

When I moved back to the States, into Chicago, in 1966—dating myself—I went to a high school as a junior, and it was the first time I'd ever been in a real classroom situation. It was an interesting experience, particularly learning, and taking tests, and paying close attention to the clock. I remember the first SAT [Scholastic Aptitude Test] test I took for college prep [preparation]. I was systematically plugging through the questions, because I didn't know how to take tests yet, and, by golly, I got about two-thirds of the way through and time was up. I got an outstandingly low score. Then by the time the ACT [American College Testing] tests came along, boy, I had learned, and ended up in the very high percentile.

My mother had been nervous about modern math, some of the new things they were teaching, but she got the textbooks and did her best. Then in high school I got very interested in both chemistry and math, and that kind of provided a background. When I went to college I majored in chemistry and had a math minor, and that was a good background for graduate school where I majored in physical chemistry. Again, that provided a good background for what I do these days at NASA. I had been aware of space exploration, and paid it some attention—always interested in nature a little bit—but never trained as a geologist or an astronomer. Sat in on an astronomy class in college, but never actually took a course.

I went to graduate school in my area, which I had studied in college—physical chemistry—and looked at surface chemistry and catalysis. Then moved up to Toronto, Canada, because my fiancée at that time was up there, and got a job at the University of Toronto and postdoc'd [postdoctoral fellowship] for two years. Then my wife wanted to go to school and started looking around, and the one place she got into was Catholic University [of America] in [Washington] DC. So I started looking for a job.

I could've said that I was inspired from my very childhood to go explore Mars, but it wouldn't be the truth. I was inspired by the fact that I needed to put my wife through graduate school. But, my background in graduate school had involved mass spectrometry, and at that point in time Goddard, with the Principal Investigator Hasso [B. O.] Niemann, had been selected to develop the Galileo probe mass spectrometer. They needed more hands-on help in the lab [laboratory]. I saw the ad [advertisement] in *Science* [*Magazine*], I believe, and applied.

My experience with mass spectrometry got me in, and ever since then I've found planetary science to be incredibly fascinating and also very appropriate for somebody with my skill level, my background in chemistry. Early on at that point in time, there weren't a lot of programs in universities that specialized in planetary science, so a lot of the folks who came in to the science end were either geologists or astronomer background. The way a lot of early planetary scientists learned was just by learning on the go. At that point the Voyagers [spacecraft] were exploring the outer solar system and new data was coming in, and the fascination of discovering new worlds and seeing things for the first time is just very captivating. And so I've kept at it all these years.

JOHNSON: You mentioned that you were aware of the space program, but, being in a different country when the early part of our space program was happening, how aware of it were you at that point? You came in '66, so you saw the end of the Apollo Program.

MAHAFFY: Yes, that's right. Just generally aware of things that were happening in the news. I remember, I guess it was '69, the first humans on the Moon, and that was inspiring, "Look what we're doing here." My focus was on chemistry and mathematics, and just the challenge of trying to understand all this was of great interest to me. My focus in graduate school and postdoctoral research was not at all on planetary science. It was all on the chemistry and the physical-chemistry end of the world.

Then when I started my first job here at Goddard, way back in the very end of '79 and into 1980, was when I started discovering all the interesting things that NASA had been doing. At Goddard of course we focus on a whole variety of astronomy and Earth science and heliophysics problems, but where I started with was the planetary program, and I just found that extraordinarily interesting.

JOHNSON: Well, talk about that. The probe was what you worked on first, right? The Galileo probe?

MAHAFFY: The Galileo probe, yes.

JOHNSON: Do you want to talk about what you were doing in those first days? And the work going toward the launch in '89, which was almost ten years later from when you started?

MAHAFFY: Yes. Of course the Galileo probe launch really was delayed by the *Challenger* [STS-51L] disaster. It took the skills of the [NASA] JPL [Jet Propulsion Laboratory, Pasadena, California] flight dynamics folks to figure out how you could get to Jupiter in six years, instead of very much longer, by utilizing Venus flybys and Earth flybys and so on.

But early on, the team was right in the middle of developing the instrument. There are many aspects to developing an instrument of course—folks who work on understanding the thermal response of the instrument, developing the electronics. My end was testing out various parts of the experiment, and trying to optimize certain parts of the experiment. For example, if you go into Jupiter you want to make sure that, as much as possible, you're measuring what's in Jupiter's atmosphere and not stuff that you brought along. Rigorous cleaning and surface treatments of what we're building the ion sources out of for the mass spectrometer were really important, so I spent time on that.

Understanding how the gases would flow into the instrument—we would basically reduce the pressure. We had to go from very much less than a bar, millibars, in the atmosphere, down to 20 bar before the end of the experiment as we parachuted down into Jupiter. So we ran the Jovian gases in through flow restrictors into the mass spectrometer. We had to understand that, so I was both involved with modeling that and then carrying out tests on the devices we were going to use.

We would want to understand the lifetime of our detectors. Were our detectors going to fail or not with the number of ions that would hit them? I would set up tests in the lab to test out the detectors, so a lot of the early work was really making sure the instrument was going to work right. It's really incredible to be able to get in at the beginning of a project—or even earlier, at the definition of a project—and then help make that happen. Then with planetary science you often have a long wait because you're getting to a target that's very, very far out there. I started working on the Galileo probe instrument when I started at Goddard in the early '80s, and we eventually launched toward the end of the decade. We got to Jupiter December 7, 1995, and it did its wonderful measurements in the atmosphere as it parachuted down for about one hour.

After that I got to work on the science because I understood the instrument, I understood what it was all about, in collaboration with world-class scientists who are trying to understand the formation of Jupiter. Our measurements were addressing that and of course people all over the world were interested in hearing what results we had established with the first-ever entry into a giant planet. So, I was traveling to Japan and Italy and various places to give talks on our results. When I finished up on analyzing the data and publishing papers and getting all that out, it was a few years later. So the project, for that one hour of data, was from 1980 to 2001, 2002 before we really wrapped it up.

In the meantime of course other interesting things came along that I was involved with, but that's the timescale of planetary projects. I think often the practitioners have to be happy with the idea that something you start, you may not be the person to complete. And if you're fortunate enough to be able to see something through end-to-end, it's just incredible.

JOHNSON: The data that was coming back from that one hour—that data went to the Galileo spacecraft first, and then back here?

MAHAFFY: The data went to the Galileo spacecraft on a tape recorder, and then it was transmitted back to Earth. In fact, the first set of data that was transmitted back, we were close enough to conjunction that the transmission wasn't all that high fidelity, so we had some bits that didn't make it. You could see in our mass spectral data—we knew kind of what we were looking for, and then we'd see a big spike and understand that probably was just a bad point. But then it got retransmitted, and all the data came through.

It was low enough data volume that all the data from the probe came back. The issue the Galileo orbiter had of course was with the antenna that was stuck, so the data volumes that they had hoped to get back were not realized and they had to make a lot of adjustments. Some of the movies, for example, they would have made if the antenna had not been stuck were never made. But we were very fortunate with the probe. It was low enough data volume that we were fine. In fact, the probe had been designed with low data volume just to make sure that we got it all back. Our instrument was 13 bits per second.

Typically these days when we build mass spectrometers we're maybe 1,400 bits per second or even more. But back then the data in the mass spectrometer was all going into magnetic core memory. It was all preprogrammed, what the sequence would be of measurements we made as we went down, and all the data came back. It was really interesting to see what Jupiter was made of for the first time. Some of that you can determine with remote sensing from Earth or from orbital assets, but some of it you just can't detect until you go into the atmosphere and take a look.

JOHNSON: Then, like you said, you had to analyze what you got back, and then write papers and distribute that information.

MAHAFFY: That's right. Back in those days—again, dating myself—we were in the advanced form of floppy disk storage. They had come out with a 3.25-inch floppy disk by then, so all the Galileo data could easily fit on one floppy disk. So I'd run around with a floppy disk of all the Galileo data in my pocket and analyze it as I went along.

JOHNSON: You mentioned that other interesting things came along.

MAHAFFY: Yes. Both the challenge and the frustration working for NASA is that programs come and go, things get selected, and then they get cancelled. Sometimes things fail in space. There have been very many things that I started that never went through to fruition in my career, but then many other things that I started that I was able to complete. In terms of missions, I've been fortunate to be involved in many of them.

One of the next set of missions we were pursuing with the group was called the Comet Rendezvous Asteroid Flyby mission. Instruments had been selected for that mission, and we had an instrument, a mass spectrometer again. I worked on that and designed the ion optics for us to interface more than one source of ions into the instrument into a single quadrupole analyzer.

Then the Cassini mission got selected—which is just ending now—and JPL decided they really couldn't handle two missions. It turned out there were more people in the community interested in atmospheres and so on, so that mission won out. Which was unfortunate for NASA, in the end, that the first comet exploration *in situ* got carried out very successfully by the Europeans with the Giotto flyby of comet Halley and the Russian Vega missions. Although we had been selected—although I worked on it—it was something that got cancelled.

But some of this work has benefit. For example, the ion optics that I developed then were used on the Cassini ion and neutral mass spectrometer that was developed at Goddard, and were also used in the Huygens probe mass spectrometer that went into the atmosphere of Titan [moon of Saturn]. Also, we used them for recent missions. Our MAVEN mission that's orbiting Mars has built on that design. Our lunar orbiter mission was built on that design. So even though the particular mission we design something for didn't go, the benefit of that work wasn't totally lost. That's the upside. Even if a mission gets cancelled, sometimes the work that you did on the mission is still used.

JOHNSON: I know you also worked on the proposal for the Sample Analysis of Mars, the SAM instrument. Talk about that process. I assume that NASA releases, "This is what we want to happen" or "This is what we're thinking," and you propose what you want to do for that mission. Talk about that because, especially on that one, from what I read, the team was all over the world. You had to work with this team and get everybody together. I'm interested in that whole process of putting that proposal together.

MAHAFFY: The process overall for the big missions, the targets are defined by decadal studies. The National Research Council essentially gets experts in to understand how NASA has been doing and what the next steps might be over the next decade, what the targets are and so on. Those get prioritized and given to NASA. NASA Headquarters [Washington, DC] then looks at what they can afford and what are reasonable things to do. They work with the community of scientists and decide they're going to do a mission. Of course that all has to get congressional approval to get a new start.

When it looks like something is in the queue to bring to Congress, then NASA starts putting together study teams to understand, for the types of science the decadal has defined, more specifically what types of measurements would you want to make. What combinations of measurements can you do within the constraints of budget, and other mass and power and volume resources?

Being interested, for example, in Mars—I always found that just a fascinating place—I volunteered to be on some of the study teams that were defining the mission. They went through several levels of iteration. We were all too ambitious first time around. When the ideas got iterated with the project at JPL, it was, "You guys are probably outside the box of what we can afford." Eventually another team was set up to scale the ambitions down a little bit.

Then what NASA typically does, if they know that some people on the study teams are going to be interested in proposing for the missions—because most of the instruments on these missions will be competed. NASA believes that they get the best quality science if the instruments and the science is competed—then they ask the people who were involved in the studies to go away basically, to not be involved in the studies anymore before the mission proposals come along.

Mars Science Lab [Laboratory, MSL] at one point was called the Mars Smart Lander, and then it eventually morphed into the Mars Science Lab. This was way before it got named Curiosity by a competition. I was involved in the early studies, so I had a good idea of the types of things we wanted to do. I started pursuing, through proposals, funding opportunities from NASA Headquarters to develop the technologies. But, NASA is very risk-averse, so we built the new things we wanted to do on top of technologies we had already proven in space. For example, the basic mass spectrometer that we proposed was nearly identical to the mass spectrometer on the Galileo probe. So I was leveraging a project I had worked on that somebody else had proposed way back in the late ’70s and been successful.

But Mars is a new challenge. It’s an entirely different atmosphere, way less pressure than on Earth, whereas Jupiter is way higher pressure once you get down there. So we tried to get enough technology to really do the science we wanted to do, but not step too far out of the bounds of what we thought the reviewers would consider reasonable and robust and low-risk. We got money to do the development and prove things out in the lab. In the meantime, we knew that an announcement of opportunity for the mission was coming along. So I collected really what was a diverse and international team of scientists, and also collected an engineering team that would help us get to our target of developing this science investigation and the instrument that went along with it, and we proposed that to NASA. In early 2004 we were working on our proposal, and then at the very end of 2004 we learned that we were successful and had won.

That project was definitely the largest instrument project I’ve ever been involved with. I’ve proposed a mission before that didn’t make the cut, but this was certainly the largest instrument project I had proposed. I had earlier, for example, proposed and won a spot on the NASA contribution to the Rosetta mission. The Rosetta mission at one point in time had two landers, a German lander and a U.S. lander. Then, with various disagreements about budget phasing primarily, the Director of ESA [European Space Agency] and the [NASA] Director of SMD [Science Mission Directorate] couldn’t agree, so the NASA lander got cancelled. It eventually morphed into what was the Champollion comet lander, a technology demonstration mission. And then, in the end, that eventually got cancelled.

But even that project gave us an opportunity to work on some of the technologies, because we were pretty well into a funded project and had money to develop things. What we put into the proposal for the Mars Science Lab, the Sample Analysis at Mars experiment, was really building on a lot of experience from instruments that had flown in space, and then things we had done to develop instruments—selected or not selected, or cancelled at some point in time, or technology proposals we had won—and put that all together in the best proposal we possibly could, and submitted it to NASA.

After that it was just, I would say, a fire drill of us working very hard to make sure that we could deliver on our commitment and put together what, in the end, was a really very complex experiment. In fact, on your way out tonight if you want to walk past the lab where we have the environmental chamber—with our Earth version of SAM that we test weekly before we do anything on Mars—it's just down the hall from where we are here.

JOHNSON: When you were putting the proposal together, did you expect it to get chosen? Since things get proposed and you think you may have a shot, or things get accepted but then it gets cancelled—did you have a hope that this one would make it?

MAHAFFY: I think, in this business, you learn not to get your hopes up too high. I think one gets so invested in the process of trying to solve a difficult problem—whether it's proposing for a mission or proposing for an instrument on a mission—when you submit, if you've done your job right you're convinced that you have a shot, or potentially a good shot.

But the competition can be very brutal, and that's good in principle. If the reviews are done right then NASA selects the best technology, or the best combination of technologies, to put on a particular mission. So I was not overly optimistic, I would say, or overly pessimistic. I was just waiting to see the outcome.

JOHNSON: Talk about the team for a few minutes. I know you said you brought together scientists and an engineering team, but about how many people were working on that to get that ready? And then once it was accepted.

MAHAFFY: I think on the team that we put together, in terms of scientists we have something on the order of 20 or so. Some collaborators, and mostly co-investigators. We had a collaborator from Mexico, Rafael Navarro-González. Part of the instrument was a contribution from CNES [National Centre for Space Studies], the French space agency, so we had co-investigators from France on our proposal.

Part of our instrument suite—it's not just one instrument, it's a combination really of three instruments that all work together—was from Jet Propulsion Laboratory. Chris [Christopher R.] Webster of JPL built this tunable laser spectrometer, which had a very specialized measurement focus to look for trace methane in the atmosphere of Mars, and to measure with precision the isotopes of hydrogen, carbon, and oxygen in water and carbon dioxide.

And then we had actually some people who had worked on Viking. Toby [Tobias C.] Owen, who passed away recently, had worked on Viking. Chris [Christopher P.] McKay certainly had experience with Viking data. We had team members who had worked on previous mass spectrometers. But the investigation was looking not just at the atmosphere and sniffing the atmosphere, trying to make the various measurements. We were also drilling into rocks and understanding what volatiles could come out of rocks. We had geologists and people who understood the mineralogy on our team. In fact, the person who eventually got selected as project scientist of MSL was on our team. Then, once he got selected he figured it might be a little conflict of interest so he dropped off, but when we proposed he was on our team as well.

What we did with a large team like that, and very diverse science objectives—we were trying to look for organic compounds in the surface rocks of Mars; we were trying to look for isotopes, both in gases that came off of these rocks and in the atmosphere; we were looking for trace methane. All of this trying to help the program understand the habitability of Mars, how favorable was this environment billions of years ago for supporting life, so we had a diversity of scientific skills on our team. We were trying to understand what the isotopes could tell us about the evolutionary history of Mars, how much of the atmosphere was lost over time, so we had people who were experts in that area.

It was really a diverse team, and we split it up into five different focus areas. We assigned a lead to each focus area so that we would be systematic and organized. Right now, now that we've successfully landed and have a lot of results, the team has expanded quite a bit. I think we have more on the order of 50 scientists working on the project—not all of them full-time, of course. We've brought various other people on as we felt we could use their expertise, either atmospheric modeling, or modeling the geochemistry of the rocks, or doing laboratory experiments that tell us about that chemistry. So, we've expanded the team as we went along.

JOHNSON: The goals of the project to begin with for the instruments—how did you, with the team, come up with those goals? I was reading something I thought was interesting, that with Viking they followed more of a "follow the water" theme, whereas this was "follow the carbon." So I was wondering how those goals were defined for this instrument.

MAHAFFY: The goals were really defined at a broad scale, with the decadal studies. "What do you want to do at Mars next?" We'd had quite a bit of exploring Mars from orbit, doing what measurements you can from orbit, so the next step was, "How do you get at more details of the geochemistry, the chemistry, the geology, that'll help us understand that early environment best?"

That was the top-level goal, and then at one level down the goals were set by the Science Definition Teams. I served on one of the three Science Definition Teams that were studying this. We looked at particular types of measurements, what combination of tools you would need to explore Mars. When the announcement of opportunity came out, the very specific goals of the mission were set forth: explore habitability, explore the geology, try and understand the evolution of the planet. Certainly the idea of trying to understand whether carbon compounds would be preserved in their surface environments is one step toward really understanding whether you can find biosignatures in the near surface of Mars.

The study teams at NASA had been nervous about doing what Viking did, which was going to Mars and getting the public and the scientific community on board with the idea that we were going to go to find life. And of course when Viking went and looked for life the early results were controversial. The consensus in the scientific community was that Viking really hadn't found life, because the gas chromatograph mass spectrometer hadn't seen a wealth of organic compounds like you would pick out of the dirt in your backyard.

One of the experiments showed a result that members of that team, to this day, thought was a signature of metabolism. But it basically was going for a home run. It was introduce nutrients to the soil, and then see if you could detect metabolism. And that was so early on, before we knew a lot of what we know now about what microbial life is. There were many geologists and members of the scientific community who, after the Viking experience, said, "Look, you put all these resources into looking directly for life, and you struck out. But we don't really understand Mars, so let's go back and try—be systematic—and understand the geology, the chemistry of Mars."

So that's the approach that the mission took. "Let's do a real systematic exploration of the chemistry, the geochemistry, the geology, the isotopes, the volatiles. Let's equip a rover to do that, and let's study the environment and understand the habitability of Mars." At some level, it's setting the bar a little bit lower than "We're going to find life." But, on the other hand, if you really want to find life you really need to understand the environment in a very careful, systematic way.

That's what the mission tried to do, and yes we certainly were focusing—we knew, by that time, that there had been a lot of early aqueous activity on Mars. You could see that from orbit. The rovers were finding evidence of aqueous transformation with jarosite, a mineral that's formed by water. But still, what we tried to sell with our proposal was, "We're going to try to follow the carbon as well as the water, and really understand the plausibility of finding biosignatures in the near surface of Mars."

JOHNSON: It was 2004 when that proposal was announced, and then 2012 before Curiosity landed. That is a long time in between and, like you said, when you're doing these kind of things the trip takes a while.

MAHAFFY: The mission was delayed by two years from the planned launch date. They just weren't making enough progress. One big issue that came up was they had thought they could get away with a dry lubricant on the wheels, and then the testing on that was just disastrous. It didn't work. So they delayed the mission two years.

We had been pushing very hard to get our delivery on time so we wouldn't be the cause of delaying the mission. But once the mission was delayed, then we took full advantage of basically changing some things and optimizing some things, and really had a chance to put a much better experiment on the surface of Mars than we would have otherwise.

JOHNSON: Did you see the landing?

MAHAFFY: Absolutely, yes.

JOHNSON: Where were you for that?

MAHAFFY: In fact, there's a picture in the hall, which is the SAM team members that were at JPL. We're all cheering and we're all smiling. We were in the basement of Building 321 at JPL. They didn't want the control room to get too crowded so they weren't letting the scientists up there right away. Shortly after landing I made my way up there, but we were all in the basement of 321, seeing the video feed along with millions of other people around the world.

Obviously we had a stake in it, so we were just overjoyed I would say. Ecstatic was the right word, because you poured your heart and soul into this for so many years. Personally, I hardly took a break from after we were selected until we landed. I can probably count my vacation days on one hand, or maybe two hands. But we got there, and that was obviously the first step on our end. The next big step was our very first experiment. We turn on our instrument to see if it worked. But at least getting to the surface safely of course was very dramatic, because it was a new landing system. It was a sky crane, and had never been done that way before. Mars is very unforgiving for getting to the surface, as Russia and the United States have found out many times. And the Europeans, with the Beagle lander.

JOHNSON: How soon after the landing did you find out that the instrument was working, and that you were able to do that experiment?

MAHAFFY: It was a few days. Early in the mission, JPL engineers and the project were being extraordinarily systematic and careful. Obviously the mast had to be unlocked and raised, and we were doing imaging to see what environment we were on.

But yes, within a few days we turned on. We have an electrical baseline test, which basically lets us know that the instrument electronics are healthy and doing what they do. So we made some good measurements. The first 90 days of the mission, the science team was all out at JPL working on Mars time. Of course, a Mars day is 39-ish minutes longer than an Earth day, so our clocks would shift every day. We would take advantage of every uplink and downlink opportunity we had.

The way this works on Mars is the commands that go to the Curiosity rover are sent up at 10:00 a.m. Mars time, directly from Earth. We have three stations on Earth that can receive data, but we send commands directly up to the rover. Then the commands get exercised during the day—whether it's operating our SAM experiment, or whether it's taking panoramic images, whether it's firing the LIBS [Laser-Induced Breakdown Spectrometer] laser at a spot and looking at the emissions, whether it's putting out the arm and getting a microscopic image, or getting an alpha particle backscatter measurement of the composition of the rock. Whatever it is, the rover autonomously during the day tries to execute those commands, and more often than not is fully successful. But early on in the mission you're very careful to understand—if things don't work exactly the way that you planned, you want to make sure you don't damage anything.

Then of course the data comes back. The rover looks for the satellites that are coming over the horizon, and the Odyssey orbiter and the Mars Reconnaissance Orbiter are the prime comm [communication] links to Earth. MAVEN [Mars Atmosphere and Volatile Evolution] now has a communication capability that's been tested, so in the future it may be the major comm link, for example for Mars 2020.

We were working, the first 90 days of the mission, on Mars time. If we were sleeping in the middle of the day we'd put blankets on the window and try and sleep, and often have science team meetings at 3:00 a.m. in the morning or whatever it turned out to be. But it was just so exciting. We were seeing new things every day, and operating around the clock seven days a week.

JOHNSON: That's a lot of work for a lot of time.

MAHAFFY: Yes. By the time the first 90 days was up we had done some atmospheric experiments; we were looking for methane in the atmosphere. We fooled ourselves at first. We thought we were seeing a big methane signal, but what actually happened is in our tunable laser spectrometer a little bit of terrestrial air had made its way into the fore-optics of the instrument, and there's methane in terrestrial air, so we picked that up. We got all excited—"Oh, we're seeing methane"—and then we rapidly figured out that we needed to pump out the fore-optics and get rid of some of the terrestrial methane. Then we could look for the Mars methane in the main cell. So we did that.

JOHNSON: And I know the instrument had to go through a lot of cleaning before it was sent, because of course you didn't want to contaminate the samples.

MAHAFFY: Right.

JOHNSON: How long did that process take, to get it ready to go? Could it get everything through that had been trapped, like that methane that you detected?

MAHAFFY: We took great pains in the design of the instrument—and in the testing, and in the processing, through bakes and so on—that we were as clean as we possibly could be. We have a check on that, because we have a very sensitive mass spectrometer, we can monitor our contamination. We always have some background. We have a little bit of background from one of our wet-chemistry cells that some of that fluid made its way into our sample manipulation system. We see those compounds, but we understand them very well. They're well known to us, so at some level they're a check every time that the instrument is working well, because we see them.

But what we were worried about, for example, was could something in the sample drill and transfer system be making its way into our sample? And in fact, just before launch, the project found that there was a possibility for a little bit of Teflon [polytetrafluoroethylene] from one of their devices to get abraded off, and some particles might make their way into our sample.

We did a whole lot of tests to understand whether that—just before launch we were aggressively working away with that. "Could we live with that contamination or not?" It turns out that we occasionally see evolved gas from Teflon, but it's a very distinctive signal and it really doesn't interfere with our measurement, and it's not really impacted any of our science. But, those are things that we pay great attention to.

For example, during development the rotary-percussive drill that gets sample from the rock—the manufacturer had basically, to get it hardened, quenched it in oil. And then we found out that some of that surface material could get abraded off. And here we are following the carbon, but that carbon is from oil. It's not from Mars. So, our colleagues at Jet Propulsion Lab went through a whole program of testing and basically cleaning all that residue off of the drills. And, in the end, that ended up not being a problem. We solved it.

On our end, we baked the interior of the sample manipulation system—and the whole mass spectrometer system, and the transfer lines—for days and days and days on end. We monitored the contamination that was coming out, and it was only when that contamination got below a certain level that we said, "Okay, we're ready for Mars."

If we were to find something that looked like a biosignature, then the bar, really, to proving that was life would be very, very high. So what we put on the front of the rover were six, what we called, "organic check materials." Basically, they're very inert silica material that the drill could drill into. Then that would get sampled through the whole sample processing system and sieved and everything. Obviously if we saw the same material there we would know it was a false positive. It was something we brought along from Earth.

We've never had to use that yet, because we're understanding our background contaminants pretty good, but we still have that capability. If we come across what we believe is something that looks like a biosignature, then that might be the right time to drill our organic check material. Fortunately, after four and a half years—pushing toward five years in August—we're still working beautifully, and we still may end up using that organic check material.

JOHNSON: Talk about some of the results that have come from SAM.

MAHAFFY: Ah, yes. I think the decision that was made to do a systematic exploration of Mars was the right decision, because it's paved the way for what's now really a NASA priority—trying to understand, with very direct measurements, if life emerged on any of the planets. For example on Mars, or in oceans of Europa [moon of Jupiter] and Enceladus [moon of Saturn] and so on.

Because we understand the environment, we now know how to look more directly for biosignatures. I'll give you one example. Before we landed on Mars, as the investigations were being defined, we didn't have the appreciation we needed to have for the impact that cosmic radiation going through the thin Mars atmosphere might have on biosignatures, though studies were just emerging and people were doing lab works. When we went to Mars, the very first site that we drilled, we drilled two drill-holes. They're named "John Klein" and "Cumberland." The second drill-hole that we analyzed sample with SAM was Cumberland. There we devised a specialized experiment to look at whether we could measure the exposure to cosmic radiation. And, in fact, we could. It was a really exciting result.

What the cosmic radiation does is it changes the nucleus of some of the compounds that it hits and it produces noble gas isotopes. The three that we could measure—two of them from this process called "spallation," where the nucleus is directly changed, are helium-3 and neon-21.

Then a third isotope that we could measure, that also gives an exposure age to cosmic radiation, is by neutron capture on chlorine. It's argon-36 that gives that measurement. So we had three independent ways of measuring the exposure age to cosmic radiation, and all three, within experimental errors, gave the same result—which was very satisfying—of 80 million years. That says that this particular sample we were looking at—and not well-shielded, not sampled from meters below the surface, but from the very near surface—that sample had been exposed to cosmic radiation for pushing toward 100 million years, 80 million years. And that's enough to really damage biosignatures.

That result, in itself, has impacted our exploration strategy for Mars. For example, the Mars 2020 rover now is looking for sites where very old samples from Mars might be exposed by erosion from the winds that expose that sample as recently as possible. So that discovery is factoring into how we explore Mars in the future.

Actually, another measurement made on that very same sample—well, a number of measurements made—but another really interesting measurement is the alpha particle backscatter experiment detected quantified potassium, and we measured argon-40. Potassium-argon pair is a clock, because potassium-40 decays into argon-40. If you heat up a rock and get rid of all the noble gases in it—like when there's a volcano and stuff is falling to the surface, and all the argon is lost—then when that rock cools enough basically to start trapping the argon as it formed, that clock is very precise, and it has a half-life, the time at which half the argon is gone is 1.2 billion years. It's a very straightforward calculation, if you can measure the potassium, if you can measure the argon, and if you understand a little about what minerals are in the rock, you can predict when that rock was formed. So the numbers that we measured from that rock turned out to be 4.2 billion years. Not 100 million years, like the age of exposure of that sample to cosmic radiation. That rock was formed 4.2 billion years ago.

That was kind of a satisfying answer, because we know that Mars itself formed over 4.5 billion years ago. So we weren't getting an outlandish answer, and then it was also consistent with what the cratering record was showing near the top rim of the crater. The density of craters basically increases the older it is, so you can kind of get an idea of the age just by counting craters.

Probably what happened is that material at the top of the crater got washed down into the bottom of Gale Crater and it got buried. Eighty million years ago, it got exposed. We sampled it, and then 4.2 billion years later we discovered at what time that rock had been formed that was on the top of the crater. That result is interesting of course in itself, but it also kind of paves the way—it's the fundamental question in planetary science, "What's the absolute age of things?"

Here we've proved for the first time that an *in-situ* chronology experiment can work. There are probably better ways of doing that, more precise ways of doing that, but at least we demonstrated that one could do that. Just on that very sample, then, we found our first organic compounds. We found chlorobenzene and chlorinated alkanes, dichlorinated alkanes. We found those quite a bit later. We had actually saved a number—we call it "doggy-bagged" a number of those samples in our cups as we moved away from that site and had optimized our experiments to look for these organic compounds, and we found them.

One prime mission objective was "Can you find any organic compounds in the near surface of Mars, or has the radiation blown them all apart?" We found them, so that's a good sign. The fact that some of the complex biomarkers might be blown apart by the radiation—we basically got a quantitative handle on that by measuring the exposure age.

In that very same sample, we measured the deuterium-to-hydrogen ratio in very high-temperature water. That's really important, because some of these isotopes—the heavy versus light versions of gases that are in the atmosphere—are basically a signature of how the atmosphere has been escaping over billions and billions of years.

There are various processes that can cause atmospheric loss, but it's a much smaller planet than Earth, so things like sputtering—where the solar wind comes in, creates ions, then the magnetic fields slam ions that created back into the atmosphere and just sputter them off like billiard balls—those processes change Mars over time. It's these processes that could've changed Mars from being an environment where a big old lake in Gale Crater could have survived for a very long time to what it is now, just a dry lake bed.

To extrapolate back in time, you want to take a rock that was basically forming this mudstone over three billion years ago in the bottom of Gale Crater. Even though the rock formed 4.2 billion years ago, the material from the rim was washed down by water maybe three and a half billion years ago. So we have a three-and-a-half-billion-year-old rock that was formed—basically basaltic material that was turned into mudstone rock—and we figured out the deuterium-to-hydrogen ratio in the water that formed the rock.

So that's one point. We know the current ratio of deuterium to hydrogen in the atmosphere. It's about six times what it is in our Earth's ocean, and the water in the rock is about three times what it is on the Earth's ocean. Mars and Earth probably started off with the same deuterium-to-hydrogen in their original composition, so these are points that basically tell us how the planet has changed over time. It's really fundamental. It's one data point in understanding the history of the planet.

The really nice thing about Mars is it's a small enough planet that very early on if there ever was plate tectonics that would bury all the evidence, the plate tectonics froze out. On Earth you have a great difficulty in finding very, very ancient rocks, because what it happens is they get subducted down as the continents moved around and they get transformed. So a lot of the evidence from early Earth gets destroyed. At Mars a lot of that is still sitting on the surface, so making measurements of very ancient isotopes and surface materials is possible. That's another exciting result from Curiosity.

An interesting result is we're finding perchlorates everywhere—those are chlorine-and-oxygen-containing compounds—and that's very relevant for human exploration. For example, there's a couple of percent of water in the materials that we sample, but if you heat up the materials to extract the water, you also decompose the perchlorates. You turn them into oxygen gas and hydrochloric acid. So if you're an astronaut trying to get a drink of water by heating up a sample, you'd want to know about the perchlorates. You would want to know that when you heated up this sample, you were going to get hydrochloric acid out. Those are some of the interesting things we've been finding.

The basic mission, then, I think early on we concluded with all the measurements—not just SAM measurements, but all the measurements—the fact that the chemistry was telling us we had an aqueous environment. The geology was telling us we had an aqueous environment. It was a reasonably neutral environment where we first sampled. It's really telling us that there was a lake there, and the lake had all the ingredients potentially necessary for life. That was core mission objectives, so very early on in the mission we were meeting those objectives.

JOHNSON: So the ingredients were there.

MAHAFFY: Did life develop or not? We still don't know. But we, I think, have set the stage for exploring that further.

JOHNSON: While you were working on that—you mentioned the LADEE, the Lunar Atmosphere and Dust Environment Explorer—you were the PI [principal investigator] on that one, right?

MAHAFFY: Right.

JOHNSON: You're working on this and you're getting samples back, and everything is exciting with that, but how much time did you spend doing this? And how did you split—if you were getting no vacation time before it sounds like, if you're working on this one too, then did you ever go home?

MAHAFFY: We had just a great team on all of our experiments. On MAVEN, LADEE, and Curiosity we have an excellent team. What I try and do is provide direction and help divvy up the work. On MSL, I personally, hands-on, did work. With MAVEN, I early on did some analysis of the data myself. But there are very capable people who can do that, and young postdocs and research scientists who are really interested in looking at data from Mars or from the Moon. So I shifted quite rapidly, once the early discoveries were made, from basically trying to provide direction and help split up the work between people who were interested in doing the work. And, knowing the instruments very well, try and provide some insight into "Is what people are looking at real, or is it an instrument artifact?" That type of thing. If they need to understand better how the instruments are calibrated, and how the data that they're getting gets turned into real numbers—that's where my experience comes in and I can help out.

On both LADEE and MAVEN we've had just outstanding teams. For example, on MAVEN and LADEE a key guy who has helped out is Mehdi Benna, who's originally from Tunisia. Just a brilliant scientist. He takes a lot of leadership in analyzing the data and making sure that we get it right. He definitely took over a big responsibility on LADEE in terms of analyzing the data and understanding what it meant, and getting the papers published.

JOHNSON: If you want to talk about those two missions—what the purpose is, what's the goal? Did you work on the proposals for both of those also?

MAHAFFY: Yes. With LADEE it was more of a directed mission. [S.] Alan Stern, who was at that time at Headquarters, was very interested in lunar science. He had written a definitive paper on what was known about the exosphere of the Moon—the very thin, tenuous atmosphere of the Moon. One motivation, from his point of view, was the thought that humans would be back on the Moon next. Certainly with all the spacefaring nations that's going to happen sooner or later, but if humans get on the Moon then this natural, very tenuous environment gets perturbed. If you really want to understand what the Moon is before it gets, let's say, contaminated by humans, then why don't we do a mission to look at it?

That tied in with [NASA] Ames [Research Center, Moffett Field, California] being interested in running small missions, so the mission got assigned to Ames, with lots of Goddard collaboration. Then Headquarters released—not a full-up announcement of opportunity, but a request for participation. We responded to that, and Headquarters had a review and selected us.

But it was busy, yes. We were finishing up SAM and developing LADEE and MAVEN at the same time.

MAVEN was a bit of a different path to getting that instrument on Mars. The mission got selected under the Scout Program, which was basically a program like Discovery but focused on Mars. NASA basically opens up the field to principal investigators, who usually team with the NASA Center to propose a mission. In this case the principal investigator, Bruce [M.] Jakosky, came to Goddard, "Would you manage this mission for me? I want to go to Mars."

The Phoenix lander was part of that program. MAVEN got selected as part of that program, but it's the same idea as the Discovery Program. It's led by a PI, usually managed by a NASA Center—typically either Goddard or JPL, and in some cases [Johns Hopkins University] APL [Applied Physics Laboratory, Laurel Maryland], as with the MESSENGER [Mercury Surface, Space Environment, Geochemistry, and Ranging] mission or the CONTOUR [Comet Nucleus TOUR] mission. They were managed by APL.

Then the PI, the principal investigator of the mission, gets to pick what instruments he wants to include on his mission, so he asked us to participate. I think officially there my title was not PI, because there was only a mission PI. We were instrument providers or instrument leads on that mission, but it was the same type of role as a PI on another mission.

We helped Bruce Jakosky write the proposal and compete it against—it went into a Step-1, where we basically got a few million dollars to mature the idea, and we competed against another mission which was looking at similar science objectives from ours, and we were fortunate enough to win this mission. MAVEN turned out to be good, as far as NASA Headquarters was concerned, because Goddard came in under budget. That makes Headquarters happy if you don't overrun. And it's still up there doing beautiful science.

JOHNSON: I was reading an article from December 2013, and they were talking about—I think on December 4, 2013—the fact that Goddard was running three experiments of the same kind at different places in space. It was kind of interesting, because it said you scored a "hat trick."

MAHAFFY: Yes. We had LADEE operating and MAVEN operating and then, "Oh, we're going to be operating SAM that day, so let's put out a little press release that we got three mass spectrometers operating all on one day."

One exciting thing about MAVEN, early in the mission, was we had arrived at Mars very shortly before Comet Siding Spring [C/2013 A1] came barreling in from the outer solar system and just missed Mars. It came very close, but the coma—the gas and dust that surrounds the nucleus of the comet—came slamming into the atmosphere. The spacecraft that were orbiting Mars were being very careful to turn things off and basically be away from where they expected the action to be.

So we were turned off, but when we turned on very shortly after the comet came by we measured ions in the atmosphere and saw all these metal ions. We saw 11 metal ions in pretty high abundance. What had happened is these very small dust particles associated with the comet had gone slamming into the atmosphere and ablated with the very high velocity of them hitting the atmosphere. If you were on Mars you'd probably see shooting stars all over the place. So we essentially were measuring the composition of a comet while we were orbiting Mars, by measuring all of these metal ions. It was really pretty exciting result.

JOHNSON: A lot of exciting work all happening at the same time.

MAHAFFY: Yes.

JOHNSON: When did you become the Director of the Solar System Exploration Division?

MAHAFFY: I think December 2015. I've been here not quite two years. Yes, this December it'll be two years.

JOHNSON: In proposing these missions and these instruments to go on missions, there's always a budget issue. As you mentioned, you propose and then Congress gets to decide what's going on. Talk about that process. In your position, and also as the Director of the Solar System Exploration Division, I imagine you have more dealings with budgets and that sort of thing. Talk about the budget process, and maybe some of the successes you've had.

MAHAFFY: Yes, sure. My job here really is to focus on the interests and capabilities of the Solar System Exploration Division as a whole, and how we can productively serve the mission directives of NASA and the public. What we try and build off of are things that we know how to do well, and there are a variety of those. For example, in developing magnetometers to measure magnetic fields, we've had a grand tradition—a guy who was here for very many years, Mario [H.] Acuña, flew many magnetometers, understanding remnant magnetic fields on Mars from the time when Mars had a magnetic dipole. He was a big player in that.

The topography of the Moon, of Mercury, and Mars has been mapped by Goddard instruments. By reflecting a laser off the surface and looking at the time it takes to get the laser beam back, you basically can understand whether you're in a valley or in a mountain. You can orbit the planet or the moon and map out the topography—the craters and so on—combine that with imagery, and basically get a tool that helps you understand the geology of that planet or moon.

Mass spectrometry, again—I talked about some of the missions that we've had over the years. Infrared spectroscopy—we had the infrared spectrometer on Voyagers way back when, and then we built on that basically to provide the CIRS instrument, the [Composite] Infrared Spectrometer, on Cassini. We have people that have been hired as civil servants, and groups that have been built up that involve engineers and scientists—civil servant and non–civil servant—that have expertise in these particular areas. So we try and build off of those. We try and understand what NASA Headquarters is interested in, what the decadal studies are interested in.

We propose to NASA Headquarters constantly for development money, to make sure that we're doing state-of-the-art stuff, either building on these areas or doing new types of instruments, new types of measurements. I described the process of proposing for our MSL suite. We propose constantly whenever there's a big opportunity in planetary science. We're lining up, together with other institutions, to propose our instruments, to form investigator teams, to do the science.

Then, if we win an instrument or a mission, it's much more working in a very rigorous engineering environment, making sure that the instrument is robust and is going to survive the space environment. Working hard to manage it properly so we stay within budget. I would say a lot of the formulation of the ideas of what we would want to do—the creative ideas of how you can best explore what's a really different environment—those come from our scientists.

We try and get support from NASA Headquarters, in collaboration with a lot of university scientists, often in collaboration with other Centers. Our JPL collaboration with our tunable laser spectrometer in our suite is one example. Traditionally, we've flown instruments on JPL-managed missions. We're constantly looking at ways of supporting these efforts, proposing to Headquarters, trying to get money, and making sure that we have the space—working with our Center—and laboratory facilities and everything to get our work done.

At a Center like Goddard, there's an expert in almost any area of engineering that you'd want to find, so part of it is trying to marry the scientists that we have in our Division—some of whom are pretty experiment-engineering savvy, but others aren't—trying to get them hooked up with the right engineers, and then directing some of the internal moneys that we have, and/or helping people propose to these NASA programs, to get the funding to do their job.

So yes, it's a competitive environment. We want to collaborate with people who can help us, but then Goddard is a terrific place to make exciting science things happen so we try and facilitate that. I try and facilitate that in my role as Division Director these days. One great strength of Goddard is that we're very strong in multiple areas. We're strong in Earth science, we're strong in heliophysics, we're strong in astronomy—we just sent the James Webb [Space] Telescope out of Goddard.

I'd say we're really the leaders in Earth science missions, and a lot of the technologies really can translate across boundaries. For example, the types of laser technology that you would want to look at how fast glaciers are disappearing is the same technology that we use to monitor the Moon and/or Mercury and/or Mars. Leveraging those cross-cutting types of things is one thing that you can do at a big Center like Goddard.

JOHNSON: While we're talking about budgets, every time we get a new presidential administration things change with NASA.

MAHAFFY: They do.

JOHNSON: We don't have an [NASA] Administrator yet [at the time of the interview in 2017].

MAHAFFY: Right.

JOHNSON: Do you have any thoughts about some of the things that we're hearing, as far as possible budget changes revolving around Earth science? Do you have any thoughts or any worries about things that are in the works for being proposed for the next couple of years?

MAHAFFY: I would say that typically the exciting things that NASA does tend to be supported by both parties pretty well. NASA has held its own and certainly grown a little over the years. It's nowhere near what we were doing when we were getting people on the Moon, as a fraction of our gross national product, but in solar system exploration it's just been a golden age discovering all this stuff.

I think that gets a large part of the public excited, and Congress excited. But that partially depends on who's on the committees, and who supports a particular area of science. For example, Barbara [A.] Mikulski was a Senator from Maryland for many, many years. Just a brilliant woman, and just a champion for space science. When the Hubble [Space Telescope] needed fixing, she got right behind that and, "We're going to get this thing fixed." And when it got fixed, she was up behind the podium leading the cheerleading. When James Webb needed more money—very complex, it's hard to predict what a big telescope like that would cost, but it needed more money—she got behind that and helped support it.

At the moment, in the House [of Representatives], John [A.] Culberson is very interested in life in the universe question, and so he's been supporting the Europa mission very robustly. An example of how this goes is right now in the President's budget there's no Europa lander, but you know that in John Culberson's committee there's quite an interest in making that happen. So it'll be interesting to see how the budget process plays out in this negotiation that has to happen between the legislative and administrative parts of our government.

Things that are more political tend to be in Earth science. Climate change—that's showing up at other agencies certainly, a little bit more than NASA. But things that were on the NASA plate, for example for understanding oceans and so on, aren't necessarily a priority of the administration. But again, there's lots of bilateral support in Congress, so how that all turns out in the end, we'll just have to wait and see.

But Earth is a planet, and it's a pretty important planet, because we're not all going to live on Mars in our lifetimes anyway.

JOHNSON: No, we're not going to grow potatoes on Mars.

MAHAFFY: By the way, news we just heard from the MSL project is that one of the young scientists on the MSL project just made the astronaut class. We're all quite proud of that.

JOHNSON: Wonderful. Yes, that's right, they were at our Center announcing that.

A lot of the teams and everything you've put together over the years, and people that are working on all these various projects, a lot of this work, as you said, crosses Centers. JPL, Ames, Goddard—you work a lot together. But there's also those international partners. If you wanted to talk for a minute about the importance of NASA maintaining those relationships with our international partners to do science.

MAHAFFY: Yes. It's very important that we maintain good international partnerships. My personal belief—or bias a little bit—is that doing exciting space exploration things is something that can really unite nations. When we land on Mars people all over the world are excited to see that and would want to participate in some way or another.

Often the collaborations that we try and set up, of course, are complicated. On the European Space Agency end of the world, they have a little bit different mold of how to do projects. Basically they have multiple countries and industries partnerships, and all that has to be negotiated very carefully. And then if they're trying to team with NASA, then somehow that all has to mesh.

There are many examples of where that's worked really well, and continues to work. For example, the Cassini mission had the European-provided Huygens probe. Then to make it all intertwine, we had our mass spectrometer on the probe. So we delivered to the Europeans and that all worked beautifully. We went into the atmosphere of Titan and measured the composition all the way to the surface, just like we had done on Jupiter years before.

We've had some really outstanding collaborations with Japan [Aerospace Exploration Agency]. There's an x-ray experiment that unfortunately failed, but before it failed it got first glimpses of the science that could be done from that type of experiment, so we're back collaborating with them again. "Let's try and make it happen," and both sides are really interested in making that work.

The benefits of teaming and sharing technologies—we've had really good collaborations with India. India got their first orbiter to Mars very successfully, so we've basically taken folks over to India and showed their scientists how to look at our MAVEN data, and we look at their data as well. They're kind of in the infancy of their planetary program. It's where NASA was early on, but there's great benefit to sharing what we know. United Arab Emirates has a Mars mission now, and there's good collaborations going on there with them as well.

In other cases, the interests of scientists to collaborate and do joint things get mixed up with geopolitical-type drivers. For example, there are laws and regulations that regulate how much we can collaborate with China. So we can't be off planning missions with our Chinese colleagues. We can talk science with them, but by law we're forbidden to go in on our own and try and get missions going without the State Department and everyone else being on board.

For example, on our SAM project we have collaborations with the French going on, so we continuously have one or more French postdocs here. Then they go back to France and basically keep those collaborations going. This is kind of a seed for future collaborations that they might have with us. So I think it's very important.

JOHNSON: If we could get the politics aside, scientists would have no problem talking to each other.

MAHAFFY: Yes.

JOHNSON: And part of it is sharing data. For just a moment, if you could talk about NASA's archive for space science mission data, the Space Science Data Coordinated Archive, and how important it is to retain that information.

MAHAFFY: We actually manage the Planetary Data System for NASA here, and there are various nodes that focus on geology, or focus on atmospheres, or focus on small bodies and so on. We manage all that out of Goddard. The idea now is any mission that taxpayers' money is spent on, it's the taxpayers' product and they should be entitled to look at the data.

The Planetary Data System is a deep archive. It's intended to be as independent as possible from technologies that would limit its use. It's fairly complicated, of course. Much of the old data from NASA is on microfiche still, so there's an effort to bring that over to digital format, which is much easier to keep on modern technology.

But that data is open to the world, anyone can go in. After we get the data calibrated, it in short order goes into the Planetary Data System, and anybody in the world can look at the results of our SAM data, for example. Images are posted daily. Every image that comes down from MSL is right up there for the public to see, which is why you get these strange interpretations sometimes of seeing aliens or something. But it makes it fun. People look at the data and often they'll produce interesting products from the data faster than the scientists can, because they just crank away on it the minute it comes down.

JOHNSON: I saw something today online. I'm not sure who produced it, but it was Cassini, and it was video of what it would look like if you were looking at it. They took the photos and put them together so that you actually saw movement and everything. It is kind of interesting how quickly people can produce those things.

MAHAFFY: There are a lot of amateur scientists out there, or people who are really interested in this stuff. It's their hobby, and they take the data and they work with it.

JOHNSON: We were at Ames talking to Dr. [David] Morrison, and he felt that it was really important for NASA to educate the public about science, and the truth in science. I think he took on himself the whole "2012, the world is ending by the Mayan calendar" thing. He answered questions from small children to anyone. How do you feel about the role of scientists at Goddard, and yourself, as far as educating the public to get rid of those—when someone finds a Martian photograph and in the photos they see, "Oh, there's a face there," or whatever? How important is it?

MAHAFFY: I think it's terribly important—as the world gets more populated, and as we depend more and more on technology—to really have a strong technical base, and to separate fact from fiction. I mean, the debate about whether climate is changing as a result of human activity is largely settled in the scientific world, but it in the political world it's not yet settled. Although most nations of the world now agree that it could be a problem and they need to do something about it.

I think things like planetary science, and Earth science, and astronomy, and all those sciences that NASA does so well—it really interests people. I go out to schools as often as I can, and these kids are just sitting there, asking great questions. "What classes do I have to take so I can do this stuff?" I think that pushes people in the direction of being both interested in the universe and understanding our place in it, and also motivated to get the technical savvy to contribute if they can. Or even, if they're not technical people, to understand that this is a bigger endeavor and there are lots of ways to contribute, whether it's outreach or support.

So I think it's just tremendously important. I think it's one of the few areas where the excitement of science can be communicated easily, if we do it right. The funding for doing that goes up and down, but I always encourage our folks, if you get an invitation to a school, go out and talk and get people excited about what you're doing.

JOHNSON: You mentioned the technology at the beginning—the floppy disk, and the size of the Galileo data—and then using the mass spectrometer, the stuff that you worked on at the very beginning and adapting it. Technology has changed a lot obviously since '79 when you first started—computers, the instruments that you'd need to analyze, and preserving the data. Talk a minute about those changes in technology, and how technology, and the explosion of technology, has affected what you do.

MAHAFFY: Yes, technology of course is exploding, and in many cases we try to understand it and take advantage of it. In other cases we push the envelope, and I think the industry benefits from what we do in many areas. Many things that were developed for space application have made their way into commercial products.

One thing that happens is that in solar system exploration there's a time lag. You want to be pushing the state of the art, but then you want to be robust, and it takes time to test things out to make sure that they're robust. So, as memory gets smaller, we test it out. We put it in our computers that fly to space. But then by the time we get to a planetary target, let's say 15 years after we've conceived of the project and decided on what our electronics are going to be, we're out of date. So we try and be at the sweet spot of that curve, bringing on technologies that we know we can mature, but always taking advantage of new technologies.

Certainly all of our mass spectrometers now are controlled by computers and flash memory. On Mars, the rover turns off its avionics at night and goes to sleep, and SAM keeps operating away. We store all our data on flash memory. So the same technology that's in your USB [Universal Serial Bus] drive is on Mars there storing the data.

Huge advances in technology, and the challenging thing in planetary science is the environments are all different. Let's say you want to explore the surface of Titan, you might land in a hydrocarbon lake, in a methane lake which is nearly liquid-nitrogen temperatures. How do you do an experiment there, compared to going to the surface of Venus, where you're as hot as your oven baking a cake? How do you operate there, and how long can you last?

The environments really challenge us and push us, so we're always working hard, I would say, to try and understand how to take advantage of technologies. Or push the envelope if necessary to develop the technologies to use in space. Radiation is another, of course. The radiation environment at Europa is just brutal, so how do you develop electronics and/or shielding that will protect your instruments long enough to get the data that you need?

JOHNSON: You mentioned Cassini, and you mentioned part of the work that you did for that and the Grand Tour that's ending now. It's exciting, and I'm seeing more and more in the news about it, which is exciting. From Goddard's side of it, and as a scientist, talk about some of these things that are happening right now. And, along with that, the announcement a few weeks ago about Enceladus and the possibility of [hydrothermal] vents, and the possibility of life.

MAHAFFY: With Cassini, as we all celebrate, we're going to remind everybody that the early part of that mission was dropping the Huygens probe off into Titan's atmosphere. So we're having a little internal celebration in December. Again, as we walk out the door you can see the engineering unit of the mass spectrometer that dropped into Titan's atmosphere and made measurements for a couple of hours all the way to the surface.

Following that, which was really groundbreaking science in understanding the composition of the atmosphere, and understanding that there were rivers and lakes of methane on the surface, the orbiter has flown by Titan multiple times. In fact, it flew by Titan the hundredth time some weeks ago, and it's flown by Enceladus multiple times as well. Totally different worlds; very heavy atmosphere on Titan, heavier atmosphere than the Earth. The only moon in the solar system that has a heavy atmosphere like that. Mostly nitrogen, but quite a bit of methane. On Mars we look for parts per billion of methane, and on Titan it's all there. Enceladus is another ocean world, just like Europa, where there may have been liquid water covered by ice for potentially a good fraction of the history of the solar system.

The question is we still don't understand how life emerged on Earth. Did the first life emerge from a deep ocean vent where all of the energy sources were available? Or was it some pond on the surface that, by stuff falling in from space? If life is present on another world like Europa or Enceladus, does it look like Earth life? And there we've got to be careful. The techniques that we think we might use to look at that life might be biased by our perception that life looks just like terrestrial life, with amino acids building proteins, and proteins building cells, and DNA [deoxyribonucleic acid] and RNA [ribonucleic acid], and all that stuff. We kind of expect that the earliest forms of life might be cellular—the cell walls help isolate you from the environment—so that's one thing we could look for. But are there other types of things, other tools that we could take? What's the range of tools that we'd want to go look for life on those moons?

Or even on Mars, where water occasionally makes its way to the surface, how do you look for life in those environments? Potentially, on Mars the life might be down where the water is—down deep, and you'd have to drill deep to get it. But wouldn't it be exciting to understand if life emerged somewhere other than Earth? It really ties to, in the grand old universe out there, is life likely or not likely?

It's really a fundamental question, and it's one that NASA has adapted. Our folks who are understanding what the big telescopes will find in other worlds are trying to look at the signatures of "What would life do to an atmosphere?" Because that's what you could see from the big telescopes. For example, most of the methane in the atmosphere of Earth is produced by life. It's produced by microbes, by rice paddies, by cows chewing their cud and whatever cows do. Most of the oxygen that we're breathing, that's keeping us alive, was produced by cyanobacteria over the history of the Earth. So maybe if you saw both oxygen and methane in the atmosphere of a small planet that you could see with a telescope, people would probably get pretty excited. Whether they would say conclusively that was life or not, we don't know for sure. But that's the program.

Our end of it is trying to understand that, but also we have places in our own solar system where we can go land on surfaces, or dig holes, and use our instruments and try and answer that question. And how do you do it right, so you don't spend billions of taxpayers' money and have the wrong experiment there. How do you get past the challenge of Viking? "Is our approach too simple? Are we doing it right?" It's hugely challenging and hugely exciting.

Certainly with Cassini we're not only understanding what that whole system looks like—what the rings look like, what Titan looks like—but we're understanding that there's a good example of an ocean world. The stuff in the ocean that might harbor life is geysering out into the atmosphere, and a lot of it falling back on the surface. And, by golly, maybe we could land a spacecraft there and scoop some if it up or drill some of it up and put it in our instruments, and find out something really fundamentally interesting. Wouldn't that be exciting?

That's what is being pushed for the Europa lander. In fact, it could be a lot easier to do at Enceladus because the radiation environment at Jupiter is just horrendous, and it's much lighter at Enceladus. The big magnetic fields in Jupiter basically whip all these particles around and make it very difficult for instruments to survive on the surface of the ice. Long-term, wouldn't you like to dig a borehole and put a submarine in there and swim around and see if there are any fish or not.

JOHNSON: Anything coming out of those vents, like there are here on Earth?

MAHAFFY: That's right, yes. It's pretty exciting, and trying to understand what the next logical steps are in this grand, golden age of exploration is a challenge. And we're trying to do our part of it here at Goddard.

JOHNSON: Are there any missions we haven't talked about, or any projects that you wanted to mention?

MAHAFFY: No, we're all looking now at how we would respond to an announcement, if Headquarters puts it out as expected, for a Europa lander, and exactly get at these types of questions.

End on a sour note, but some of our grand failures, where we got a mission into space—one of those was CONTOUR, where we actually got into Earth orbit, then fired a solid rocket to get us flying by a comet, and then the spacecraft disappeared. A few days later, the remnants of the spacecraft were found by astronomers on Kitt Peak [National Observatory, Arizona]. There were pieces floating around. So it's a risk.

There are no guaranteed successes, but when you're exploring unknown worlds it's pretty incredible. We get used to seeing new Mars data from Curiosity every few days, but every so often, even though it's been four and a half years, you have to say to yourself, "We just came over that ridge, and nobody's seen this site at the resolution that we're seeing. Isn't that amazing?" It's a new world, and it's just amazing that we have the opportunity to explore it.

JOHNSON: It is exciting. If you look back at your career with NASA, what would you say was your biggest challenge?

MAHAFFY: I think, in terms of projects I've been on, the SAM experiment for Curiosity. Just a huge challenge, trying to help a really talented team march in step, and get things done and solve problems.

Always solving problems. You think something will work and it doesn't work, and you just go back, and you beat on the engineering and get it right. And then you test it, and then you get the scientist involved with understanding how to optimize the experiment, and think about what you would do on Mars. You collect the scientists even before you get to Mars and, "Well, if we were to go over a hill and we were to find this, what would you do?" We're training them to try and understand how to do the science best.

We would take our instruments out to field sites, and sometimes we would operate in the blind. We would get samples from a field site and we didn't know where it was. We would only look at it through the eyes of what were like the cameras on Curiosity. "Here's an outcrop, do we want to drill or not?" We drill, then we would get some of the sample shipped back to where the instrument providers were. We'd do the analysis, and then we'd all make like we were on Mars, "Can you interpret what you saw?"

That's training to get the team ready, to understand how to function efficiently on Mars. And that's all part of also helping us understand who has capabilities, who can help us with interpretation. Who the leaders are, who the follows are, and so on. I think certainly the Curiosity SAM experience has been the biggest challenge of my career, and also, I would say, probably the most satisfying.

JOHNSON: Well, it was a big project. And it's still going strong.

MAHAFFY: Still going, yes.

JOHNSON: I was going to ask Rebecca if she had anything.

WRIGHT: I've just got one. Is there a project you really would like to do, but may never get a chance to? What's your dream project that you really would like to work on?

MAHAFFY: Well, I think now I'm in a mode of trying to help the junior scientists be successful on their projects. What I'd like to see that builds on the skills that we've developed at Goddard, and the instruments we've built would be exploring an icy moon, Enceladus or Europa, something like that. So we work away on getting ready for that, and getting the right scientist to lead that. I try and help them as much as I can.

WRIGHT: What do you look for, that you'll know that that's the scientist that's going to be able to take that project forward?

MAHAFFY: Yes. Leadership, ability to motivate people and get engineers, who don't necessarily understand the science, excited about the science. Efficiency, and I guess a vision for what might be done in these exciting exploration experiments.

WRIGHT: Are those skills that you can teach someone, or is that something in their personality that helps them create that environment or others to become part of that team?

MAHAFFY: I think it's some of both. There are people that naturally have leadership talent, but then NASA, and even Goddard, has kind of their own culture. Certainly trying to help people understand the culture and how best to function in this environment is something I can—after being here since 1980—something I can help them with.

WRIGHT: And do you feel that the type of career that you have, is that still available for other people who are interested in doing what you love?

MAHAFFY: Yes, I think so. It gets more difficult as we go further and further out in the solar system. Mars and Venus are nice because you can get to them in a few short years. In other words, we land in 2012 on Mars and started doing science. We really started the project in 2005, so seven years later there we are. Of course, I'd started four years earlier trying to get ready for it. But in some of these outer solar system missions, it depends a little bit on what rocketry NASA decides to use for these missions. On the low-end rockets, it can take a long time. We're looking at Enceladus missions now, for example, that would get there in the mid-'30s. If they were started this year, they would get there in the mid-'30s.

That's where we look for teams that have a combination of experienced people and junior people who can be mentored and move into leadership roles. When I came to Goddard, most of the principal investigators on the Galileo probe were approaching retirement age, or would retire shortly thereafter, so understanding how experience and leadership gets passed on, I think, is very important.

JOHNSON: Anything else that you wanted to mention before we go?

MAHAFFY: No, I don't think so.

JOHNSON: I appreciate the time you took today to talk to us. Thank you.

[End of interview]