# Discovery 30th Anniversary Oral History Project
# Edited Oral History Transcript

Keith S. Noll
Interviewed by Sandra Johnson
Ellicott City, Maryland — July 27, 2023

JOHNSON: Today is July 27, 2023. This interview with Dr. Keith Noll is being conducted for the Discovery 30th Anniversary Oral History Project. The interviewer is Sandra Johnson. Dr. Noll is in Ellicott City, Maryland, and talking to me today over Microsoft Teams. I appreciate you talking to me today and agreeing to participate in the project. I'd like to start by asking you to briefly describe your education and your background and your interest in astronomy and exploration science and how that brought you to NASA.

NOLL: To start back at the very, very beginning, one of the biggest influences on me is that I was 10 years old when the Moon landing occurred. That was just a pivotal event. And not just that but the whole space program, being a kid and rockets and everything. I was really, really interested in all that stuff from a young age. I also have this memory. I was probably only three or four years old, standing by my mother in the backyard. She was talking over the fence to our neighbor. I was pretty small because I can remember sort of hanging onto her skirt or something and looking up. I saw this fireball cross, a bright green fireball, visible disk, and then a few seconds later there was a sonic boom. That just blew my mind. I guess that stuck in my head too, so I was really interested in all this space stuff.

In high school, I was doing all the courses. We got to physics, and we had this physics teacher who was just wonderful. Instead of lecturing nonstop, he would give us problem sets to do. He'd give a short lecture and then problem sets, and then we would go off and do these problem sets. We could work on our own. It was a level of independence that I hadn't experienced yet. It's more typical of what you get in college, but to get that in high school was pretty influential. So, I decided that I loved physics and decided I wanted to major in physics in college. All through college, there were more space activities going on, especially Voyager and some of the Mars Missions. Back in those days, there was no Internet. I would write a letter to NASA asking for their latest photos, and weeks later you'd get an envelope with some glossy photos in them. I had those up all over my dorm room. There was a sort of constant reinforcement, I think, of what I was interested in.

And then the last thing that really was influential, I went to graduate school and got a master's degree in physics at University of Illinois. I had been interested in astronomy. My undergraduate professor tried to talk me out of it. He said, "There are no jobs in astronomy. Do something more practical."

I said "Okay, well, I'll keep going in physics." I just didn't love it in the master's degree program there. It seemed soulless to me I think was how I felt. During that year was when Cosmos [with Carl Sagan] came out. It was an extremely rigorous first year at this university. They took twice as many graduate students as they intended to keep, so we all knew that our heads were on the chopping block. You were working from the minute you woke up until the minute you went to sleep. The only time I allowed myself off was Sunday afternoons, and that's when Cosmos would come on PBS. I would go to some local grocery story, get some kind of freeze-dried meal or something, and then come back and watch Cosmos. I think that was what made me realize even if there's no jobs this is what really gets me excited. This is what I need to do.

I started applying for PhD programs in astronomy, and that's how I ended up going to the State University of New York at Stony Brook; I had a wonderful thesis advisor there. That was the start of my planetary science career.

Once I got there, within the first year, one of the professors needed some help observing at the NASA IRTF [Infrared Telescope Facility] on Mauna Kea [Hawaii]. As a kid who hadn't really traveled all that much, I got a plane ride to Hawaii. At that time, the road up to Mauna Kea was extremely primitive. It's much better now, the Saddle Road over the Big Island. But this was a road that had been built in World War II. It was really windy and one and a half lanes, potholed everywhere, and you're in these lava fields. It was quite the experience. That really cemented in my mind that I had made the right decision.

Then from there on, I was doing the usual. You do a postdoc and then you look for jobs. My undergraduate professor was right. There were very few jobs, which is true, I think, at all times. But I was lucky and ended up going to Space Telescope [Science Institute, Baltimore, Maryland] when they were, I guess, desperate for people because it was right after a spherical aberration had been discovered [Hubble Space Telescope, HST]. I got hired there, and I was there for 20 years. That was a great experience.

And then 12 years ago, Amy [A.] Simon from NASA approached me and asked me to apply for a position at Goddard [Space Flight Center, Greenbelt, Maryland]. I don't know what made me do it. I was all set. I was fully tenured, could've just stayed at Space Telescope forever, but I decided what the heck, let's try something new. I think the thing that I was really looking for was—back then I was working on JWST [James Webb Space Telescope], I'd already been working on it for 5 years, and that was 12 years ago. JWST is wonderful now, but it was pretty clear that it was going to be a long time of waiting and waiting and waiting for this. I was interested in something that happened on a quicker time cycle, so I came to Goddard with the idea that I would get involved in a mission somehow. Unbelievably, luckily, it worked out. That's sort of the story in a nutshell. That's how I ended up where I am.

JOHNSON: When you first came to NASA, on your resume it says that you were the chief of Planetary Systems Laboratory. At that time around 2011, what were you working on as chief?

NOLL: At Hubble, the main thing I ended up getting involved in there—I started out doing giant planets and giant planet atmospheres infrared spectroscopy with the instruments on Mauna Kea, and I continued that. But when I got to Hubble that was more of an Optical UV Telescope. I started poking around for projects there that would be interesting, and so I did some things. In the late 1980s, the first Kuiper Belt objects were discovered. I got extremely interested in the Kuiper Belt and wanted to think about what we could do with Hubble with the Kuiper Belt. We started out trying to use NICMOS [Near Infrared Camera and Multi-Object Spectrometer] to get some infrared color measurements. Those were interesting. But actually what turned out to be more interesting is we started finding a lot of binary objects, and so that became my big project while I was at Hubble. We ended up finding something like 75 binaries, which is still most of the known binaries. There are a little bit over a hundred known now.

That was extremely productive, and that really turned into one of the more scientifically important bits of knowledge that we have about the Kuiper Belt because it really stands out as different. When you look at the different subpopulations within the Kuiper Belt, some of them have many more binaries than others. You take that information, try to weave that into a story of how did things get there, how they evolved, how were they affected back at the very earliest part of the solar system. Once I got to NASA, I was still doing that, and I still do that now. I think that's been such a productive bit of science. But what I started thinking about was getting involved in a mission. Pretty soon after I got there, I put together a mission idea and did the work for that. We ended up proposing to the Discovery Program.

JOHNSON: The mission idea for Lucy, is that the first one?

NOLL: No.

JOHNSON: What was that first one?

NOLL: The mission that we proposed was called DARe [Dark Asteroid Rendezvous]. It grew out of my interest in the Kuiper Belt because it was clear that the Kuiper Belt was unique and different than other small body populations, and that had a lot to tell us about how the solar system formed. But it was frustratingly far away for spacecraft. New Horizons was already on the way and had that amazing encounter with the Kuiper Belt object, although we didn't know at that time that it was going to happen. That was something that I was involved with finding that object with Hubble, but at the time we didn't know. The idea of how could you study the Kuiper Belt with spacecraft, got thinking about there are these other asteroids that are similar to the Kuiper Belt. Maybe they're similar enough that studying them is going to tell us some important, interesting things.

What we proposed with DARe was to look at certain kinds of asteroids in the main asteroid belt that are called D-type and P-type asteroids. That gets into spectral classification. But the important thing about those is that we think those are among the most primitive kinds of asteroids, and they're similar to the spectra that you see in the Kuiper Belt. They look like, as far as you can tell from spectra, to be at least close cousins but they're much, much closer. We could put together a mission that would go to a couple of these objects, go into orbit around them, really gather a lot of information about the compositions. And try to understand how are they related, how are they different from other asteroids, and what's that telling us about the whole history of how things formed and then got mixed later on and how planets were built and all of the various things you have to do to make a planetary system.

We were competing for Discovery, the one where Lucy was selected. We were competing with Lucy and other missions. Lucy has, I think, very similar science goals in the sense that it selected another group of objects that also have a very strong relationship to the Kuiper Belt, the Trojan asteroids. They have a lot of the same science goals that we had with DARe. DARe was not selected at Phase A and Lucy was. Hal [Harold F.] Levison, who's the PI [principal investigator] of Lucy, and I knew each other very well from previous science things we had done together. We had written papers together. They needed to have a project scientist who was at Goddard, so they asked me to join Lucy. It was an easy perfect fit because it was the same science goals, just a different set of targets. I joined right after the Phase A selection, and then I've been with Lucy since then. I think that was in 2016, January.

JOHNSON: I hadn't realized that you were proposing a different mission. Were you the PI for DARe?

NOLL: I was the PI for DARe, yes.

JOHNSON: You mentioned that you wanted to join NASA because you wanted to have missions and you wanted to have something happening sooner. Was Discovery one of the things that drew you to NASA, or were you aware that the Discovery Program was doing those PI-led missions?

NOLL: Sure, of course, yes. If you want to do a PI mission it's either Discovery or New Frontiers, and both are being done. I liked it that Goddard was a little bit of an underdog in the game. Most of the missions, I think, had gone through JPL [Jet Propulsion Laboratory, Pasadena, California] and they were the big player in the game. But Goddard had a really good track record of being selective and efficient and getting their missions done on time, under budget. That was pretty appealing. But also it was just a geographic thing. I didn't have to move. I didn't have to drag my family—I had kids in high school and didn't want to do any of that stuff. That was another factor, but I really did like that they were kind of a lean and mean operation. It was really just a good fit for what I was interested in doing.

JOHNSON: Talk about the process of going through after the announcement of opportunity and then a team forms. You have this idea. Talk about that process for DARe, when you get to that first phase, how you form that team and what it's like answering that announcement of opportunity.

NOLL: For me, it was a very steep learning curve because I had not been on a mission before other than Hubble. But Hubble was so big that you only see little slices of what's happening. To be in a PI position where you have the whole thing to consider, there was a lot of stuff that I did not know. I really relied a lot on people at Goddard. One of the first things you want to do is think about your science team. That was fairly easy because that's something I knew about. I selected different people for science. I had a deputy PI, Lucy [A.] McFadden, who did have experience with other missions, including Dawn[1] which was very similar to the kind of mission we were going to have. She was wonderful. I don't think I could've done it without her because she had the experience and knew some of the ins and outs.

But really more important is your engineering team. I think that's been, in my experience, the thing that I've learned the most about and has been the most satisfying. You really rely on engineers to make these missions work. They have slightly different ways of thinking and working than scientists do, and you have to be open to that. Your first reaction could be, well, that's not how I would do it as a scientist. But they have all these processes for a reason, and I've really come to appreciate what they do and enjoy working with some of the really good engineers. We had another engineer working with us, Keith Walyus, who was absolutely essential, had tons and tons of experience. We had a little bit of growing pains, but in the end, we put together a strong proposal, at least scientifically.

I think the other thing that was tricky to learn at first was this sort of accepted process of putting together your matrix. You think about you have your science goals and then science objectives and then instruments and the measurements that you're going to make. Of course, as a scientist you start with, "There are things I want to do, but tell me what I can do. What instruments do I have? And then I'll work backwards from there and tell you the interesting measurements that I could make." But you have to write it in a way that it flows from the goals down to the objectives and the tasks. That took a while to get my head wrapped around. I had some good help

[1] Dawn was NASA's first truly interplanetary spaceship. The mission featured extended stays at two very different extraterrestrial bodies: giant asteroid Vesta and dwarf planet Ceres. Both small worlds reside in the debris-strewn main asteroid belt between Mars and Jupiter.

from Lucy [F.] Lim, who was one of our co-Is who had been on OSIRIS-REx[2] [Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer] and so was aware of this process. In the end, we really did get to a good place with the science.

The other piece of it that was even harder for me to get my head around was the budgetary side. There, I think we did not do as well. In part, I think, because—well, I don't want to say anything negative. In the end, the thing that was weakest about that proposal was the budget. In hindsight now, I don't think I would propose it because I don't think it would be approvable primarily because of the budget. We were depending on contributed instruments, and I think we under budgeted some of our instruments.

Seeing how the budget process works for real on Lucy and how costs grow even on things that are just rebuilding an instrument that's already been built before, you get a sense of why the budget is really so important and why the structure is set up the way it is with large reserves and margins because wiser people know that you're going to eat those up. I've come to a really strong appreciation for the whole program and the way it's set up. I think I'm a little bit biased because Lucy, in particular, has been such a wonderful mission, and I've got a strong team in every aspect of what we're doing. Hal Levison is a wonderful PI. He really knows how to build a team, get people to invest personally and want to work for it. It's been probably the most fun that I've had in my career. It's been a wonderful process.

JOHNSON: That's great. Did any other of those DARe members move to Lucy or were you the only one?

[2] OSIRIS-REx is the first U.S. mission to collect a sample from an asteroid. It returned to Earth on Sept. 24, 2023, to drop off material from asteroid Bennu.

NOLL: I think I am the only one. Alyssa Rhoden, who was a postdoc at the time, was very interested in the mission so she joined onto the science team. She was great. She was very effective. She is now at Southwest [Research Institute, Boulder, Colorado], and she's proposing missions and is getting very involved in missions. I think that experience really had a big impact on her. Lucy Lim is involved in other missions but not on Lucy. Lucy McFadden retired. I think some of the other co-Is that we had were on multiple missions so there's probably some overlap. I don't honestly remember who our co-Is were.

JOHNSON: That's okay. It was a few years ago. Talk about, just for a minute, what you think the benefits of a PI-led mission, like in Discovery and New Frontiers, and how that helps NASA with these types of exploration missions as opposed to those big missions that take years and lots of money that NASA is well known for.

NOLL: Again, I'm looking at it through the lens of Lucy. I think that having a single person being responsible for the mission makes a difference in terms of wanting to get things done on time, on budget. Hal's been really great about saying no to things that, "Oh, we could do this or we could do that." If there's a strong reason and a justification, we've gone ahead and done those things. But when things are just sort of nice to have but you don't need it and it's going to raise the cost, he's able to say no. I think that's harder to do when you have a less identifiable person in charge. For Flagship missions, I guess it's harder to identify who has the final word on things like that. The scope is more well defined. That's just more about the size of a mission. I don't know that the way it's managed is the thing that makes a difference, but it definitely works the way that it's being done right now.

I think the Discovery Program in general has been a tremendous success. We're doing science that, in the Decadal [Survey][3], was originally designated as New Frontiers science. That was a big part of the selling point for Lucy was we're going to do New Frontiers science on a Discovery budget. You're pushing people to compete and innovate with this competitive process. I think that's an example of how you get value by having a process like that rather than just a, "Hey, we want you to go do this mission." What usually happens in those cases is the cost goes up and up and up because there's less of incentive to not do that.

JOHNSON: You mentioned that one of the things that set Lucy apart was that New Frontiers type mission on a Discovery budget. Are there any other things that you think may have led to it being one of the two missions chosen for that selection?

NOLL: We had a great proposal. We—every part of that—went over with a fine-tooth comb so many times. Hal and I wrote the science case. I think we did all the things that you need to do. We had a low-risk mission in the sense that we were using instruments that had flown before, some of them with small modifications but not anything truly revolutionary. The one thing that was new was the solar arrays, which have given us a big headache. I think that combination of really strong

[3] NASA relies on the science community to identify and prioritize leading-edge scientific questions and the observations required to answer them. One principal means by which NASA's Science Mission Directorate engages the science community in this task is through the National Research Council (NRC). The NRC conducts studies that provide a science community consensus on key questions posed by NASA and other U.S. government agencies. The broadest of these studies in NASA's areas of research are decadal surveys. As the name implies, NASA and its partners ask the NRC once each decade to look out 10 or more years into the future and prioritize research areas, observations, and notional missions to make those observations.

science, ticking all the boxes, and doing it at cost and low risk is what Discovery looks for, and we met all those criteria. We had a great site visit. I think we knocked it out of the park at the site visit.

We had a couple of glitches there. One was we had to redo the radiation exposure report. John Loiacono, who was the deputy project manager, pulled that together in a record amount of time during the site visit and came back by the end of the site visit with a revised thing. It was one of those funny things. It was probably not consequential but there was an error in the original one and they fixed it. None of our instruments are very subject to radiation, so it's not anything we were super concerned about. One of the reviewers had found this little, tiny mistake, and something like that can sink you.

But I think that part of what the review board is looking for at a site visit is how the team works together, and I think we were able to demonstrate what a strong team we had. That even with these unexpected bumps, we were able to keep our heads up and deal with things because that's what you need in a mission. No matter what you think is going to happen, something's going to surprise you. It's really how you deal with that adversity that determines whether you have a successful mission or not. I think that's been a real strength for us because we've had our share of adversity, but it's never broken the team. It's never caused any fighting or anything like that. Everybody just dives in and does what needs to be done because they all feel like they have a piece of the mission and they're invested.

JOHNSON: You mentioned building this team and being able to communicate is important, and you were talking earlier about scientists and engineers sometimes have almost a different language they're speaking. In that team, you're working with not only fellow scientists but engineers, managers, budget people, PR [public relations] people. Talk a little more about that and the importance of that communication, especially because you're NASA but you're working with Lockheed Martin, you're working with APL [Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland], you're working with Arizona State [University, Tempe Arizona] for all the different instruments. You have people from a lot of different worlds getting together to create this successful mission.

NOLL: One of the things that I think we're pretty proud of, and I've heard people say this, is that Lucy's really a badgeless mission in the sense that we do not—I've never encountered a situation where somebody says, "Well, I can't do that because I'm this and you're NASA." Everybody knows where people are from, but it's just not important. The Lockheed people are as much of the mission and the instrument people, everybody. I was joking at the beginning about one of the skills is you have to be able to sit for hours, but Hal and I and Cathy Olkin, when she was a deputy, and now Simone Marchi sit in on essentially every meeting that there is, including all the engineering meetings. I don't know if that's typical, but I've heard that on some other missions it's not that typical that the PI just kind of lets the engineers do their thing and doesn't get involved.

I think because Hal hasn't been on a mission before and I haven't, we felt it was really important that we be present. I think that makes a big difference. People know you're there, know you're listening. When we don't understand something, we ask questions. Hal's really good about understanding that in a mission that's hierarchical, people tend to take any random thing that a PI says as, "Oh my God, he said, 'Do this.' Now we have to have a tiger team." He's good about not doing that. But also, I think he's been good about creating an atmosphere where people will say, "Wait a minute, did you really mean that because that doesn't make any sense." He's totally fine with that. That has been a big help that we stay focused. People know what he wants, but they also don't over-interpret or they're not fearful. It's been this very open process, so that contributes to the badgeless team. We're doing the same thing on the science side. We have open science team meetings. We have people coming that are not officially on the science team. They're interested and they want to listen in. That's fine. They can be collaborators. It's created a nice little community.

JOHNSON: With Dr. Levison being the PI and you're the project scientist, talk about that relationship a little bit and about what your responsibilities are compared to the PI since you're the project scientist for NASA.

NOLL: Project scientist is one of these really ill-defined roles. On a non-PI mission, the project scientist is the top scientist on the mission with the project manager leading the mission. In a PI-led mission, I think the role of the project scientist is a little less well defined. There are missions where the minimum role for the project scientist is to organize and lead the science team meetings, communicate between the PI and the science team if you need an intermediary. We have our science team divided into working groups, and so part of what I do is attend the working group meetings just to make sure if things come up that need to be communicated out that gets done. That's sort of the minimal role, I think.

I've leaned more towards a maximal role. As I said, I attend all the meetings no matter what they are. I think that Hal would agree that we have sort of a leadership group for the mission. That includes him, the deputy PI, the project scientist, the deputy project scientist, and that the four of us tend to make most of the major decisions together. Hal ultimately is the one that decides, but we're sort of his inner circle. He also works very closely with the project manager and the deputy project manager, and the mission operations manager. That's his closest orbiting group of people that he relies upon.

JOHNSON: Thanks for explaining that because I wasn't sure.

NOLL: I think one of my most important jobs is to tell Hal that he's wrong.

JOHNSON: I'm sure he appreciates that.

NOLL: Well, he just tells me, "No, you're wrong."

JOHNSON: Let's talk more about the reason for Lucy. What is it that makes this mission important for exploration and the science goals? And, actually, the name Lucy and how does that apply to the mission?

NOLL: I'll start with that first. Lucy, the name was selected for the first iteration of the mission, and that one was not selected. Hal was not the PI of that. It was somebody else, and I wasn't involved in it. The idea was that to evoke the idea of fossils. And that just like Lucy was this very important fossil in understanding the early development of hominins and upright walking and all that kind of stuff, getting to these Trojan asteroids would give us an equivalent view of the early history of the solar system. That's the idea. They liked the idea of not having an acronym, so it's not an acronym for anything. That's the extent of it, although we've had a lot of fun with that because we worked with Donald Johanson, who was the paleoanthropologist that discovered the Lucy fossil. I had the pleasure of meeting him a couple of times. He's a wonderful person.

Lucy the fossil was named after "Lucy in the Sky with Diamonds" because it was discovered in 1974 right after the album *Sgt. Pepper* came out. They were in this remote region of Ethiopia in a camp and somebody had a tape. They didn't have much in the way of entertainment, but they had this Beatles tape and they just kept playing this over and over again. Somebody in the camp suggested, "Hey, why don't we name the fossil Lucy?" because they don't typically give them nicknames like that. Its official name is AL [288-1]. But that stuck and so that's the line that connects us back to the Beatles. Since Hal and I are old enough to remember that time, for a lot of our PR stuff, we've sort of leaned into the artistic style of that era, sort of this psychedelic style that we've used on some of our posters. We've had a lot of fun with that. I think anything you can do to make missions relatable is important.

One of the things I did when I was at Space Telescope was I started the Hubble Heritage Project which was this outreach project that used Hubble to get images that were more about the image than the science, although they were scientifically useful too. What I think motivated that and what I learned from that is that—we often say that those images saved Hubble because after the disaster and [NASA Administrator] Sean O'Keefe was going to cancel the servicing mission, that would've been the end of Hubble. The outcry from people was, "You've got to save Hubble because of the pictures." I think people realize that the pictures themselves may not be everything about the science but they represent to them how powerful this telescope is and the science that it can do. It's sort of the way of entry into the subject.

I think you have to have a way to hook people into taking a look, and then if they're interested, they'll dig deeper and get into more of the nitty-gritty. Or maybe they won't, and they'll just remember, "Oh, there's this mission called Lucy," or, "Hubble takes great pictures." But no matter what, you're giving them some value for the investment that they've made as taxpayers into what we do. For the kids like me that mail off and get the pictures back from JPL, that may be what gets them into their career later in life. You never know. That's kind of what we think about when we do the outreach stuff, how do we get that teenage kid that's thinking about what they want to do with their lives and they like science, how do you spark their imaginations. The other part of your question was—I've already forgotten. I'm sorry.

JOHNSON: That's okay. One of my questions was about that outreach and the work you did with Hubble. People, like you said, were invested because they wanted to see more and the pictures were cool. I think the same thing happened during Apollo, like the Apollo 8 photo of the Earth. It made people realize we're on that blue marble, and this is our solar system with Hubble. This is where we live. I think it's important. I did notice that Lucy had several different ways of doing outreach. The Lucy Soundscapes, and they had the patch for kids in school to design and different things like that. Were you involved in a lot of that?

NOLL: Tom [Thomas] Statler was the one that came up with the idea for the Soundscapes. He's our program scientist at NASA Headquarters. He is quite a musician in his own right. He came up with that idea. He composed a piece himself. It was really good. He gets all the credit for that. For the other stuff, I've been pretty involved in most of the outreach stuff. We've got Katherine Kretke who works at Southwest who leads our outreach stuff. The one thing that I'm really bad at, and that Hal's also really bad at, is social media, so we have to have somebody else that is much younger than us that can do that. She takes care of that. We've got a fairly active effort, and

Goddard has been helping out. We've got some wonderful videos—I don't know if you've seen them—that are sort of cartoon-based videos for Lucy. Those were all produced at Goddard, and they are great. If you're interested, I would check them out.

JOHNSON: I'll go look for those, yes.

NOLL: And then we've made these posters that we had them at launch. We've circulated them some internally. We haven't used them a lot, but I can share those with you too. They're a lot of fun.

JOHNSON: Yes, that'd be great to see them. The plaque also.

NOLL: The plaque was Hal's idea, and that was something that he put together. Anne Streeter, who was the administrative assistant working with us, did a lot of the work in contacting the people that eventually contributed quotes for that. But it was a great idea and a lot of fun.

JOHNSON: Yes, I've read the quotes from it. I did talk to Hal last week, and he was talking about who the plaque was for basically. The people that come after us, however many thousands or a million years from now, that will be able to see that plaque and know the way humans thought at that point.

NOLL: Yes, it's a fun story because I think the Pioneer and Voyager plaques were for people or for something far away, but Lucy's just going to be here. If it ever gets found off in the far-off future, that's our message. That's a nice thought.

JOHNSON: Yes, it is and nice messages too. The other part of that question that I had earlier was talk about the importance of Lucy and the science goals and the importance for exploration. What do you want to accomplish and how does that fit into what we need to know?

NOLL: This ties back to this sort of drastic change in the way we understand the solar system that started with the discovery of the Kuiper Belt, the discovery of exoplanets and realizing that they looked very different than our solar system. And then some of the theoretical work that Hal Levison's been very involved with, which is putting together these computer models simulating how you form the solar system, how you form the planets. One of the big problems that existed for a long time was nobody could figure out how you make Uranus and Neptune. We have this basic idea that you get gas and dust, it collapses, and it's spinning so it forms a disk. And then in the disk you get condensation, so you form planets. So far so good. But when you try to work out the details of that, you can make Jupiter okay. You can make Saturn. But Uranus and Neptune take 30 billion years to make, so the disk is gone. There's no way you could do that. It can't happen, and so we were really stuck there for a long time.

The big realization was that the planets don't have to have formed where we see them now because we see these other exoplanetary systems where Jupiter-sized things are right up next to their stars. That was the first ones that were found because they were easy to find, but they also couldn't have formed like that. The planets had to move around. Once you unlock that bit of freedom that, "Okay, I can move the planets around. Maybe Uranus and Neptune didn't form where they are." People started playing around with that, and this is where Hal's models were involved. If you form them in a much more compact configuration—so Jupiter, Saturn, Uranus, and Neptune are all pretty close to each other, and maybe some other planets that are lost now—as they interact with each other, they naturally expand, and you can get a planetary system that looks like ours.

The bonus is that you can use the Kuiper Belt as a test, because as this expansion goes on it's shaping the Kuiper Belt, and so we can compare what the model would produce with the real Kuiper Belt that we see. That allows us to really nail down, well, it had to happen like this, and there had to be jumps. But we can see clear evidence that this expansion happened in our solar system just by looking at the orbits of the thousand or more bodies that we know about in the Kuiper Belt and a clear fingerprint of that happening. That has been a profound change in the way we think about the solar system.

As a corollary to that, as this expansion is happening, the disk that was there that formed the planets is just getting scattered everywhere. Think about a snowplow coming down the street. It's plowing the snow, and the snow is this disk of dust and gas and small things. The snowplow is Neptune. It's plowing into this disk. It's pushing stuff ahead of it. That becomes the Kuiper Belt. But it's also scattering stuff off in all directions, and that stuff—a lot of it gets ejected or lost. Most of the small things are lost from the solar system, but some of them end up being trapped as the Trojans. That gives you this connection between they were in the same place as the Kuiper Belt. What's in the Kuiper Belt now just got pushed outward. The Trojans are the ones that got pushed inward.

And so if you want to understand what's going on with this process and if you want to test that idea—this is an idea at this point. It's a hypothesis. You should be able to test that by making predictions and then testing whether or not those are true. The Trojans should have similarities to things in the Kuiper Belt. They should be low density. They should have extra volatiles. They're closer to the sun so they're hotter. Any ices near the surface have probably been lost, so they might be hidden under fairly thick layers of dust. But to test that, we're going to have to go there and look at the deep craters, fresh craters. Do they have ices in the bottom? Do we see differences with depth in the craters indicating that you go from a dry powdery material to icier or rockier stuff down deep? Those are all the things we're going to look for with Lucy. We'll measure the masses and shapes so we'll get densities for all these objects. We already know from the satellites of some of them that they have low densities, so it looks like part of the hypothesis is bearing up. But with Lucy we'll learn a lot more. That's the motivation.

And then once you make that connection, so if Lucy gets there and we say, "Yes, just as we thought, these things look like they came from the same group of objects that are in the Kuiper Belt," of which we only have one example. Well, Pluto plus Arrokoth[4]. Then you can really start to put more weight on this model of how the early solar system evolved. I think that's an important thing for us to understand. That's what Lucy's going to do. The best thing about Lucy is that we go to so many objects. Instead of going to just one, we're going to five Trojans. Three of them have satellites, so eight objects in total. Maybe more because there may be more satellites that we haven't seen yet.

[4] Arrokoth is a small Kuiper Belt object also known by its original designation (486958) 2014 MU69, and its nickname, Ultima Thule. The most distant and most primitive object ever explored by a spacecraft, Arrokoth was discovered in 2014 by NASA's New Horizons spacecraft's science team, using the Hubble Space Telescope. New Horizons flew by Arrokoth on Jan. 1, 2019, snapping images that showed a double-lobed object that looked like a partially flattened snowman. It's also very red – even redder than Pluto. The object's strange shape – unlike any ever seen – was the biggest surprise of the flyby. Nothing like it has been found anywhere else in the solar system.

Doing all the comparisons between all those objects is really a much better way to do science than just going to one and then trying to infer everything about an entire population from a single object. You can do that. Sometimes you're forced to do that in astronomy because you've only got one so that's your only choice. With the Kuiper Belt, it would be wonderful if we went to five Kuiper Belt objects instead of just one. We're going to have to wait another generation for that to happen probably. But in the meantime, this is the best way for us to really get at what is going on in the outer protoplanetary disk as the planets are forming, and then as they get scattered away and we end up with the structure that we see now in the solar system.

JOHNSON: Talk about those asteroids that will be visited, the ones that you mentioned, and the moons. Did the trajectory of Lucy determine the asteroids, or were those asteroids chosen first and then the trajectory was adjusted, or was it a little bit of both?

NOLL: It was a little bit of both. I wasn't around when they did this. Hal probably gave you a longer version of this, and he would have a more accurate memory. My understanding is that Hal wanted to go to Eurybates, which is the first of the ones that we go to, because we know that it has been involved in a major collision. We can see all the fragments of it, and they have a very distinctive orbital distribution so we know that this happened. It's also unusual in that most of the Trojans are P-type and D-type spectral types, and Eurybates is a more neutral C-type. The idea is maybe the collision has something to do with changing the colors of these things, and that would be an important thing for us to understand about how these planetesimals evolve in general.

And then so you can do comparative science, we have another object, Orus, which is almost the same size and in very similar orbit to Eurybates but it's a D-type. So now you're really doing science. You've got two things. You've controlled all your variables except for the one thing. This one had a collision and this one didn't. Now you'll be able to answer the question: Is this one red because it didn't have a collision and this one is not so red because it did? Or is there something else going on that we are missing? That's what they started with, those two objects. We go out in loops. The first loop goes through the group of Trojans that are in the L4 Lagrange cloud. That's the one that's about 60 degrees ahead of Jupiter in its orbit. Then the next loop comes back and goes back out. Six years later the L5 cloud has rotated into that position, so now you're going through the trailing group of Trojans, the ones that trail behind Jupiter about 60 degrees.

Hal noticed in there that they came close to this binary object called Patroclus and Menoetius. It's a binary object. The two objects are about the same size. They're among the larger Trojans, about 100 kilometers across each. I mentioned before that we found so many binaries in the Kuiper Belt. Those look like a Kuiper Belt binary. Kuiper Belt binaries tend to have these equal sized components. And so it's another way of testing this idea that these are closely related populations by looking at this binary. Does it have evidence of having been disturbed or less disturbed? What's the cratering record look like? What can we tell about the shapes of the objects?

We know they're elongated and they're pointing at each other, but the details of the shapes might tell us if they were originally further apart or closer together because they have a certain shape, an equilibrium shape that is based on this tidal distortion that they get stretched kind of like pieces of taffy. That's among the most interesting objects in the Trojans. If I were going to plan a Trojan mission from scratch, that's one that I would definitely want to be on the list. Hal felt the same way. Once he realized that he could get to that one that really locked down this trajectory that went to Eurybates, Orus, and Patroclus. That was the way the mission was originally proposed, just those three objects.

JOHNSON: Are binaries as common in the Trojans as they are in the Kuiper Belt?

NOLL: They are not, and we don't really understand why. It's a hard question to give a definitive answer about. Wide binaries that you can see with Hubble Space Telescope are not as common in the Trojans as they are in parts of the Kuiper Belt. That's a very qualified statement. There are parts of the Kuiper Belt that don't have very many binaries, and those may be more similar to the Trojans than the parts where there are lots of binaries. But all of the Kuiper Belt has some binaries. There are some binaries in the Trojans, but they tend to be closer together. We're now learning if binaries are too close you can't even see them with Hubble. They're too close to see with Hubble. But you can look at the variation of light over time, light curves, and there's a distinctive light curve shape that is associated with binaries that are very close or in contact with each other. There seem to be a lot of those in the Trojans. So it's possible that whatever happened when they were being scattered, that either broke up the wide binaries or caused them to come closer together. That's part of what we want to understand by going there.

JOHNSON: Talk about how Hubble has aided your team in finding things before you go. I'm thinking of the Eurybates and Queta and that sort of thing. Talk about that and how Hubble's been used to make these other decisions about where to go.

NOLL: Hubble's been great for us. One of the things that I do on the science team is the satellites studies. That's one of our major science objectives is to understand satellites and rings and other near asteroid activity. So we wanted to start by just doing the deepest possible survey we could with Hubble. We did that for all of the targets, and we found this satellite of Eurybates. That was an interesting process in itself. We had two observations. We could see this little blip. The images from Hubble have a lot of little smudges in them because of the point spread function. Knowing that something is a real object versus just an aberration from the mirror, you have to see it move. In hindsight, we probably took them too close in time. They were only separated by two days. It barely moved just the smallest amount, but it was enough that we said, "Aha, that looks like it might be a real thing."

We went back and asked for more time to confirm it, and we were awarded three visits, three different chances. They said, "If you don't see it in those three chances, then that's it. You're done. But if you see it, then we'll give you some more time with Hubble so you can get the orbit of the thing." The first two attempts we made we didn't see anything. Then we started getting nervous like, Oh, okay, maybe it was just a smudge and the focus changed a little bit so that's why it moved. It wasn't real. We were really starting to doubt ourselves. And then on the third and last attempt we saw it luckily. By that time, we had worked out what the orbit would have to be a little bit better, so we had them spaced more than two days apart and we had guessed about right in terms of how long we had to space them. For parts of the orbit it's too close to see with Hubble, but this third one it had moved out far enough away and we could see it. Then we got the rest of the time and we went back.

We had a couple more misses, but mostly after that we had figured out where and when we should be able to catch it and eventually came up with an orbit. We're still working on that. We have a proposal pending with Hubble to go back and get another image to see if we can make the orbit better because when we get there with Lucy, we have to know—we have a pretty good orbit for it now. Where it would be when you're there with Lucy could be over a pretty big angular range, and we don't have time to just go searching for it so we need to know pretty well where it is. We're going to keep observing with Hubble right up to the encounter in 2027 to try to narrow down where we should point the cameras with Hubble when we get there.

JOHNSON: That's interesting that you're able to use Hubble after working with Hubble for so long.

NOLL: It is.

JOHNSON: Is that pretty common for this type of mission, to use Hubble, because you mentioned using it for the Kuiper Belt?

NOLL: Yes, certainly for New Horizons it was essential. New Horizons, after Pluto, wanted to go to a Kuiper Belt object, and they had to find a target they could get to with the limited amount of fuel that they had. They had been looking for several years using ground-based telescopes. Back in 2011, I think, I had proposed, along with my postdoc, Susan Benecchi, that we should use Hubble to do this. We guessed it would be about 100 orbits that you would need. At the time, they said, "No, we don't want to do that just yet. We want to try and see if we can do it from the ground." But time was running out and they had not found anything from the ground, so finally the team came around and said, "All right, we're going to try it with Hubble."

That's a big ask. That's a lot of time that you need, but John Spencer led the proposal and did a fantastic job on that. John Spencer is our deputy project scientist now. He made a really convincing proposal and it got the time. They ended up finding three objects that they could potentially get to, which was far fewer than we thought, and that has to do with the Kuiper Belt itself. There aren't as many smaller objects as you might think. They selected the one that used the least amount of fuel to get to, and that was Arrokoth. Without Hubble, they would not have had a target to go to. There would not have been a visit. That was clearly essential.

I can't think of another example that is as critical to a mission as that one, but certainly other missions have worked, gotten data with Hubble to help them out. I think for Lucy, it might be maybe the second most important in terms of finding the satellite. That gives us an estimate of the mass of the system from the orbit. Interestingly, we did not find the satellite of Polymele with Hubble. That was found by a different method. Polymele has a satellite that Mark [W.] Buie and his team found with a ground-based stellar occultation. We've seen that twice now. We had this massive deployment in February this year (2023) to try to catch the satellite for a second time, and we saw it again. We still don't know its orbit. We're sure it's there, but it's too close for Hubble to see. That's what gives us some hope or some reason to expect that there may be more satellites.

In fact, the satellite of Eurybates, Queta, is unusually wide. There's a thing called the Hill sphere, which is this region of gravitational influence where you can have satellites where the gravity of the asteroid is more than the gravity of the sun or other things. Satellites are only stable up to about a third of the Hill radius, and once you get out further, they get perturbed enough that they're eventually lost, so stable orbits are only out to about 30 percent of the Hill radius. Queta's at 10 percent of the Hill radius, which is wide; most satellites we know about in the solar system, asteroids or planets, regular satellites are at a percent of the Hill radius, or a couple percent. So if this satellite had been even half as close to Eurybates as it is, we wouldn't have been able to see it with Hubble. We know that asteroids in the main asteroid belt, there are quite a few that have multiple satellites, especially ones where there's evidence that they've been in a collision, like Eurybates has. So I really do expect that there are more satellites at Eurybates.

We definitely didn't expect the satellite for Polymele so that was a big surprise, the one that we found with the stellar occultations. Leucus rotates very, very slowly. I think there's a possibility that it is a contact binary. That it was originally wider and is two lumps that came together. We'll see that when we get there. Donaldjohanson, which is a main belt asteroid that we're going to—it's not an official science target of the mission but we're going to go there as a practice target—it also has a very large amplitude light curve that looks like it might be a contact binary. I think satellites and binaries are going to be a very interesting part of the story that we eventually tell with Lucy.

JOHNSON: It sounds like it. What about the first one that was added really just in January, Dinkinesh? From what I've read, it's really to test the spacecraft's target tracking system.

NOLL: Yes. Raphael Marschall, who was a postdoc and is now a researcher in France, he was working with Hal. He had this little side project—we had already looked for asteroids that Lucy would come close to down to about 5 kilometers in diameter. Even at 5 kilometers it's very hard to do very much with them, and our smallest target is more like 20 kilometers, which is Polymele, but he (Raphael) extended it down to really tiny objects. Dinkinesh is probably less than a kilometer in size. He wanted to know are we coming close to anything? He found that there's this one asteroid, which didn't have a name yet, that we're coming really close to. It was only going to be 64,000 kilometers, which is about a quarter of the distance to the Moon or less. It's really close.

Space is big. You could fly through the whole asteroid belt and never come that close to anything. But we got this lucky coincidence, so we looked at it a little bit more. With a very tiny amount of fuel, we could divert and have an encounter, have a close flyby. What turns out to be really wonderful about it is that the geometry of that flyby is very similar to the geometry of the flybys we have with the Trojans. We're coming in at sort of a 90-degree angle. The sun would be down here, here's the asteroid, here's Lucy coming in. We come in at half-moon phase and we go around like that. At Donaldjohanson, the target we already have to practice on later, we're coming in almost straight out of the sun. That's a very different geometry than most of our Trojans are like this.

It gives us a chance to test this piece of onboard software that we really rely on. We have this thing called Terminal Tracking, which is there because we're many light-minutes away so we don't have time to steer it ourselves, so the spacecraft has to steer itself. The thing that you don't know very well about your targets is how far you are from them. You know where they are in the sky plane. But since you're coming almost straight at it, it's really hard to know exactly how far you are, the range. You're traveling at, in this case, about 3 or 4 kilometers per second, and the object itself is only a kilometer across. In one second, you can whiz by it. If you want to keep your cameras pointed at it, you have to do this range finding on the spacecraft as you're coming in. We have a whole system onboard for this, the Terminal Tracking cameras which are these widefield cameras. We'll also use them for science, but they're mainly there to do this tracking. And then there's a computer program onboard that says, Okay, how much did it move? It's sort of triangulating as you come in, and it keeps solving for the range.

Things like that have been flown before but not exactly this system, so we really want to test it. We want to make sure we understand all the ins and outs, all the little quirks that it might have; make sure that when we get to the Trojans that it's working as we expect. Another thing that we want to test with this is—because the one solar array didn't latch all the way, the spacecraft is floppier than we want it to be. If it's flopping around too much when we take a picture, the images will be blurred. So we want to get an idea of how much blurring there is from this extra floppiness we have. We think it'll be okay, but we won't know until we actually make the measurements. This really gives us a chance to do these two crucial tests of the Terminal Tracking and the jitter early enough that if we find something, we have a chance to fix it maybe or work around it.

It'll be fun to get an image of a small main belt asteroid. It's about the same size as some of the near-Earth asteroids we've been to recently. It's very similar to Didymos, which was the parent body of Dimorphos. That was just the impact site for the DART [Double Asteroid Redirection Test] mission. They're similar spectral types. The near-Earth asteroids have these very distinctive shapes that look like these almost diamond shapes. It'll be interesting to see what a main belt asteroid—because all the near-Earth asteroids come from the main belt. So, do they get changed or are they the same? We'll have a chance to see how this one looks compared to the NEOs [near-Earth objects] that we're more familiar with. That'll be fun.

JOHNSON: Good opportunity. Did any of the photographs that you took for those test images, I think, in November of 2021 and then again in February of '22, were any of those blurry? I know you were doing them of the Moon, but were any of them blurred from that floppiness or can you not tell from those?

NOLL: We can't tell from those because the Moon is so bright that the exposure times were as short as we could make them so even if it were jittery, it wouldn't be jittery that much. We do know that the camera, the high-resolution camera we have, L'LORRI [Long Range Reconnaissance Imager], is not as optically good as we would like. It has some aberration in the images, which is probably due to—well, we're not sure, the mirror, it varies with temperature. We're still trying to figure out what's the best temperature to operate at to get the best possible images. It will meet our requirements. But, of course, we always want to make things even better than our requirements if we can, so we're still playing around with that. But as you saw with those Moon images, especially for an extended object like that, it doesn't really have a big impact on the image. One of the requirements we're trying to make sure we can meet is measuring tiny craters. That was the reason for those Moon images to see how small of a crater we can see and does that meet the requirements we have for measuring craters when we get to the Trojans. It turns out it does. Again, if we can make it better, we'll try to make it better.

JOHNSON: As far as the solar panels, I think I read that they're not trying anymore to get it latched.

NOLL: We're not.

JOHNSON: I think they'd gotten to 98 percent.

NOLL: Yes. That was probably one of the most challenging things we've had. Right after launch, I went over to the press area to do a quick interview with—I forget—somebody. From there, I was driving back to the—I forget which building—wherever we were where we could listen in to the comms, so about an hour after launch. The first thing I heard when I put the headset on was, "Hey, we have a temperature that doesn't look right." That was the first hint that there was something that was wrong. People started discussing, "Yes, but—" then the latch light didn't come on. Somebody had already told Hal that the panels had latched, but what had happened was the motor stopped. That was what we knew – that the motor stopped, but it hadn't latched. So then it was, Well, is the latch light broken? What's going on? And the temperatures.

That kicked off a year and a half of real anguish in terms of what are we going to do. Luckily, it deployed enough right away that we had power. We weren't in an emergency situation, so we didn't have to do anything drastic right away. That gave us time to build simulations on the ground. This is where the engineering team really shone. They tracked it down. They figured out a plausible explanation for what had happened. This lanyard had come off the spool and gotten wedged in between. And then we spent months and months on which side is it on? Is the panel going to crack? Is cracking the panel a good thing or a bad thing? There was a motor that was used to reel in the spool and it had a backup winding. Like a lot of things, it has the main thing and the backup. But it turns out you could power both the main motor and the backup winding at the same time and double your torque on the motor. That was what we eventually ended up doing. How you use the thing in that configuration is tricky because you can overheat it pretty quickly and melt off the coatings on the wires, and that would be very bad. You wouldn't have a motor anymore.

We eventually came up with a way to try to open it more, and we did that—how many times did we do it—six different times. By the end, we were powering the motor and we weren't getting anymore retraction. This wad of this lanyard has become wedged in there so tightly that even with the maximum power we can deliver with the motor, we can't move it anymore. It's possible that when we get that close to the sun, it would be possible to get some more motion. But we think it's stable enough at this point. It's incredible to me how much information we've been able to deduce from—we don't have any images of this. We don't have a camera. We can't see how it is.

But you can look at the vibration modes and the motion of the spacecraft itself that's recorded on its inertial motion units, and we've been able to figure out that the way these—there are some springs that are between the panels on the solar panel, individual segments on the solar panel. We can see that they're starting to tension, and they tension from the inside out. There are three sections going from the inside, middle, and outside. The inside section is fully tensioned.

In the last two attempts to deploy, we started seeing evidence that the middle section was getting tension on this spring. The outer section is not tensioned. But we think that gives us enough stability that when we fire the main engine, what we're worried about is that the un-tensioned array, the segments can flop around like this. There are wires that go over this flexion point. If they were to break because of this flexion, you would lose some of your strings in your solar panel array and you might end up with not enough power. That's the thing we're afraid of. We think now that with this tension on the middle and inner springs, that that floppiness is not going to be enough that we have to worry about things breaking.

That's where we've decided that we're just going to leave it alone. We don't really have much choice at this point because even if we wanted to, it doesn't look like we would make much more progress. It's so close. It literally is probably this much—I'm holding my fingers about six inches apart here—of lanyard left to go. We just don't quite have enough oomph to make that happen. The whole mission now is riding on this piece of lanyard—literally, like a lanyard you would have around your neck at a meeting—holding on for 11 and a half years in space. We've done tests. We've exposed it to accelerated aging with UV and everything, and we think it'll hold.

JOHNSON: I hope so. It would be very sad to get this far and then lose your power.

NOLL: I know, right. But bad things can happen on missions. You worry about that. People used to ask me when I was working for Hubble, "Well, you know, Hubble could die any day. Doesn't that bother you?" My answer would be, "Yes, I know. But it's worth the chance because the payoff is too good to resist." Same with Lucy. Sure, any mission any day could get hit by a meteorite or you could have some other crazy thing bail on you, power supplies or something. But if you don't try, you're never going to succeed.

JOHNSON: That's right. It's all about exploration. We talked about that during the proposal some of the instruments were from other flights or the same type and so they were tested and they had been proven. I think L'TES [Thermal Emission Spectrometer] was from OSIRIS-REx and L'LORRI and L'Ralph were both on New Horizons, or a version of them. Talk about the instruments. I did read, which I thought was interesting, that on L'TES there is actually a diamond so there will be diamonds in the sky with Lucy.

NOLL: "Lucy in the sky with diamonds," right? L'TES is a Michelson interferometer, which is a very famous instrument in physics. Basically, you take a beam of light. You split it into two directions with this thing called a beamsplitter, and that's where the diamond is. It's a diamond beamsplitter. The light, some of it gets reflected, some of it gets passed through. And then as one of the mirrors is moving in this configuration, you get these interference patterns when those two beams of light come back together. We all know that light's a wave. If you have the two crests coming back in time together, you get a bigger bump. And if they're coming back out of phase, then they cancel each other out. That is a very effective way of measuring spectra. It's too complicated to get into because you have to do Fourier transforms and everything, but there's a long history of this working.

For Lucy, the way we're going to use this is basically like an infrared thermometer. If you've ever had one of these thermometers where you just put it up close to somebody's skin and it measures the temperature, we're going to use this to measure the temperature of the Trojans. We want to measure the temperature on the night side and on the day side. Since we're coming in at about 90 degrees, it'll look like a half moon, so there'll be a dark half and a light half. If we put the aperture of the instrument on the dark half and the light half—what happens is that on these bodies as you go from day to night, the temperature changes. Obviously, it heats up once it gets in the sun. But how fast that temperature changes tells you something about the surface itself. If it were a solid rock, it would have one particular profile of heating up, whereas if it's very dusty and loosely compacted material it heats up in a very different way. And so by measuring this temperature difference, we'll be able to tell what the surface is like, whether it's loose, dusty material or whether it's bigger chunks of rocks that are more solid. That's the main goal of the test instrument is to make that particular measurement.

L'LORRI's our high-resolution camera, so it's going to take all of the most detailed images. I mentioned that we have T2CAM, which is our wide-angle camera, so it's about 10 times as wide of a field of view as L'LORRI. That's mostly for navigation, but when we have our closest approach, it'll also give us some very useful images that will be great context images for science.

L'Ralph is two instruments in one. Part of it is called MVIC [Multi-Spectral Visible Imaging Camera]. MVIC is a series of imagers that have filters in them. It's not a camera imager, but it builds up an image by scanning across the scene, so a little bit more like a copy machine that scans your piece of paper as that light goes by. We have six different filters in there that help break the light up into different color bands. Judging the ratio of brightness as a function of those color bands tells us something about the composition of the surface.

And then in the infrared, we're doing a similar thing but in a more detailed way. There we have a spectrograph called LEISA [Linear Etalon Imaging Spectral Array], so instead of just six color filters we have hundreds and hundreds of color steps. That is going to look for variations in the composition of the material across the disk. You can imagine if you see a fresh crater with some bright stuff in the bottom and you get a spectrum of that, now you can ask, "Okay, well, there's that place where there's that bright stuff. How does it look different in the spectrum? Do we see more water ice there or is it something there?" On Ceres[5], for example, there were some very bright regions and they had very distinct spectra from the rest of the object, and you're able to figure out what those deposits were. There, they were carbonate salts.

We'll do the same thing with Lucy and LEISA will have an important role there. One of the things that we've done recently is we used JWST—not HST but JWST—to get spectra of all of our targets. We now have global spectra so we know where the features are that we're going to look for in the spectrum. Those will be the things that we're going to look to see do they vary across the surface and are they associated with certain geological features. It's another example of this cooperation between Earth-based assets and the mission itself.

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[5] Dwarf planet Ceres is the largest object in the asteroid belt between Mars and Jupiter, and it's the only dwarf planet located in the inner solar system. When NASA's Dawn arrived in 2015, Ceres became the first dwarf planet to receive a visit from a spacecraft.

The last science experiment we'll do will be using the radio telecommunication system. With that, we send all of our commands up to the spacecraft, how it sends all the data back to us. As we're communicating with it, it works at a particular frequency. But as it accelerates into the gravity well of the asteroid and then decelerates on the outbound, there are small, tiny changes in the frequency that we can measure from the Doppler shift. That will tell us the mass of the objects. For the objects that don't have satellites, that's the only way we can measure the mass. Even for the objects that have satellites, it's possible that will give us a better mass measurement. The other important piece of that is from all the imaging we're going to do; we'll get a very good measurement of the volume and that lets us determine the density. The density is one of the key tests for these objects. If they really are outer solar system things that got scattered, they should have low densities. We'll be able to test that with the experiment. I think that covered all the instruments.

JOHNSON: Yes, I think so. How soon after you arrive—I know Dinkinesh, that's for a different type of test. But when you actually get to the Trojans, how soon after you get to the first will you be getting information back? How long does that take?

NOLL: Just an aside, Dinkinesh is the Ethiopian name for the Lucy fossil so that's why they chose that. It means "you are wonderful." We'll get some data back right away within hours. We've got a few selected observations. If you're a photographer you're familiar with the idea of a safety shot probably. As soon as you get your camera up, you push the shutter because you don't want your subject to move. Then you take your time to line it up perfectly. These will be our safety shots, so some of the best data just on the off chance that we don't get anything else for some reason, we want to get these data down right away. That'll be a pretty small amount of stuff, and that'll be down within hours, I think, of the encounters. The rest of the data will take longer. We rely on the Deep Space Network to communicate with the spacecraft, so it depends on the schedule we have for those. Within a few weeks we should have a lot of data down. All of the data might take a few months.

JOHNSON: Are there plans in place as far as letting people know, as far as the public and also as far as the scientific community, what the findings are? I didn't know if there was anything planned. If we have a landing or if we have something special, NASA will do a whole PR thing around that moment, ribbon cutting.

NOLL: For sure there'll be press releases. The data is all covered by a Data Management Plan. It all gets put into the public archive within six months of being downloaded. We will have plans to write up papers describing what we find in the scientific community. For sure I would guess within a week of the flybys, there'll be some kind of press release where we'll give at least very preliminary results. That's all TBD [to be determined].

JOHNSON: You're a project scientist, but sometimes on these Discovery missions it's maybe a year or two long, but this is a longer mission. Will the team stay together for the entire mission within as much as you can determine that right now because things happen? Is that the plan?

NOLL: That's the plan. We are all cognizant of 2033 being 10 years away, and we're all going to be grayer by then. We have a succession plan. We've tried to bring in young people at least as collaborators who are aware of what's going on with the mission. A long mission also means a very tight budget on Phase E because the dollars have to stretch over a long time. That's the biggest constraint. I can't help but think that at some point NASA's going to have to say, "You need to inject some younger people in here, and we'll have to find a way to create positions," whether that's participating scientists or something else. I think we'll be okay. Most of the team is young enough that 10 years from now they'll still be very active. I think the plan is we'll stick together.

JOHNSON: This was the first mission with NASA that you've worked on as a NASA employee. Based on your experience with Lucy—and I know this question may be a little more difficult since the purpose of the mission really hasn't happened yet. But what are some of the lessons learned up to this point about this Discovery class type mission?

NOLL: Up to now, I would say the lesson that stuck the most with me has been the way that Goddard likes to run these missions really works. Their approach and Mike [Michael] Donnelly, who was our first project manager and then succeeded by Donya Douglas-Bradshaw—we've been really lucky to have really great project managers. They are not afraid to spend money up front to solve problems. That has really worked. They prioritize the schedule. Everything is about keeping to the schedule. If you need to throw extra resources to stay on schedule, that's what they do. That's how they use their reserves, and that's been super effective.

One of the best examples was during COVID, which nobody could've anticipated. We were really set back, especially at Goddard, because we weren't even allowed to get into the labs for a long time. L'Ralph ended up being way behind schedule and ended up delivering late, but we addressed that by giving them a significant extra boost in resources once they were back working. Same with Lockheed. Donya had this plan of breaking up into two separate teams. Nobody from one team would ever be in the same room as somebody from the other team so that if anything happened, you wouldn't lose both teams at once, or at least we hoped. That also required more money because you had more people and people were working weekends. It was quite a huge effort to overcome the impact of COVID, but it worked. We did it. That, I think, is the lesson that I've learned so far.

I think the other lesson that I would say is probably the most important lesson is that the culture of the project depends almost entirely on the PI. The PI can either make the project wonderful for everybody or they can make it pretty miserable if they let their egos get in the way or if they're not having the right skillset to deal with people. I don't know how you select for that. That's harder because that really comes down to individuals. Maybe there's some training, but I think a lot of it is just the right individual. I think the way that Discovery does it though is that you test that with the proposal process.

We all like to gripe about the proposal process and it's a lot of work, but that's the real first test of your team. If you can't do that very well, then you're probably not going to do a mission very well. By selecting the best proposals, you're already starting to select for the teams that really work well together. I know DAVINCI[6] [Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging] was another one that was in that round and eventually got selected. They have a great team, just really, really work well together. Those are the ones I'm familiar with.

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[6] DAVINCI will study Venus from its clouds down to the planet's surface – the first mission to study Venus using both flybys and a descent probe.

Other missions would probably say the same thing. I think that the process works in that way, and maybe unintentionally, but I think it does work.

JOHNSON: I've spoken to some of the management people at Headquarters for Discovery, and they did mention that watching those teams at the site visits was important as far as who got chosen because of the way they interacted with each other. That whole teamwork was so important with Discovery.

NOLL: Right. And I think for us, it was a question because Hal had not done a mission before. So a first-time mission and being the PI, it's a legitimate thing to question. Can you do this? Do you know what's involved in running a mission? Fortunately, he was really invested in learning that. He knew up front that he didn't know. And I think knowing that you don't know helps you stay humble and helps you be open to learning things that you need to learn rather than going and assuming you already know everything.

JOHNSON: Yes, you're not the smartest person in the room necessarily.

NOLL: Absolutely not.

JOHNSON: Always important to remember that. Thinking about Lucy, what would you say you are most proud of so far?

NOLL: Me personally, I think I'm most proud of the work that we've done with the satellites. I think that's been a really fun way of getting some solid science out early and getting previews of what we're going to figure out. I'm pretty excited about what's going to come out with the JWST spectra too. That's another early look that I think is going to help us plan things. That's been scientifically the most rewarding things that we've been able to do so far.

JOHNSON: I know we talked about the solar panels as being a stressful time. Is there anything else that's been difficult to work through?

NOLL: Back before launch, we had the whole crisis with the reaction wheels. There was a discovery that the manufacturer of the reaction wheels at some point had changed their process. The one person that had been the quality control person for 30 or 40 years had retired and there was a new person. Basically, you have these ball bearings that come out and they have to be perfect. If they're not perfect, they put them back in and try to clean them a couple of times in cases and then qualify them or reject them. There was a flaw in that process so they were clearing ball bearings that they shouldn't have cleared.

These reaction wheels were starting to show evidence of increased friction, and that is a precursor to failure. We didn't know if ours were affected or not. That was pretty stressful. In the end, we got some information which led us eventually to decide that the ones we had were probably okay. They've been okay so far, but that was stressful.

At launch, the first Atlas that we had had a problem with one of the valves sticking so we couldn't use it. They told us, "Well, not to worry. We have an extra one. This is a pretty rare failure mode, so the next one will be fine." But sure enough, it also had the same problem. So now we were down to no launcher. The only way we got to launch was that the Boeing Starliner launch was supposed to occur, and it was on the pad ready to go when they scrubbed it. It was also on an Atlas. They scrubbed it and they realized they weren't going to launch for a long time, so we had to use that Atlas. It was not in the right configuration for us. It had solid boosters attached, which we didn't use so they had to take those off. Those are kinds of stressful things where it's out of your hands. You don't have any way to control that, but it still keeps you up at night.

JOHNSON: Yes, I can imagine. Is there anything we haven't talked about that you wanted to mention before we leave?

NOLL: No, I think we've covered this really well.

JOHNSON: Okay, that's good. I appreciate you talking to me. I'm going to go ahead and stop the recording and we can talk for a second.

[End of interview]