DISCOVERY 30TH ANNIVERSARY ORAL HISTORY PROJECT
EDITED ORAL HISTORY TRANSCRIPT

HAROLD F. LEVISON
INTERVIEWED BY SANDRA JOHNSON
LONGMONT, COLORADO — JULY 19, 2023

JOHNSON: Today is July 19, 2023. This interview with Dr. Hal Levison is being conducted for the Discovery 30th Anniversary Oral History Project. The interviewer is Sandra Johnson. Dr. Levison is in Longmont, Colorado, and talking to me today over Microsoft Teams. I appreciate you taking some time out of your schedule to talk to me today for this project.

LEVISON: My pleasure.

JOHNSON: If you don't mind, briefly describe your education and background and where your interest in planetary exploration came from.

LEVISON: Let me start at the beginning. I grew up just outside of Philadelphia and back in the '70s. Our high school actually had a planetarium, and so I volunteered at the planetarium all through high school, wrote planetarium shows, decided then I wanted to become an astronomer. I went to a small liberal arts college in Lancaster, Pennsylvania, called Franklin & Marshall [College]. I chose that because they had a planetarium associated with the college and there were several astronomers who were faculty members there. I went there, continued my interest in astronomy, worked the planetarium as part of my work-study job for the entire time I was at F&M. Again, my goal was always—since probably I was 13 or 14 years old—I wanted to become an astronomer. I got my degree in 1981, a bachelor's degree in physics, went to graduate school at the University of Michigan [Ann Arbor]. My original interest actually—like I said before we started the recording, this will take a long time because I bopped around a lot and did a lot of different things. Back at the time I was at Franklin & Marshall, this was in ’78 through ’81, computers were just coming onto the scene and I got an interest in building instruments for telescopes while I was at F&M. I went to graduate school in Michigan.

Let me take a step back if I can. When I was at F&M, my honors degree, a little thesis that I did was building a computer interface between a Mac II, if you remember those, and our telescope to measure the brightness of stars as a function of time. That actually led to a publication. My first publication was in *Byte* magazine back in 1981. So I had this interest in building telescope instrumentation. When I applied to graduate school, University of Michigan, at the time, was building what was considered then a large telescope. It was a 2.4-meter telescope on Kitt Peak Mountain [Arizona], and I decided to go to Michigan in order to build instruments for that telescope and help to put together all of that.

While at Michigan, I did an almost totally 180 degree turn, took a class from Doug [Douglas O.] Richstone, who ended up being my thesis advisor, on how stars move around in galaxies. Stellar dynamics is what that field is called. I got very interested in that, decided to do my dissertation on that topic. There were two parts planned for my dissertation: The theoretical work where we were building computer models of stars orbiting around galaxies and trying to understand, by what we could see of the galaxies, how the stars moved around. And then an observational program to collect the data we needed in order to constrain those models. That work, the observational work, was supposed to be done with the new telescope, but unfortunately—well, I can’t say it’s unfortunately because I’ve had a good career. But that telescope was delayed and

I never got the observing part of my thesis done, so my thesis ended up being a totally theoretical one of the motion of stars in galaxies.

I had a postdoc after that. Notice so far, I haven't said anything about planetary. I had a postdoc at NASA Ames [Research Center, Moffett Field, California] with a scientist by the name of Bruce [F.] Smith, who also worked on how stars moved around in galaxies. I was there for two years and worked on just theory. I sort of lost my interest in, at least for a short period of time, doing anything having to do with instrument building or things like that. That was a two-year postdoc at NASA Ames.

Then I started applying for a second postdoc. That's pretty typical in this field. I got called out of the blue by somebody from the U.S. Naval Observatory in Flagstaff [Arizona]. They were interested in having me come and build instruments for them again. This is in the early days of CCD [charge-coupled device] cameras on telescopes. I decided to take that job, moved to Flagstaff. I was hired to work on a new type of CCD camera that they were having built for them. The Naval Observatory is interested in measuring, as accurately as possible, the locations of stars and planets and asteroids. It's called astrometry. They were building an instrument specifically to do that, so they hired me.

That was a three-year position. I went there. Again—I guess this is sort of the theme of my life—the instrument that they were building never got delivered in the three years I was there, and they left me basically to do what I wanted while we were waiting for that thing to be delivered. It was one of these things, "Oh, it'll be here in six months; now a year." And it never showed up and actually never worked, so it's probably good that I didn't spend much time doing that. But in the meantime, they had decent computers so I continued my work on stellar dynamics and working on galaxies.

I got interested in planetary when I was there. I had a colleague by the name of Martin Duncan, who was at—he's retired now—Queen's University in Kingston, Ontario. He did both stellar dynamics, so I worked with him. He was one of my main collaborators actually in the field of stellar dynamics, but he also dabbled in the planetary a little bit. He and some colleagues—Scott [D.] Tremaine is probably the most famous of the people on this—wrote a paper where they were looking at the orbits of a certain type of comet called a Jupiter-family comet and argued that the orbits of those comets, which are very flat and disk-like, means that they have to come from a disk-like population beyond the orbit of Neptune. This is way before what we now call the Kuiper Belt was discovered. Basically, it was one of the principal papers that led observers to go out and search for the Kuiper Belt.

The Kuiper Belt is this population of small bodies beyond the orbit of Neptune. Pluto is the largest known of the Kuiper Belt. But at the time, Pluto was the only object we knew in the Kuiper Belt. This work predicted that there should be other objects like Pluto there, and that got me—although I said I was doing mainly theory at the Naval Observatory, the Naval Observatory had gotten what at the time was the largest CCD camera in the world. It was horrible, meaning that pictures taken with it were fuzzy and there were a lot of structure in them that wasn't real. It was a horrible CCD but it was huge. Basically, the people at the Naval Observatory told me, "Why don't you try to figure out something to do with it?" My friend Martin Duncan suggested that we look for this Kuiper Belt, so we did. He and I did a search for the Kuiper Belt. This is in the late '80s. Didn't find it but we also started working together on the dynamics of these objects in the solar system and the comets that come from it. I started working in the field of planetary.

To sum it all up at that time, interested in this population that at the time hadn't been discovered that we now call the Kuiper Belt and doing the theory of what the structure of this population looks like and how it leads to the comets that we see. Or better yet, using the cometary orbits to try to figure out what this population looked like. Again, after the survey we did and didn't find it, it was purely dynamics but this time it was dynamics of the solar system. I never thought about observations again after I left the Naval Observatory in Flagstaff; I went and did a stint at the Naval Observatory in [Washington,] DC. Dan Quayle was the Vice President at the time. That's where the Vice President lives is the Naval Observatory in DC. My claim to fame is Dan Quayle's dog loved me. Every time I got out of my car, Dan Quayle's dog would run up and ask for a pet.

I spent a couple years at the Naval Observatory and then got hired by Southwest Research Institute in San Antonio [Texas] initially. And then Alan Stern and I, if you know who Alan is—he's the PI [principal investigator] of New Horizons[1]. He and I together founded the group in Boulder [Colorado]. When we opened in 1994, there were four of us in the office, and now we're about 100 people. Several PIs, including Alan and myself and Craig DeForest, who runs PUNCH [Polarimeter to Unify the Corona and Heliosphere][2] and various other things, are now being done out of our office. For almost the entire time of my career since starting at Southwest, I was a theorist, very unusual from a PI's point of view. I basically specialized in what small body populations, mainly in the outer solar system, is telling us about the formation and history of the solar system. I worked, as I said early on, on the orbits of comets. Then we started doing the planet formation simulations themselves where we were building planetary systems and using the small populations mainly to constrain what those models look like and what that history looks like.

[1] The first spacecraft to explore Pluto up close, flying by the dwarf planet and its moons on July 14, 2015. In early 2019, New Horizons flew past its second major science target – Arrokoth (2014 MU69), the most distant object ever explored up close.

[2] A NASA Small Explorer (SMEX) mission to better understand how the mass and energy of the Sun's corona become the solar wind that fills the solar system. Four small satellites will work together to produce images of the entire inner solar system around the clock.

Let me just say for background to put things in context, almost all the codes people use, or a lot of them, particularly then, for this were written by me and Martin Duncan. I mentioned him before. We wrote all our own codes and then used those to study planet formation. One of the things we're probably best known for—this is with collaborators like Allessandro Morbidelli—for this idea that the planets, particularly in the outer solar system, that we see today didn't form where we see them. They formed in a much more compact configuration, and then there was a dynamical instability where the orbits of the planets went nuts for a while that led to their migration to their current locations.

JOHNSON: Is that the Nice model?

LEVISON: That's the Nice model. Martin and I thought of the idea, or the initial version of this idea, back in 1998, got published as what we now call the Nice model—Martin wasn't involved in that because he went off and became a dean—in 2005. We thought it was a crazy idea, but it's one of those things. If you asked me then, I would've said, "We'll publish and maybe somebody will follow up on this." But it's still now the leading theory on how the solar system evolved and it's still around almost 20 years later, which still shocks the hell out of me that the Nice model is still around. Let me just finish the story to get to Lucy.

One of the things that occurred during the Nice model is that material gets trapped in what we call Lagrange Points, which are these dynamically stable regions that lead or follow Jupiter in its orbit around the Sun. During the Nice model, how that happened, the orbits of these things and where they came from tell us a lot about that history. We now call those objects Trojans [asteroids], and Lucy is going to study them with the hope that it'll help us understand that process better. Boy, that's a lot of it, isn't it?

JOHNSON: That's good because I was going to ask you how the Nice model led to that idea for Lucy, so that's a good explanation.

LEVISON: Yes, that's basically it. One question I get a lot is why I moved from a theorist to doing something like Lucy. The basic answer to that question is that when I was young and got into this field, we had better data than we had ideas. For example, we didn't understand how Uranus and Neptune could form where we see them. Or we didn't understand how the Trojans have the orbits that they have. They actually are what we call dynamically excited. They have high inclinations and eccentricities, which the formation theories at the time would predict that they would almost be circular coplanar orbits. I can explain that a little bit more if you want. At the time, there were a lot of mysteries that we just didn't have any ideas of how to solve. Over my career, mainly because of the development of fast computers and fast computer codes, we evolved to the point where I think we have more ideas and we can't tell which one is right because we don't have enough data. That said, to me we need to go and find more data, and that's basically what led to Lucy.

JOHNSON: Had you been aware of the Discovery Program with NASA before you actually were involved in that proposal for Lucy?

LEVISON: Oh, yes, of course. The Discovery Program, there are tons of things. Is Kepler[3] thought of as the first Discovery mission?

JOHNSON: Yes.

LEVISON: To me, Kepler is one of the most important things NASA's ever done. I was suddenly aware of Kepler. I remember the formation of the Discovery Program and the missions that were done before Lucy. I was peripherally interested in them as somebody who's interested in space exploration. It never occurred to me then that I would be doing anything like what I'm doing now.

JOHNSON: The Discovery Program was a new model for NASA for planetary exploration because it was PI led which is different than some of the missions that came before. Was that something that you were interested in and other people in your field were interested in because it gave the PI more control over the projects or the missions themselves?

LEVISON: To me, that paradigm was an important change because it allowed—I'm trying to think of the best way of putting it. You actually went to the community and asked them what they think they could do. And so you're actually allowing people like me to be creative and try to put together something that we can convince NASA to do because the science is interesting. I think that was an important paradigm shift.

[3] The Kepler space telescope was NASA's first planet-hunting mission, assigned to search a portion of the Milky Way galaxy for Earth-sized planets orbiting stars outside our solar system. During nine years in deep space Kepler, and its second act, the extended mission dubbed K2, showed our galaxy contains billions of hidden "exoplanets," many of which could be promising places for life.

JOHNSON: When did you start thinking about Lucy as a mission and start taking it seriously as something that you wanted to propose and start building a team for that proposal process?

LEVISON: It's a little complicated, or perhaps subtle is a better word. There was a mission called Lucy that was submitted to Headquarters as part of the 2010 call. Remember, my Lucy is the 2014 call. That was the call that led to InSight, for example. I didn't have very much to do with it except for sitting on the red team during the development. It was a mission that was based basically on the New Horizon spacecraft to be built by Ball [Aerospace]. Cathy Olkin, who ended up initially being my deputy PI, was the PI of that mission proposal. The targets were just one Trojan and one Centaur, so it was a totally different mission. But there is a little bit of history to a Lucy that occurred before I got involved. We started working on it as a proposal. I look back at one point, and the first email that I sent or received—I think it's both—that had Lucy in the subject was in March of 2014. I guess you can say that's when we started.

In my own life, I was looking for a new challenge. Although I was still doing decent science, I felt like I was a little bit in a rut and I needed to do something different. If you remember my early history, I was sort of bopping around all over the place doing different things from theory to instrument building and things like that. And then after I settled into my career, I just stayed at the same thing, in a way, for 20 years, and I was looking for something else to do. I, as I said before, realized that we really probably couldn't understand the history of the outer solar system without some better data. Think of it as our capture manager here at Southwest, he and I are drinking buddies. He convinced me that given where I am and what I'm thinking, we should write a proposal together. His name is John [P.] Andrews. He's got a big role to play in making Lucy a success, particularly the proposal because he was the proposal manager. He organized—orchestrated is the word I would like to probably better use—the development of the proposal.

JOHNSON: You said Lucy existed before that, but your Lucy you kept the same name. Was there a reason for this name?

LEVISON: Yes. I kept the same name because I thought it was cool. Lucy the spacecraft is named after the human fossil called Lucy. It used to be called the Missing Link. It was Cathy's name, so she should be getting credit for it because I do think it's a perfect name for a mission like this. The Lucy fossil told us about the history of our species and taught us a lot about where we came from, how the human race evolved. We decided to call the mission Lucy because these small bodies we're visiting are, in a way, the leftovers of planet formation. In a way, they're the fossils of planet formation.

If you think about it, the planets that we know—the Earth and Uranus and Neptune and, of course, Jupiter and Saturn, all the solid surfaces in the solar system—formed from these small bodies. But the planets themselves have evolved a lot because of internal processes since they formed. The small bodies we see today are leftovers of the planetary formation process, and yet they remain relatively unchanged since they formed. This gets back to an interest that I said before, remember, using these small body populations to constrain what happened in the early solar system. These small bodies are fossils of planet formation, and so it seemed appropriate to name a mission that was going to study them after a well-known fossil.

JOHNSON: Let's talk about the team. You've mentioned that Cathy continued as your deputy PI. Were some of the other team members the same as on that first Lucy? How did you form that team going forward?

LEVISON: I think of teams at several different levels. Probably the most important use of the word team is the collaboration between institutions. Lucy is a collaboration between [NASA's] Goddard [Space Flight Center, Greenbelt, Maryland] and Southwest and Lockheed Martin. That team is totally different from the original Lucy and had an interesting—well, I'm going to tell the story. They can't get mad at this. They had an unusual history. We had the idea. Through connections that we have with Lockheed Martin, somebody in San Antonio, we sort of put together a collaboration with them. They were interested in seeing if they could design a spacecraft that fit within the Discovery budget. As you probably know, Discovery's been amazingly successful but they're relatively low-cost missions. Lucy had a cost cap of around 450 million dollars in [Phase] A through D, which is through development. It doesn't include the launch vehicle. At the time, those cost caps did not include operating costs which we call Phase E. And so we first reached out to Lockheed Martin to start even discussing whether we could build a spacecraft to do this that is reasonable.

At the time, we did not actually have the collaboration of Goddard, and so we didn't have a management team really put together. We thought about trying to do the management ourselves, but we just really don't have enough people here, the bench depth that you actually need to have been successful, I think. We reached out to Michael [J.] Amato—I don't know if you know him, he's at Goddard; he's their capture manager—with the idea of them becoming our management, where the PM [project manager] would sit and that kind of thing, the role they played. They actually weren't very interested, but after some discussion, we came to an agreement with them. While typically in the missions that they're involved in they are very active in writing the proposal and putting the proposal together, the deal that we made with them, because they had other missions to compete with us, was that we would basically do all the work: Lockheed and Southwest. And if we're selected, then they'll take on the role of the management. That's highly unusual, and that's exactly what we did. That's why I'm saying John Andrews at Southwest really took the role of orchestrating the proposal, while most of these it would've been done at Goddard.

JOHNSON: That is interesting.

LEVISON: Yes, it's a little unusual how this all came together. Of course, we did win, or we got selected for Phase A. That's when Goddard started getting very active in the mission. That's the first meaning of teams, and that's the history of that. The second is we needed to put together a science team. There, we actually heavily relied on New Horizons. If you think about it, New Horizons is done at Southwest. We were at Southwest. It's about small bodies in the outer solar system and what their telling is about how the outer solar system formed. Same with us. We decided to basically clone the instrument suite from New Horizons on Lucy.

One of the things that you need to do with these really low-cost missions, like Lucy, is you need heritage. You need to be able to convince NASA that everything you want to do is low risk and will be within budget. And so the way we decided to handle that was by cloning the instruments as much as we can that are on New Horizons on Lucy. We only chose some of them, and we added another one because we're going to a different class of bodies. But the whole idea was to clone that and say that we're going to be making a very similar set of observations as New

Horizons had done. I think that's one reason that we won, by the way, is because we had that high heritage. Scientifically, it made a tremendous amount of sense. A lot of the people that we put on our Lucy science team are people who are also on the New Horizon science team.

JOHNSON: I was going to ask you why you thought you won in the selection, but you mentioned that it's that heritage and proven products.

LEVISON: Yes. Well, I think we won because we had great science. This is going to sound a little arrogant, but I'm going to say it anyway. There are a lot of people that come in this field with the idea that they want to do a space mission, and so their interest is instruments and spacecraft and things like that. But you can't be an expert of being at the cutting-edge of science and do the mission stuff at the same time, I would argue. It's very hard to do. I think Lucy benefited because I could paint a scientific picture of how important and the impact it was going to be in a way that somebody who comes from the mission world initially probably couldn't do. It turns out that the combination of Cathy, who does have a lot of the mission experience—she was almost second in command in New Horizons for a while. She leant the mission the mission experience while I could lead the mission scientifically in a way that a lot of PIs can't do. Does that make sense?

JOHNSON: Yes, it does.

LEVISON: As a matter of fact, if you look at particularly the selection in 2014 of Psyche[4] and Lucy, both the PIs came from the science world in order to do the mission rather than have been in the mission world their entire career. I think that helped both of us make a case for why the missions are important. The way I think about it is the science wins the mission, and everything else in the proposal can just lose it.

JOHNSON: Okay, that's an interesting way of looking at it.

LEVISON: Yes. If they look at your proposal and they say, "This will never work," or, "You can't do that for this budget," or, "The schedule is all messed up and you can't build the spacecraft in time for the launch window you have," that's losing it. But what's going to get people excited and say, "Yes, we need to do this," is the science case.

JOHNSON: Yes, you had the science. And other than your work at Ames earlier, this is the first time that you had worked with NASA on any projects.

LEVISON: Well, I've spent my whole career except when I was at the Naval Observatory being funded by NASA through the R&A [Research and Analysis] programs. But that's right, yes. Even at Ames, I was just a postdoc and a theory postdoc. As a matter of fact, I wasn't even paid by NASA. This was a National Academy postdoc that I had.

[4] The Psyche spacecraft is traveling to a unique metal-rich asteroid with the same name, orbiting the Sun between Mars and Jupiter. By August 2029 the spacecraft will begin exploring the asteroid that scientists think – because of its high metal content – may be the partial core of a planetesimal, a building block of an early planet.

JOHNSON: When did you get the news that Lucy had been selected?

LEVISON: On a very cold day in January. It was January 4, 2017. It was a cold day. At the time, I took the bus to work every day. [Thomas] Zurbuchen called me when I was trying to walk from the bus stop to the office. The three blocks that I couldn't really talk to him because I had very thick gloves on, he called me. Dropped the phone, and when I finally got the phone to my ear he said, "This is Thomas Zurbuchen. Do you have time to talk to me?" It was funny because I couldn't get the phone because the gloves—because I knew the announcements were going to be done on that day. And so the night before I'm strategizing. When can I go to work? Should I drive or take the bus? I decided to take the bus because if he calls when I'm on the bus I can take the phone call. I knew there were a couple of 10-minute slots where, because it was so cold, I'd have limited access to my phone. And decided to go really early because of course he wouldn't call me before 8 o'clock my time, and he did.

JOHNSON: Always the worst possible moment, right?

LEVISON: Yes, it was funny.

JOHNSON: Let's talk about some of those instruments, if you will, and what they were designed for and what their role was on Lucy.

LEVISON: The main scientific argument of Lucy—let me talk about the science before I can talk about the instruments. These Trojans occupy actually a really very small region of space. When people started studying them from the ground, the expectation was that they all formed in the same area near Jupiter's orbit. They probably led to the formation of Jupiter's core. But because they were in the same place, they likely formed in the same place and they should all look the same. When we started studying them with telescopes, we found out that that's not true. They actually can be very different from one another. From the ground, we can basically just measure colors. We found that while there are some objects that are sort of gray colored, most of them are actually fairly red in color. Of course if you looked at them, picked up a rock from them, they would all look like basically asphalt. The red ones would be a red tinge. But those differences from a point of view of what they potentially could be made of means they're very different.

Now, the Nice model predicts that the stuff that's in the Trojan swarms now formed at very different places in the solar system and were trapped during this instability. If you look at the Nice model calculations, the expectation is you should find about equal numbers from different locations in the outer solar system in the Trojan swarms because during the instability everything gets mixed together. I would argue, and I have, that the idea that these Trojans are very different from one another supports this idea of something like the Nice model happened. But it's very circumstantial because we don't understand what the different colors mean. If something's red we don't know why it's red, and that's particularly true for the outer solar system. We see a lot of really red things and some gray things, and we don't have a good idea of what makes the red things red. The main theme of Lucy has to do with understanding that diversity. The only way we can understand that diversity is by visiting a lot of objects that cover the observed diversity that we see. Does that make sense?

JOHNSON: Yes, it does.

LEVISON: The goal of Lucy was to go by as many of these things as we could. We're now visiting eight. It's amazing, and that's a whole story in and of itself which we can get to, if you're interested, in a few minutes.

JOHNSON: Yes.

LEVISON: You know, how we found the trajectory. But in order to be able to visit a lot of objects, Lucy has to be moving really quickly. Indeed, we're having five flybys of Trojan systems. The main core of the science of each encounter is about 2 hours. Although Lucy is a 12-year mission, all the important science is being collected in basically a day. We're spending most of the time just traveling from object to object. We can't stop and sniff. We can't land and get samples. This is a reconnaissance mission that is being done with high-velocity flybys. That's exactly what you want really if you think about it. Given that you have a population with a huge amount of diversity that you don't understand, the first thing you want to do is you want to get a broad-brush understanding of what the population looks like. And then you can go back later and do more detailed studies of the objects you think are most important. That's the argument we made in the proposal.

Because we're moving fast and we're not scratching and sniffing or anything like that, all our instruments are remote sensing instruments, basically cameras and spectrographs. Given that, we wanted to cover the entire wavelength region that we possibly could with our instruments.

That's what our instruments are designed to do. The purely scientific instruments are an instrument called the L'LORRI [Long Range Reconnaissance Imager]. L' means Lucy. I'm a Francophile, so I wanted to take advantage of the fact that the French used the L'. So we have L'LORRI, which is almost an exact copy of the LORRI instrument on New Horizons which is a high-resolution panchromatic imager. That's going to do basically almost all our geology.

Then we have L'Ralph, which again is functionally—there are now substantial differences but it's functionally a copy of the Ralph instrument on New Horizons. L'Ralph has two instruments in one. One is a color camera and the other is an imaging near infrared spectrograph. That's the one that's really important when it comes to telling us what these things are made out of is looking at the infrared. Those are the two or three, because L'Ralph is really two instruments, instruments we've taken from New Horizons.

Then we added a thermal infrared spectrograph from ASU [Arizona State University]. That's an instrument that wasn't on New Horizons because Pluto was too cold for it to be useful, but it is on Lucy. That's going to tell us basically how fluffy the surface of the Trojans are. I should've said that L'LORRI, the geology we're interested in primarily—although, hopefully we'll see more—is understanding craters on the surface of the Trojans. Because by understanding the craters, we can determine what the impacting population of small bodies look like.

That's important from a scientific point of view. Because remember, planets grew by these small bodies moving around, hitting one another, and growing because they hit each other at low velocities. But during that process, some things hit at high velocities. So in addition of building big things, you grind away little things. Understanding the sizes of these objects that come out of the accretion process of the planets will tell us important understanding of the physics of how these collisions worked. In order to understand that we need to understand how the population varies with size today. We can't observe small Trojans, but we can see their impacts on the surfaces of the bigger ones. Does that make sense?

JOHNSON: Yes.

LEVISON: If you ever wondered why looking at holes in the ground on these bodies are scientifically interesting, that's why they're scientifically interesting. Because it lets us understand what the whole population looks like, and we can't see the small guys from the ground.

JOHNSON: Let me go back. I'm going to ask you a question about the teams again. You had that working relationship with Lockheed Martin, and that grew the whole mission out of that. Working with different teams from different areas, like Lockheed—you're at Southwest Research Institute. Lockheed Martin, they build things. They're engineers. And then you have the [Johns Hopkins University] Applied Physics Lab [Laurel, Maryland], you have Arizona State, you have different—is it the radio science team is from the University of Cologne in Germany? You have a mix of not only people and specialties but personalities on all of these missions, and Lucy is a good example of that. Talk about how important being able to communicate across those disciplines and with different people, how important is that to making sure—because you said in those proposals, the science was going to sell it, but the engineering and building it could ruin the proposal if it wasn't correct. Talk about that relationship and how that worked with these different teams from all these different areas.

LEVISON: For us, it worked wonderfully. Really, we have the best team ever. I know all PIs would say that, but I actually mean it. I talked about how Goddard didn't sign on until late and they weren't really interested until we already had sort of won. That's a true story. But once they signed on, they gave us the A-team. Everybody gave us their A-team. These are brilliant people. After all, it is rocket science. From all these different disciplines, from the scientists to the managers to the engineers. We got the most professional and very experienced team that we could possibly get, and they were brilliant.

One thing that is very important, I think, is that whenever you walk into a room, or in the last few years into a Teams meeting—because don't forget we did all this in COVID, or a lot of it in COVID—you leave your ego at the door and you emphasize the idea that everybody's free to say what they want, no one will hold stupid comments against anybody, and made it a badgeless and ego-free environment. That was one of the things that I think I probably contributed to the most is making sure that stayed that way. Never call people out. If you're unhappy, you call them in private later. You make sure no one's ever embarrassed, or you try to keep them from being embarrassed. That was the kind of culture I felt we needed to develop, and we did. We still have it, even though people moved off the project and new people come. I think the PI plays an important role in setting the tone and the culture of the mission.

JOHNSON: You mentioned that you did all this during COVID, and that was one of my questions. How did a global pandemic and everyone at one point being sent home to work remotely, how did that affect the mission? Did it have any schedule impacts or any delays? A lot of what COVID caused was delays in having things delivered as far as materials.

LEVISON: We were lucky a little bit in the sense that when the pandemic hit, we were near the end of building pieces and starting what we call ATLO. Assembly, Test, and Launch Operations, that's what ATLO stands for. We didn't really get affected—although there were a couple things—very much by impacts on getting pieces delivered because a lot of it had already been delivered. The real challenge was to develop a system for people to allow members of the team to remain isolated from one another. It was basically Matt [Matthew] Cox and Donya Douglas-Bradshaw who were our PMs—Donya was from Goddard, and Matt Cox was from Lockheed—who came up with this team idea of dividing the people who actually have to show up to build the thing into different teams that never cross paths with one another.

The idea was that if somebody were to get infected, we wouldn't be shut down entirely, although that never happened. A lot of effort went into making sure the teams were isolated and healthy and that they never met each other, and that changed schedule. They had to reschedule things several times to make it all work. Again, it was a brilliant piece of management to watch that happen, but it got us through it. We launched the microsecond that the launch period opened and under budget even with COVID. That tells you something about the quality of the team.

JOHNSON: It does tell you something. When the spacecraft was being built at Lockheed Martin, did you visit at any point?

LEVISON: Yes, we were there. Another advantage that we had when it came to COVID is that Southwest and Lockheed are within driving distance of one another. We didn't need to get on a plane to go down and see things, or in the rare situation talk to some people in person. That helped us a lot too, I think.

JOHNSON: Let's talk about the science and the actual asteroids that Lucy will visit. You mentioned that there were eight. But I think I read that the first target is the last thing that was added, and that was Dinkinesh. I may be pronouncing it wrong.

LEVISON: Dinkinesh, that's how I pronounce it. I can't pronounce any of them, particularly the Greek names. One of the colleagues from the Nice model is Greek, and I sat down with him and tried to get him to teach me how to pronounce it. Nope. He was never happy with my pronunciation. To me, I was saying exactly what he was saying. As a matter of fact, a couple of our targets that within the team, people use slightly different pronunciations. We decided that's okay.

JOHNSON: Some of them are a little hard. That one was added, but also, I was reading that the team used Hubble [Space Telescope] to find some satellites before launch. One of them was Queta—another was "Shaun" [nickname] around Polymele. Talk about that and how does all of those asteroids that were chosen and why they were chosen.

LEVISON: Nature chose them for us in a way. I told you that we're hauling ass, we're moving very quickly, can't carry a lot of fuel. This is a small mass spacecraft. You allow nature to define your set of asteroids. We're basically the zeroth order just on Kepler orbits around the Sun, but we're choosing the Kepler orbit to get us to the most objects we can. It turns out we're actually extremely lucky when it comes to this. First of all, let me take a step back. Dinkinesh is not a Trojan. It's a main belt asteroid. The first two encounters are basically there to test our system—

they're not scientific targets—to make sure that the system is going to work once we get to the Trojans. After all, like I said, these are very high speed. There's no going back and trying it again. We're using the main belt asteroids to basically exercise everything and make sure it works the way we think they are going to work.

When it comes to the Trojans and the objects in the main belt we have to be going by basically, or close enough that—we added Dinkinesh, for example, because just by random chance we were getting within 64,000 kilometers of it as we were flying through the main belt. That's a quarter of the distance between here and the Moon. So, if we're getting that close, we might as well use it as the test. It turns out it's a better test than the next one, which was DonaldJohanson, because the geometry's better and other things. There are other reasons to do it too. When we chose our targets, we were just interested in Trojans. The basic idea when we put Lucy together was that we were going to visit two. Remember I said they're different colors. They're red and they're gray and sort of everything in between. It turns out they're bimodal. There's a wide range of colors.

What we wanted to do was find two objects that are roughly the same size and are on similar orbits around the Sun but one was red and one was gray. That was what we set out to do in order to be able to try to compare what red and gray means. This very brilliant guy, Brian Sutter—he's at Lockheed Martin, he designed this trajectory—went off and tried to find a trajectory for Lucy that would allow us to see two objects. That's how the first two were chosen. Eurybates is the first one and Orus is the last in the L4 swarm. That's the swarm leading Jupiter. Those are almost the same size as one another on very similar orbits. The argument we made in the proposal is because they're the same size and on the same orbit, they've been in the same environment since they were captured in the Trojans. So any difference that we see between them—craters, colors, that kind of thing—is due to their formation rather than their history in the Trojans. Does that make sense?

JOHNSON: Yes, it does.

LEVISON: That's why we chose—we started out just choosing those two. Eurybates turns out is an interesting object in and of itself because we know—and I won't go into the details of this—that it was involved in a major collision. That a good fraction of it was blown off as it was hit because it's a member of what we call an asteroid family. Again, remember, collisions and dynamics are what make planets, and so we thought that that would be a good case study of understanding collisions. It's part of this asteroid family, and therefore it's a remnant of a major collision. That's how we started out. Then everything else is just luck. It really is.

I'd basically like to say that I've been studying dynamics for 40 years, so I've been worshipping at the feet of the celestial mechanics gods and they're paying us back. One thing you want to argue when you're doing a proposal to NASA like this is that it's timely. You need to answer the question of why do we need to do this now and not 10 years from now. As part of our proposal, we actually did the exercise of what we could do if we launched in 2030. We did the same process that found the Lucy trajectory and did it in 2030 and found the best that we could do was three objects and none of them were particularly interesting. While on Lucy, we had the five objects and we knew, at least at the time, that three of them were very interesting. That's the argument we made, but it's just luck.

We found Eurybates and Orus. And then Brian did an experiment of asking the question of how close he gets to the other targets in the L4, and it turns out that we went by two of them just at random, Polymele and then Leucus is how it's pronounced. We knew that Eurybates was interesting because it was part of the family. Leucus is just weird because we know it's got a very elongated shape and it's rotating very slowly, and we don't know why. So we had two interesting objects out of those four. Then—I remember this day—Brian had to do a calculation. NASA's worried about planetary protection. NASA doesn't want a spacecraft that isn't really treated to make sure there are no microbes on it hitting either Mars or Europa. He had to show that Lucy wouldn't hit any of those bodies, and I think it's a 50-year timescale. So he just continued the orbit of Lucy that he found for 50 years.

He made a little movie of the whole trajectory so we could see where it was going, and he happened to put a bunch of famous asteroids on the movie. He thought it was cool. I have an asteroid named after me. He put that in his movie. He has an asteroid named after him. He put that in the movie. He put a couple famous Trojans in the movie, one that is called Patroclus. As we're watching the movie, I noticed that the spacecraft looked like it was going right by Patroclus. I basically said to him, "Can we go there?" He said, "Probably not because Patroclus is on a high-inclination orbit," which means its orbit is tilted with respect to Lucy's orbit. He was saying, "What you were likely seeing is just a projection. Although it looks like when you're looking down on the solar system, near each other, Patroclus is probably above or below the spacecraft at the time it looks like it's flying by." So he said, "Probably not." But then he went and looked, and it just so happens that Patroclus is traveling through the plane of Lucy's orbit when it's flying by. Again, all this is luck. So, we could add Patroclus.

Patroclus is one of my favorite objects in the Trojans. It's a near equal-mass binary. It's two objects that are basically siblings of one another. They are 100 kilometers in diameter. They're almost exactly the same size, and they're on a nearly circular orbit around one another.

That's really weird. We knew it existed for a long time. It seemed just to be an oddball, but it turns out probably not. Once the Kuiper Belt was discovered, the Hubble Space Telescope started doing deep surveys looking for satellites of the Kuiper Belt objects. It found in a region that we call the cold classical Kuiper Belt, which is a distant region far beyond the orbit of Neptune that we believe is the most ancient and pristine region of the protoplanetary disk. Arrokoth—if you know about Arrokoth, New Horizons went by it—is a member of that population.

We really think it's the region that hadn't been very disturbed by planet formation because it's so far beyond the orbit of Neptune. When you look in that population, they're all binaries like Patroclus. Not all but 50 percent of them. What we think is that the first large objects that formed in the solar system formed as part of binary systems, and there are now new theories that explain this. And that these systems in the inner part of the solar system, and in this case, I mean inside the orbit of Neptune, didn't survive as binaries because planet formation process is so violent, lots of impacts and things flying by the growing planets. It's so violent that the binaries mainly didn't survive. If that's true, then Patroclus is a rare remnant of one of those primordial systems. I think that's cool as hell.

JOHNSON: Yes, that's very cool.

LEVISON: And it just so happens we can go by it. Going to the proposal, we had Eurybates, then Polymele, then Leucus, and Orus all in the leading L4 swarm; and then we go to Patroclus in the L5 swarm. That's what we proposed to NASA. Since that time, we used the Hubble Space Telescope to look for satellites. As you said, we found Queta around Eurybates. And then using ram-based stellar occultations, watching stars blink out as the asteroids move in front of them—

it's a very interesting way of getting shapes and positions of these asteroids—we discovered a satellite of Polymele. It hasn't been officially named yet because we don't have an orbit for it, and we can't name anything until we have an orbit, that we're unofficially calling Shaun. It's a nickname.

JOHNSON: You mentioned that he had projected that out for 50 years, and then through occultations and different ways you're seeing other things. Is it possible that Lucy could go on beyond 2033?

LEVISON: Absolutely. The way the orbit of Lucy evolves over time, we launched into an orbit with a one-year orbital period. It was a lot like the Earth except it was slightly more eccentric. Then we're using a series of Earth gravity assist to pump up the orbit so it can get out to the Trojan swarms. To get out to the first Trojan swarms, we need two Earth gravity assists. The first one happened last October and the next one happens in December 2024. After that, the spacecraft's basically in an orbit where it's perihelion distance, or the closest distance that it gets to the Sun, just inside the orbit of the Earth, and it's aphelion distance, or the furthest distance it gets from the Sun, is just outside of Jupiter's orbit.

It turns out that the solar system has weird dynamical coincidences. If you don't mind me using the word again, the celestial mechanics gods are smiling on us. Once you put an object in an orbit like that, it's orbital period is roughly half that as Jupiter's orbit. That's why on the first orbit around the Sun we can go to the L4 swarms, and then basically in the same orbit we'll use another EGA [Earth gravity assist] to target a little bit but basically on the same orbit. The next time it orbits the sun and goes back, you're going through the L5 swarm. That geometry will continue forever. Six years after the Patroclus encounter, we'll be back into the L4 swarms again.

We could keep Lucy going as long as it has fuel and other resources that it needs and continue doing this. Not we. I'll be 76. I'll retire, but somebody. Yes, so we can continue. It's going to be the health of the spacecraft, resources like fuel, and scientific interest—maybe Lucy's doing enough and we can turn it off. Or particularly given NASA's budget problems, who knows what they'll be able to do.

I said that Lucy will basically stay in its orbit. If we do nothing after the Patroclus encounter in 2033, it'll stay in its orbit. Remember, I'm a dynamicist. I'm a theorist. One of the first things I did was put the orbit of Lucy as we thought it would be at the end of the mission and figured out what would happen to it. It turns out that it will spend, on average, about two million years in its orbit.

JOHNSON: Oh my gosh.

LEVISON: It'll eventually either hit the sun or Jupiter will throw it into interstellar space. But it's going to spend a lot of time in the orbit that we're going to put it in at the end of the mission. I had this idea of putting a plaque on Lucy. As you probably know, this Pioneer Plaque which is a message to aliens and are the records on Voyager[5]. We took a slightly different idea for Lucy. If you look up Lucy plaque on the Web, you'll see images of what we put on the spacecraft. The basic idea is you can easily imagine 1,000 years from now or 500 or 200 or 10,000 or 100,000 years from now, some astroarchaeologist is going around the solar system trying to find our space

[5] The golden Pioneer Plaque was the brainchild of Carl Sagan who wanted any alien civilization who might encounter the craft to know who made it and how to contact them. It gives our location in the Galaxy and depicts a naked man and woman drawn in relation to the spacecraft.

junk to learn about our society, like archaeologists do on the Earth. Rather than putting messages to aliens on the spacecraft, we put messages to our descendants on the spacecraft.

We went around and reached out to, let's say, cultural leaders. We reached out to people who won Nobel Prizes in literature, people who are pop culture leaders—I'll talk about that in a second—scientific leaders. We have quite a few U.S. Nobel Laureates. We had Amanda Gorman. If you remember, she's the young woman poet who spoke at [President Joe] Biden's [2020] inauguration. All those people contributed. We have a bunch of people who passed away and we took famous quotes from them; Carl Sagan, people like that, Albert Einstein. And we put their wishes to our descendants on the plaque. I just want to make sure that story is told.

JOHNSON: Yes, I was going to ask you about that so I'm glad you brought it up.

LEVISON: Included in that is the Beatles because remember I said the mission is named after the fossil. Well, the fossil is named after the song. There's sort of this synergy, in my view, between the fossil and studying fossils and "Lucy in the Sky With Diamonds", and the idea in my mind that scientifically the Trojans are diamonds because they're so valuable and all of that thing. It has this synergy in my mind about how it all works. You can actually see we were aware of all that in the very beginning. We didn't want to make too much of a big deal with connection to the Beatles song initially at least because we didn't know how the PR people of NASA would react, LSD and all that stuff. But if you actually look at our logo, our logo is diamond shaped. That's why we shaped our logo the way we did is to make sort of an indirect reference to the Beatles song. Although now NASA has embraced this idea, that connection to the Beatles song. But before we were selected, I was a little worried, so it was originally subtle. It's not so subtle anymore.

JOHNSON: I'm glad you brought that up. I talked to Arlin Bartels. I haven't talked to him about Lucy but I was talking to him about another mission, but he mentioned that Ringo Starr had come by and he sent me the pictures.

LEVISON: Yes, that's cool, isn't it?

JOHNSON: It is cool. I've talked to him a couple of times and I'm going to talk to him again in August about Lucy. He's been involved in a lot of the Discovery missions.

LEVISON: He was, again, one of these guys whose professionalism and character helped us get through COVID. He was brilliant.

JOHNSON: Yes, he's been very helpful with this project.

We have 20 minutes left in your time. Let's go ahead and talk about the launch then, where you were and that experience of seeing this spacecraft that you had worked on and were looking forward to getting the results from go up.

LEVISON: It was amazing and heartbreaking. You must be aware that one of our solar arrays didn't open correctly.

JOHNSON: Yes, how quickly did you find out that that was happening?

LEVISON: By the time we closed up shop for the launch we knew that there was a problem. It started out being a brilliant day, ended up being actually not as bad as it could've been, obviously, but a hard and stressful thing particularly given the timing. We launched at 5:34 in the morning. That made it for a beautiful launch. As a matter of fact, people that I know down there who live down there and have seen many launches claim that Lucy's launch was one of the most beautiful launches they've ever seen. Have you taken a look at the videos?

JOHNSON: I've seen the photos of the launch. I haven't looked at the video, but I've seen the photos.

LEVISON: Take a look at the videos. I don't know which pictures you've seen. There happened to be a cloud deck over the spacecraft. If you look at the videos, you can see that the spacecraft takes off, disappears into the clouds but then erupts, if you're far enough away, above the clouds. When I saw the videos of the launch—and I'll get into that in a minute—it looked like some of the opening scenes of *Close Encounters of the Third Kind* where these fingers of God are coming out of the clouds as the rocket rises above the clouds. It's quite spectacular, so I encourage you to go look at pictures of it. Given the earlier morning launch, we went to stations at around 11 p.m., I think, if I remember correctly. I was in the launch facility that ULA [United Launch Alliance] has there. We did our countdown and our checkouts. I wasn't supposed to do this but I did it anyway. About 30 seconds before the launch, I ran out of the room and ran up the stairs and got on the roof to watch the launch.

Now, from my perspective, I was so close that I was underneath the cloud deck. For me, the rocket just took off and disappeared in the clouds and I never saw it again. That's why I was saying you have to take a look at the videos. My experience was much more muted. Then I went back down to our stations.

The spacecraft, it was awesome. We've worked almost 10 years full-time on trying to make this happen, and to see it launch was spectacular. There's no doubt about it. The thing that we were most worried about was the solar arrays, and it turns out we had just cause to be worried about it. The spacecraft separated from the launch vehicle. There was about an hour delay until the Canberra DSN [Deep Space Network, Canberra Deep Space Communication Complex, Australia] became in contact with the spacecraft, and then it started to deploy solar arrays and one of them got stuck. We didn't know how bad it was, and it turned out—I mean, I can go into more of that story. But by the time we left at breakfast the next morning, we knew there was a problem and we had to deal with it.

As a matter of fact, one of the hardest things that happened for Lucy is we'd been up basically 27 hours, or something like that. My wife and I rented a house in Florida and we were going to have, that evening or late afternoon, a big party. A lot of people were coming, including Donald Johanson which was cool, the discoverer of the Lucy fossil. I was trying to grab a few hours' sleep. About an hour after I fell dead asleep, the phone is ringing, "You have to get up. We have to deal with the solar array." It was hard. Emotionally draining, let's just put it that way, that day.

JOHNSON: Talk about having to deal with that. Were there contingency plans? Did you think at some point the mission was lost?

LEVISON: There was always that potential. Frankly, there still is that potential, although I think it's extremely unlikely. We really wont' know until February when we turn the main engines on for the first time. We have yet to fire our main engines. Again, I think this is something that is important for a PI—again, this may sound arrogant, but part of the leadership of a PI is you don't tank. And so one of the things we needed to do, the leaders of Lucy, was say, "We don't know what's going on. Let's take one step at a time and figure it out before everybody goes spinning out of control about what might happen." We knew we had a lot of time. We basically had a full year before the first EGA to get a handle on what we think happened and the state of the array.

One thing that we knew almost right away is that the array was producing over 90 percent of the power we expected. We knew it was almost open, although we didn't know what almost meant. There was no short-term danger to the mission so we knew that we could take the time to figure out what was going on, which is exactly what we did. I must admit the most impressive thing that I've seen as the PI of Lucy is how the engineers got to work and figured out what was going on, the state of the array, and what we could do to attempt to fix it all within months. It was really an impressive piece of work. Our two system engineer leads were Jessica [A.] Lounsbury at Goddard and Mike [Michael] Sekerak. They were brilliant, and the whole team was brilliant. They figured out what went wrong. They, in the long run, figured out the state of the array. It took them a while and a couple false estimates.

We made some attempts of opening it up again until we convinced—we made good progress. We didn't get it all the way. These things open like oriental fans. Full deployment is 360 degrees, and we probably were at 335 or 330, or something like that. After our attempts we were probably at 355, so we're really close but no cigar. Power's not an issue. These things are made out of cloth. If you think about it, a lot of strength in a parachute or something like that, comes from tension in the cloth. There's not as much tension as they were designed for, so we're a little worried about their dynamical stability and the effect, whether they're vibrating too much, or when we turn on the main engines whether some damage is going to be done. Lucy is probably—I know it's the best study, at this point, spacecraft Lockheed has built, or at least unmanned, deep space spacecraft that they've ever built trying to figure this out. They're confident that the system can do its job, and so we're just going to fly the mission as if there was nothing wrong.

JOHNSON: I'd read that there's a lock and they couldn't lock it, but other than that as far as power you were getting enough to continue.

LEVISON: Yes, they're just more floppy than we had hoped.

JOHNSON: Well, hopefully it won't cause any problems.

LEVISON: Yes, I think we're okay. They've built computer models of this thing coming out the wazoo. They've been working really hard to understand it, so I think we're okay.

JOHNSON: After the launch, there were some first test images in November of 2021 and then another set in February of 2022. Talk about that for a little bit, what those images were and how that worked out and if everything's working the way you expected it to work.

LEVISON: Yes. Early on we were taking images of the sky looking at stars and things like that. Zeroth order everything's working the way we expect. The L'LORRI instrument's a little fuzzier than we had expected it to be, the images are, but not enough to really affect quality of the science that we'll get. During the first Earth gravity assist back in October, we took images of the Moon and the Earth—there are some cool images there, take a look—trying to understand the stability of the spacecraft and calibrate things like what the exposure times need to be when we get to the Trojans. We have some beautiful images of the Moon that we took in order to—remember, I said one of the goals of Lucy is counting craters. We were asking ourselves how small a crater can we see. By looking at terrains on the Moon that are well understood and we have much better images from things that orbited the Moon than Lucy got, so we can actually compare what we saw, count craters on the images that we saw and then compare them to the craters that we know are there.

One cool thing that we did was we observed DART [Double Asteroid Redirection Test] impact onto Didymos[6]. Remember the mission NASA did, so we observed that and got some interesting results for that because we were looking at the collision from a different perspective. You have observations from the Earth and observations from Lucy, and that tells us something about the kind of particles in the dust cloud that was created. That's pretty cool. And, of course, in November we have our first encounter with Dinkinesh, so we're getting ready for that.

JOHNSON: That should be exciting.

LEVISON: It will indeed.

[6] DART was the first-ever mission dedicated to investigating and demonstrating one method of asteroid deflection by changing an asteroid's motion in space through kinetic impact.

JOHNSON: Well, I think this might be a good place to stop for the day. I have a few more questions and maybe we can get back together for an hour or so and continue to talk.

LEVISON: Sure.

JOHNSON: I appreciate you talking to me today for this and look forward to talking to you again.

LEVISON: Yes, it was fun.

[End of interview]