NASA DISCOVERY 30TH ANNIVERSARY ORAL HISTORY PROJECT
EDITED ORAL HISTORY TRANSCRIPT

HARLAN E. SPENCE
INTERVIEWED BY SANDRA JOHNSON
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JOHNSON: Today is February 23rd, 2023. This interview with Harlan Spence is being conducted for the Discovery Program 30th Anniversary Oral History Project. The interviewer is Sandra Johnson, and Dr. Spence is joining us from the University of New Hampshire in Durham, New Hampshire. We're talking over Microsoft Teams. I appreciate you agreeing to talk to me for the project and coming to see me today over Teams.

I'd like to start by asking you to briefly describe your education and background and how you first became interested in astronomy and physics.

SPENCE: Great question. I have a Ph.D. in geophysics and space physics from UCLA [University of California, Los Angeles], a master's degree in that same field. I earned my bachelor's degree from Boston University [Massachusetts], and that was in astronomy and physics with a minor in math. I actually started college as a trumpet major, and somewhere along the way decided that that was a great hobby but not a career for me. I took an intro astronomy class when I was a freshman and it really captivated me and excited an interest that actually my father had instilled in all his kids. He was an amateur astronomer, so I didn't fall far from the tree, I guess.

JOHNSON: I read that you had a chance to see the Apollo 15 launch in 1971. Talk about that experience, seeing that when you were younger.

SPENCE: Yes. As I said, my dad and my mother both were really keen on having their kids be exposed to all the great stuff going on in the world at that time. My dad was as I said an amateur astronomer. When the Apollo era was really in full swing, they decided that we should pilot our 1965 Chevy wagon that was a rattletrap and made the trip from north of Boston down to Cape Canaveral, Cape Kennedy [Florida] at the time. We were able to in the summer of '71, I just turned 10, witness the Apollo launch from probably Titusville. I'm not quite sure exactly where we were. My memory is a little bit vague. I have some videos of it that are really fantastic. But just the memory of watching that Saturn V lift off and then feel the blast wave and the heat and just the energy, I was captivated at that point.

Even though I tried a number of different things along the way, I think my path to becoming an astronomer and physicist was locked in probably at that time.

JOHNSON: That Saturn V, I have heard, was something to behold going off. That's exciting that you got a chance to do that. You mentioned where you got your degrees. You got your Ph.D. in 1989. What did you do after that? What kind of career did you pursue?

SPENCE: Great question, I spent the first five years of my post-Ph.D. period working for The Aerospace Corporation. I was I think very keen on doing something to serve the nation, and I was able to do that through The Aerospace Corporation supporting their mission of providing all the things that are needed to support the DoD [Department of Defense] flight programs. I was in what I considered a really cool part of that organization that was doing the basic science needed to understand the space environment. It was a very practical application of my training as a space scientist, being able to use that knowledge to advance our basic understanding of the space environment.

That was right at a time beginning where we were starting to use the word space weather. The kind of work we did I would say was really at the forefront of what we now call space weather, but places like The Aerospace Corporation had been doing that for many many years. But it was an exciting place to be at that time.

JOHNSON: Did you have a chance to work on any NASA missions or any experiments or instruments for those?

SPENCE: Yes, I did, and just about my first few months at Aerospace Corp my mentor who I still value greatly, Dr. [J.] Bernard Blake, he pulled me in his office and said, "I know your training is not in building instruments, but I'd like you to go to Los Alamos [National Laboratory, New Mexico]. We have a partnership with them on an upcoming mission, and I'd like you to help lead one of the instruments we're building in this instrument suite for the NASA [International Solar] Polar mission." It was part of an International Solar-Terrestrial Probe [STP] program, and there were a number of different satellites. The U.S. had two, three or so parts of different missions. We had a suite of particle instruments on the Polar spacecraft. That was pretty exciting coming in and really not knowing which end of the soldering iron to hold. But you learned quickly.

JOHNSON: You had a chance to actually physically build that instrument.

SPENCE: Yes. With great team partners. I learned so much from the engineers that I worked with and the senior scientists who were very gracious and patient with me as I was learning the way. Really some great mentors who I've been blessed to work with over the years. Really started even before that back in my undergraduate days, but certainly at Aerospace that was where I really caught the bug of building instruments and making measurements in space.

JOHNSON: That's more of an engineering side, not just the research science that's coming from the instrument. But actually being able to build it.

SPENCE: I always encourage that of my students, to be able to do an experiment of some kind. Exploration of space I think has just such an appeal to be able to build something that goes to space and make a measurement no one's ever made before, and then do science with it. If you can do all of those, that's really a great well-rounded scientist who can do anything, can move around. I think it's very satisfying.

JOHNSON: It sounds like it would be. As your career progressed, you went to Boston University, and that's where you were when President George [W.] Bush in 2004, when he announced *The Vision for Space Exploration*. He asked NASA to undertake lunar exploration activities to enable that sustained human presence for Mars and beyond. Did you see that as an opportunity for your university at that point?

SPENCE: Absolutely. Yes. I was very happy at Aerospace Corporation but when I had a chance to return to my alma mater in the department I kind of grew up in, that was very exciting to become a faculty member. It was shortly after being back at Boston University that this initiative to go back to the Moon was brought up.

It was the summer of 2004, I think June of 2004, there was a summer workshop that's organized by the National Science Foundation every year with a topic of looking at the solar-heliosphere regions. I was with a bunch of colleagues who were also at that meeting and we were talking about this opportunity and from that meeting, it was Big Sky, Montana, we envisioned this instrument that eventually I had the privilege to lead, be the principal investigator [PI] on, that eventually flew on the Lunar Reconnaissance Orbiter [LRO], which was the first of the missions from that vision that President Bush had. But it was amazing to me just the speed at which that program went. On the back of a napkin in Montana in June of 2004 to the proposal sometime around Thanksgiving to selection around Christmas and start the whole program in January of the next year. That was very unlike any NASA experience I'd had to date.

JOHNSON: Yes. With the Discovery Program at the beginning, that was the vision, to turn these missions around quickly. That is different as you said than anything you'd experienced before as far as NASA is concerned. Let's talk about that because the announcement of opportunity [AO] came out in June 2004 for the instruments themselves and then they were having a target launch date of 2008. Of course the end of 2008 at that point. That is quite a turnaround. Did you start right after that meeting that you were talking about and that announcement of opportunity? Talk about how you started that and how you built a team or how it was decided that you were going to be the PI on that. Talk about that whole time period of getting ready to put your proposal in and going through the process of selection.

SPENCE: Great question. It's a little bit fuzzy in my mind because it's a few years ago now. But there are certain parts of it that will forever be locked in place. As I said, we literally drew the concept for the instrument that eventually flew—is still in orbit on LRO, and we're getting great data from still all these years later—in Montana at that meeting in a restaurant somewhere in Big Sky. I forget which one exactly. That basic concept is what we carried through on, of course with many refinements and changes along the way. It was really developed with a team that grew out of that experience I had at Aerospace Corp, so a number of the same people who were key in that development where I was learning the ropes with the more senior people in the leadership position, that kind of flipped. They entrusted in me the leadership of this, and I'm forever grateful for that. It really, I think, had a big impact on my career and my directions since then.

It's interesting. The announcement of opportunity didn't really fully identify the instrument that we proposed. A lot of them were directed. We need an instrument to measure topography. We need an instrument to measure the terrain at very high spatial res [resolution] to make images. There were instruments talked about to measure radiation. But mostly for detecting neutrons.

We came up with an idea we thought would be important, to measure the radiation effects on humans. This is not just the neutrons but also the charged particles that make up the galactic cosmic rays and solar energetic protons. There are a lot of different ways to do that. Many instruments that have flown before and have flown since measure the direct particles that cause the radiation. When these particles pass through matter, they give up energy and that produces ionizing radiation. Instead what we did is we flew an instrument that tried to mimic a human with sensors throughout the volume. The secret sauce of our design was incorporating this material called tissue-equivalent plastic. We created essentially a tube of that material about the thickness of a human torso with detectors at the outside, in the middle, and at the back, so we could see how the radiation changed throughout that volume.

It's not what I think NASA was thinking they were looking for, but we sold it to them. I think the merits of that have paid back manyfold, including in ways that we're only now discovering. We just published a paper. One of my former Ph.D. students who's now a senior research scientist published a paper that looks at how water in the lunar regolith is modified by radiation and how the chemical changes occur. It uses a unique capability of this peculiar instrument that a scientist without a mind for effects of that radiation on humans, or matter for that matter, would really think about, but because of its unusual aspects it's allowing us to do things that we never imagined we could, which is cool.

JOHNSON: You said NASA wasn't necessarily looking for that but you convinced them. Was that something that wasn't being done at the time, looking at the direct radiation effects on humans as you said? That's what you wanted to do. Was that just not being considered?

SPENCE: I have to be a little careful there. It certainly was being considered. There were groups particularly at Johnson Space Center [Houston, Texas] and others where there's been a long, long history all the way back to pre-Apollo of measuring dose and dose rate to consider the effects on humans. What we were trying to do was to make a nuanced version of that and to do it with an instrument that had just incredible capability. I'll never forget when we had our kickoff meeting. That was probably January of 2005 at NASA Goddard [Flight Research Center, Greenbelt, Maryland]. We had a conversation about what each of the instruments would need in terms of their measurements and in terms of their data rate for getting the data back from LRO to Earth.

The instrument that we proposed had a design that assumed that we wouldn't get much data back. We would use some clever approaches to select interesting things that we knew that we would probably be measuring with the instrument in flight, and then select that out of this huge volume of data and send that back.

But at the kickoff meeting we had the conversation. They asked me, "What's the highest data rate you'll ever need?" My mind went to when we have a big solar proton event for a very short period, we'll have really intense rates. So I said that number. They said, "Okay. You can have that all the time." It's like oh. That's really cool. That really in some ways completely changed how we thought about the instrument. We were able to operate it and are still operating it in this very high time cadence approach where we literally send back each and every detection that's ever made. For an instrument of this kind, that's absolutely unprecedented. Usually you collect 1,000, 10,000, or 100,000 times more data than you can send back. Suddenly instead of having a little pencil stream we had this giant pipe. We were sending it all back. Honestly, it took us a while to figure out what we were seeing. Thank goodness we did get that, because we'd just uncover all kinds of cool stuff that we never would have thought to send back.

JOHNSON: That's exciting that that all came together to allow that. Like you said, it's still flying, and you're still getting that data. Were you competing with any instruments that were in the same line? Why do you think yours was chosen if you were?

SPENCE: That's a really great question. I'd love to know the answer to it. We really didn't know who we were competing with or what other instrument teams might propose. We assumed, and probably I think correctly, that there were at least some instruments that were more like the traditional cosmic ray spectrometer as opposed to measuring the effects of the cosmic rays, trying to measure them directly. We really thought the novelty of adding that extra little nuance was important. I gather we made a convincing case because we were selected. There was another radiation instrument selected that was focusing on the neutrons. I remember during the development, with any mission that is going to space, there are a number of factors. You have schedule, you have cost, you have technical risk. In this case schedule probably was the one thing everybody was managing against just because the race to get it into orbit was on.

Because schedule was so tied to cost, there were always what we called descope options. Our instrument, which is called the Cosmic Ray Telescope for the Effects of Radiation, and the acronym for that is CRaTER, which little sidebar on that, at the time that seemed like a cute clever name, but in retrospect whenever you google trying to find the instrument you find the crater at the Moon of course. Everyone references the real craters at the Moon. There you go.

At any rate, I think a combination of our novel design, our team that included people who didn't just measure the cosmic ray populations, which is important to know, but we also had people who really understood radiation transport and understood how that radiation affects humans. We had a team that I think went beyond just the basic science or engineering crew but actually thought about the end result. That might have been enough to compel people that this was worth the investment. But we were always on the descope list, coming back to that comment. I think because we weren't the core of what had initially been envisioned would be the payload, we were that oh yes, we're going to invite that group to the dance. We like something about what they propose to do. We don't quite understand how that's going to work. But if it goes a little funny maybe they won't come on a ride with us.

Honestly, knowing that you're on the descope list really compels you to greatness. We delivered faster than on time and cheaper than on budget. We made sure that we weren't a problem.

JOHNSON: I can imagine that would be an incentive. When you were proposing this and going through that, the mission itself, I don't think anyone knew at that time that it would still be going on at this point. Not knowing the exact length and what would happen and the way it was more of an engineering mission that first year and then it was turned over strictly to science after that, but what were you hoping to learn when you were building this and getting it ready to go? What exactly did you think you would get from it? Also, I want to talk a little bit more after that maybe about that human tissue equivalent and where that came from and if it had been used before.

SPENCE: Great questions. On the first part. What did we hope to learn? I think we always had in our mind that we were first and foremost, we had requirements that were to meet the exploration aspects of the mission, because that was why we were there. I think everyone was excited to be contributing their part of the mission goals. Ours were really rather simple. At a high level we were to characterize the radiation environment at the Moon. That had never really been done before. We'd been to the Moon with Apollo. Those were short visits with instruments that were provisioned in the '60s and early '70s. There had been some returns to the Moon with Clementine[1] and other missions in the more modern era prior to LRO. But we were going to go there. We were going to do it deliberately. We were going to map the Moon and do it with multiple instruments.

[1] Clementine was designed to test spacecraft components during extended exposure to space, and to study the Moon and an asteroid. The mission succeeded in its lunar objectives, but a malfunction forced the asteroid flyby to be canceled.

Really our goal, which we achieved quite well in that first year of exploration, was to do precisely that. We understood for that year of time what the dose and dose rate looked like, how the galactic cosmic rays contributed to what we call the linear energy transfer spectrum that's produced by the cosmic rays, which is important for those who consider medical effects in humans.

That was very satisfying to be able, with an instrument that was based on a fair amount of heritage but put together in a novel way, to get that built and flown so quickly. It was fun times. We had just such a fun team. Even through the hardest trials and tribulations of any flight build we all had fun. I think with that end purpose that was great.

That said, we all had in our mind this belief that we could do some really great science with this instrument. When we found out shortly after selection that we were going to get this data rate, we went back to the drawing board and said, "Okay." Instead of doing all that logic we were talking about to select this event and maybe figure out when you get this and that in combination we'll take that data, we were able to just say, "Heck with it, we're going to send all the data down, and it's going to be fun. We don't know what we're going to get."

I'd say the instrument was designed to do the exploration, but as a knockoff we were able to do great science. I think that's true for all of the LRO instruments and that's proven itself over the decade or more.

JOHNSON: The tissue-equivalent plastic. Is that something that has been used before in space? Or was this a unique use?

SPENCE: It has been used. It had been used I think quite effectively on earlier missions. A lot of use of it in low-Earth orbit on [International] Space Station [ISS]. It's kind of a go-to material.

You can pick different materials that are tissue-equivalent plastic or bone-equivalent plastic. The medical community has developed this material that really just looks like plastic but that has enough of the same properties that you can use that as a proxy for human material, which is a good thing to do.

Putting it in this particular configuration in deep space, that was a first, we believe.

JOHNSON: Let's talk about the team you've mentioned and how well you got along and worked together. As you mentioned, they were varied with a lot of different scientific expertise. I'm assuming the team also includes engineers. You had that experience of doing science and engineering early on, but sometimes work between scientists and engineers sometimes causes a disruption in communication because of so many different people on the team and different backgrounds. Talk about how you work with that team as the PI and how that worked for you as a team.

SPENCE: Great question. I always like to say that as a PI your job is when something goes wrong, you're responsible but when things go right the other people did it. I really try to—particularly with this mission, my first really leading an instrument—to embody that. Really the team, I think when they know that I've got their back but that they're the ones who are going to make it really succeed through teamwork, that really helped create the working environment to get through some tough times. I can tell you, there were some tough times. Time is short, people are stressed, you've got a test you've got to complete, something's not right, a cable is broken or something, and people's temper might get short. But we really had a team that had just excellent people who figured out how to work together even though maybe they were oil and vinegar or in the working environment might have big disagreements, but when we left the lab, everyone would be smiling and going out for dinner together.

It was kind of magical. I don't know that it was anything I did in particular other than get this group together and make it happen. It was a team that was more or less already in place but we changed it up and added some elements, and that same team is still together after all this time, which is really, I think, a testament. Everyone's got other things they're doing but LRO is still at the core for a lot of the team members.

JOHNSON: How often do you see them or talk to them?

SPENCE: We have weekly meetings still to this day. We've gone through many and varied incarnations of that. We've settled on weekly half-hour meetings in the pandemic era just to make sure everyone's plugged in. We're still actively delivering data and writing scientific publications and supporting meetings and supporting Artemis. It's been a really exciting time. It's continued to be just a great team and a great mission I would say because of that. I would say that extends beyond our instrument team. The LRO project team has been fantastic. When we were building the instrument, Arlin Bartels was our instrument manager from Goddard and he was fantastic. It was funny though because his name sounds a little bit like my name, A-R-L-I-N versus H-A-R-L-A-N. His administrative assistant was also Arlyn, A-R-L-Y-N. There were times where like who's talking now, got a little complicated. It really was I think soup to nuts a fantastic group of people and just a really great ride.

JOHNSON: You were talking about the fact that they allowed you more of that data transfer than you expected. But were there any constraints put on CRaTER at all at any point during the design sizewise or anything else that you had to work around?

SPENCE: Not really. I would say the spacecraft team was extremely accommodating for us and for the other instruments. They had a devil of a time with the spacecraft. When you think about having a set of instruments that have to point down at the Moon and have to point reliably down with very good accuracy and at the same point have to be powered as it goes around the Moon, and so you've got a solar panel that's got to wiggle around to make sure that you're pointing down but also looking at the Sun. Then with a high-gain antenna that's got to point at the Earth, which is off in some other direction. To be able to do that and accommodate all the needs of the instruments was really remarkable. Just a real credit to the ingenuity of the spacecraft team at NASA Goddard. Just a fantastic group.

There's always the personal stories. Our project manager [Craig Tooley], he's since passed away, but I remember he came to visit us in Boston one night. Craig kind of had this sense of adventure and he was full of life and would often put on a pirate act with the eye patch and everything. I remember being in Cambridge after a dinner and out in the street and just acting like kids. That was, I think, a lot of how the success of the mission was because we had those lighthearted moments after days of hard work, just having fun together.

JOHNSON: I've heard that about him, that he was a good person to have in charge as far as getting people to have fun as well as work hard.

SPENCE: Yes, terrific.

JOHNSON: I would imagine that always helps to have that kind of personality. Let's talk about the testing because you were talking about everything moving fast. Everything had to move fast. But as you said you were ahead of some of those times that you had to make certain things happen. The milestones. Let's talk about some of the testing that you had to go through with your instrument, and if there were any problems when you were testing, or if you found some things that you had to work around or fix, and how were they handled.

SPENCE: It's always in some ways the hardest part of a project, in some ways building is a little more straightforward, but actually the testing and understanding what it is that you just built. You meant to do this but it now seems to be doing something that's that but also a little bit different. The testing is just so incredibly important. It's not just the calibration but also really how does the instrument operate. In our case our challenge was to take an instrument that's designed to measure cosmic rays and figure out how to test it on the ground. We've over the years done a number of different things that are all just really fantastic.

We made great use of the NASA Space Radiation Lab, which is a beam facility in conjunction with Brookhaven National Lab [Upton, New York]. They have an area off of one of the main beam lines that's dedicated to NASA where folks who are studying space radiation could do their experiments, whether it is biology experiments literally with living material, or in our case a physics experiment where we were able to put our CRaTER instrument into a beam that simulates a solar proton event or galactic cosmic rays of every atomic flavor from hydrogen to iron. We were able to do that.

Always going to a beam facility is tricky because you're taking an instrument that you developed in your lab to somebody else's home so to speak. You've lost your home court advantage. Did you bring all the right cables? What happens if your power supply decides not to work or doesn't work the way you thought it did? Those are the kinds of things you learn to have plan A and plan B and sometimes plan C. You build up I think an arsenal of tricks of the trade to make sure you can make it through.

That was one of the first facilities we went to. In a way the one that is most memorable, some of the testing we did, we discovered that at Mass [Massachusetts] General Hospital there is a facility there that goes back in history quite a ways where a cyclotron that was used in the Boston area had been put to medical use at Mass General Hospital. It was a proton therapy beam for cancer treatment.

In some ways the remarkable thing about that is here we are going, taking our instrument, which we could do it on weekends, so the facility was available for patients Monday through Friday. It would be the weekend that we would go where we could work with the beam operator there to bring our instrument into a part of the facility that wasn't one of the treatment areas, but a place where they could direct the beam. Put it in the beam, and basically produce a beam of protons that would allow us to look at the primary component of galactic cosmic rays and solar protons at the right energies and at the right fluxes so that we could really explore how the multiple detectors in the instrument worked and worked together with our tissue-equivalent plastic.

The cool thing for me with all that is in thinking through the use of this facility we were basically using a surgical tool that uses ionizing radiation to very strategically and mindfully use that ionizing radiation to go after cancer cells. Those cancer cells are buried often in someone's body. A property of that radiation is that if you pick the right energy that particle can move through healthy tissue without losing much energy, and then when it stops, if you make it stop right where the bad stuff is, you can go after and surgically attack the cancer cells.

Here we are using the physical understanding of radiation transport in matter with a manmade device that tells us how to put that energy right in the right spot as a therapeutic device for cancer. We're using it to calibrate an instrument that's going to space, where the radiation is indiscriminate, it's every energy. It is attacking every part of a human torso at will. There's not much you can do to shield some of this radiation.

Just the yin and the yang of this, of figuring out how to calibrate an instrument using the surgical tool, then take it to space to figure out the radiation environment so that we can make sure people don't get cancer basically by doing appropriate shielding. There was a real synergy to all of that that went on.

The beam operator at Mass General Hospital became a real fan of our instrument. He was almost a member of the team. We still hear from him occasionally even after all these years. We wrote some papers together even. Really cool stuff.

JOHNSON: Like you said, it's almost a full circle there. Trying to treat a disease that you're trying to prevent with this instrument. Was there any other testing that comes to mind? Any other anecdotes about any of the testing?

SPENCE: No. I think for the most part our testing went very very well. We benefited from access to some of these really world-class facilities that allowed us to get the data we needed, and in many cases, we've been able to go back to that original data especially during the early parts of the missions to try to understand something we were seeing. But those measurements, even if we didn't use them all at the time, we didn't appreciate all the details, I think we benefited from that after the fact.

There was one other experiment we did or test we did after we'd already been in flight. That was an experiment motivated by some measurements we were getting that we wanted to understand better. We were able with LRO to watch not just the cosmic rays that were coming from deep space and solar protons raining down upon the Moon, but also, we were able to see the secondary radiation coming back off the Moon. We call this particle albedo. When we first made a map of the Moon looking at this albedo you could see features that mimic the maria and so forth, the highlands and the maria. That just got us thinking about what exactly are we seeing.

This albedo is produced by the cosmic rays interacting with the surface at depth and then coming back out. We got interested in what could it tell us about let's say how much water is in the regolith at different places. We devised an experiment where we purchased some regolith simulant, some material, and then introduced differing amounts of water into it, and then basically in that bucket of regolith we would illuminate it with a particle beam, and then look at what was coming off of it with a sister instrument that we built. We built a flight spare that we were able to use for testing on the ground. We could compare with what measurements were being made at the Moon.

We did this in a facility in Chiba, Japan. During that experiment the beam got a little bit too intense. I don't think the beam operator made a mistake, it was just a high dose, and activated that regolith to the point where we couldn't bring it home. It's still sitting in an underground chamber 13 stories or something underground. You can keep it.

JOHNSON: We don't want that back.

SPENCE: We don't want that back.

JOHNSON: Did any of the testing that the actual instrument went through for flight—it was shaken—did any of that cause any lack of sleep or worry? You felt like it was ready to go?

SPENCE: Yes. I think this particular instrument didn't present much in the way of concern in terms of vibration, although any time you shake an instrument, if you actually go in and are able to listen to the sounds that it makes when you put it on a shaketable, it's kind of scary. I think it wasn't LRO, I think it was the Polar instrument, where it's amazing what you put on these shaketables. The thing that was in there before we were able to get into that shaketable was a lavatory from an L-1011. They actually shake the toilets on the airplanes before they put people in them. Not to the same levels that you would get on a launch vehicle.

That went without a hitch, and our thermal vacuum testing really went without a hitch. That's a long and kind of lonely set of tests to do, a lot of overnight with people bleary-eyed, staring at a screen watching nothing happen. That's exactly what you want it to be.

JOHNSON: I was going to say that's the good news, right?

SPENCE: Absolutely, it's a good day.

JOHNSON: Where were you when LRO launched?

SPENCE: I was right down there at the Cape [Canaveral, Florida] in the viewing stands there. It was fantastic. I guess you could say I had the bad fortune of seeing a Saturn V because the memory of that, that rocket was so incredibly powerful that when you see some of the more modern big launchers they seem more like firecrackers. I was a little jaded by my Saturn V experience. That said, breathtaking when you put all this time and energy into building an instrument to accomplish a mission of national priority, been entrusted by the taxpayers to do that. You've got it, you're sitting in anticipation. Is the rocket going to get off the pad? Is it going to get to the right orbit? Is it going to get to the Moon? Will the spacecraft power up? Will the instrument turn on? Will the data look?

You've got all that anguish sitting in your mind as you're sitting and watching that countdown clock go. Honestly, I think we were so confident at the time. We had done all the testing. It just felt like everything was going to go well. It did.

We had some launch delays, and that's always inevitable. Probably the hardest thing with the launch delays is it's always great to have family come with you because even if they weren't in the lab, you were in the lab when they weren't. They know that you were gone doing something, and what was that? A launch is one of those moments where you can share a little bit of the outcome of it all.

When there's a launch delay and people have schedules and they miss the launch and have to go home, that can be tough. There've been a number of those over my career. That's really probably the hardest part.

JOHNSON: You mentioned the schedule that you had to keep preparing for that moment. Talk about that a little bit. What was that like? Were you working daily long hours every day for that couple years?

SPENCE: It's another good question. Yes. You work and you're single-minded. If you're not careful it can kind of consume you. If you're obsessive it probably will. Finding ways to keep grounded is what was important. Honestly, I think the team in keeping things lighthearted found ways to do that and I think looked out for each other in that regard.

We would always have opportunities when we were going beam testing or so to stop and take a little time off and have a little fun. But yes, it was a long haul. Even though it was a rapid pace, it's still long because you're doing what you need to do today and you're planning for what you need to do tomorrow, next week, month after. With an eye on that milestone. You know you've got a gateway review coming up. You better do this, that, that, and that.

We had some great, we still do, program managers and system engineers and our technical staff that were just fantastic. The science team stayed on track too. There's always one member of the science team—it's a nameless person because it's different every time—who has the idea well, if we change this, we could do that. Part of my job was we're not going to change that. It would be nice, but I want to get this thing delivered and in orbit. There's was always that little dynamic tension.

JOHNSON: Did anything ever get changed because of that? Or was there just a cutoff time that after this point nothing changes?

SPENCE: Actually we did fly something that was a late addition. That was a kind of new special device that our colleagues at Aerospace Corporation had developed for some of their flight programs to support the DoD. It was a microdosimeter. The CRaTER instrument is about yea big, foot on a side, let's say cube. This microdosimeter was about as small as your pinkie fingernail. Couldn't do everything that the big instrument could but could do enough that was interesting in such a small volume to make it worthwhile figuring out how to incorporate it into the flight unit.

As I said we had a flight unit and we had a flight spare. We were able to get this microdosimeter only in one of the two flight units. Fortunately both instruments in terms of calibration and performance were nearly identical. We just went ahead and we picked the one with the microdosimeter in that.

That little instrument is still going. It is incredibly functional. It's generated several papers. We've been able to watch a whole solar cycle of dose rates over the course of the mission. Because of that flight experience now, that device has been developed and improved in many generations. But this was actually the first flight of that particular device. That was pretty fun, and that was something, the opportunity came along, there was a little window of time where that was allowable, and so we snuck it in.

JOHNSON: You mentioned you had a flight spare. So you had two instruments. Other than that one difference from adding that. Is that normal how you do instruments for these kind of flights? Do you always have a spare that's exactly the same?

JOHNSON: I'd say the norm is different depending on what kind of instrument you're building. For these kind of particle instruments, yes, it's pretty common. There's a lot of benefit from having that flight spare if something goes a little sideways. The worst case is somebody drops the flight instrument putting it on the spacecraft. Very unlikely to happen. But weird stuff can happen. Environmental things might cause a detector to get a little funky if the humidity gets too high for instance. Any number of things.

Having a flight spare that you've developed in parallel if you're building one, building a second one actually is incremental cost. All that nonrecurring development happens on the first one. For the cost of having a second one it's good insurance. The other argument we made was because this was such a novel instrument, having a twin essentially in the lab would allow us to better understand what we were seeing in space. That I think again has really allowed us to do some things, like that experiment in Chiba, Japan, that we couldn't have done otherwise if we didn't have that access to basically the twin. For the longest time we actually had—and we have what we call an engineering model, which is the prototype that we develop before we build the flight model. It's very very close to the final flight model. But it's also one that isn't built to flight quality and that you can tolerate being out. We would have that running in the lab and be looking at data that we're getting on Earth while the instrument at the Moon is making its measurements. It's really interesting just to compare what radiation we see on Earth way down here protected by our magnetic field and the atmosphere as opposed to in deep space where you're out there where the breeze is blowing. Everything is coming your way. It's been nice to have that second or third unit.

JOHNSON: Once it was launched and LRO arrived at the Moon, when did you first start getting results back from the instrument? I know you mentioned that lunar radiation that you were seeing. Just talk about those first days once it arrived and what you were seeing, and if anything else surprised you.

SPENCE: Another one of those memorable moments. At the time one of my graduate students who's now a colleague, Tony Case, he figured out how to get access to the real-time datastream coming from the LRO Mission Operations Center. He was involved in our Science Operations Center. He was able to develop a little app on his phone so literally we're in the grandstands watching the rocket take off and go downrange out of range, and he's getting data on his phone seeing the temperature of the instrument change. How cool is that? That was our first glimpse of the data.

We then raced home to Boston and by then we were already cruising on our way quickly through the radiation belts. The one constraint you mentioned, we really wanted to launch the instrument hot, which is to say making measurements all the way up through the radiation belts and out to the Moon. But that just wasn't possible given all the things associated with the spacecraft. We actually had a little bit of time to get home and to get situated before the data started coming in.

I can remember us sitting around a table all together, the science team and some of the engineers, waiting for those first data to come in. We had just been to a little Chinese restaurant across the street. I had my fortune cookie, opened it, and the fortune cookie had "Here are your special numbers." You get six numbers or something. We had six detectors, and the first thing we saw were the countrates coming in on those six detectors. One of the first captures matched the fortune cookie. So we had this whole thing. The likelihood of that happening was pretty high actually because they were all kind of small digit numbers, but it was kind of fun. Very exciting seeing that first glimpse of data.

Then as you get more and more trying to figure out why did that just go up, why did that go down, how come it didn't go up. Just those moments of peering into a new kind of dataset looking at really the universe in a way no one's ever looked at it before. It's really an awesome moment as a scientist and as an explorer. I think we're all natural-born explorers and maybe somewhere along the way we lose that sense of wonder. But boy, I tell you, it comes right back at you when you start looking at something and it's talking to you and sometimes you can't listen right away.

JOHNSON: The rate of data, as you said, it was quite high. How did you capture that so that you could start looking at it and people could analyze it?

SPENCE: We had spent a fair amount of time developing some tools that would allow us to look at the data in the ways that we thought would be the best. We certainly used those. But I think we quickly discovered that there were things in that dataset that we hadn't anticipated and that were wonderful. We had to devise new ways to look at the data.

This is where I think another aspect of our team really started to come through. We had team members who were extremely knowledgeable about radiation transport in matter. In a way this was really what the instrument was all about. To make the measurements of that happening in deep space with the radiation fields that we're going to have to contend with when we go back to the Moon or Mars or anywhere, asteroids, anywhere without an atmosphere.

These modelers I think really became in a way essential for the understanding of the data. The datasets were multidimensional and so complex. This is precisely what the modelers deal with every day when they create a model and have a physical description in the computer of how particles transfer through material. They generate datasets that are enormous in volume, just like our dataset in reality, and they have to contend with all of the same issues that a dataset based on actual measurements present to a scientist.

We found that we were able to bootstrap our understanding by interrogating the models in parallel with looking at the data. That was really interesting to me. Just our ability to model in exquisite detail all the ins and outs of this rather complex geometry of our telescope, and then be able to go into the model and say, "Okay, I see that feature. That is because that process is happening. If I turn that off in the code it disappears."

You could really very clearly distinguish all the interesting little fingerprints if you will when you looked at the data. Traces and shapes and various arcs and curves, and how they related to the various aspects of the instrument and also aspects of the environment that we were measuring. That was very cool.

I think if we hadn't had that kind of team, I think there would have been a lot longer of head-scratching and inefficiency. Eventually those modelers would have discovered us, and we would have discovered them and we would have made progress. But they were really integrated with us right from the get-go.

JOHNSON: As we talked about earlier, it was intended to be an exploration mission and then transitioned to science after about a year. It's been renewed several times or extended several times. But because it was still working in 2012, I read that you were able to observe a coronal mass ejection that hadn't been seen since 2005 and actually measure that. Talk about that opportunity to do that.

SPENCE: Yes. As we went through the early parts of the mission, we were able to, and really up until present we have now had the really remarkable opportunity to watch the Sun go through an entire solar cycle. From the depths of a solar minimum, and when the Sun is inactive that means your galactic cosmic rays are very intense because partly the Sun when it's quiet doesn't present much of a force to inhibit access of galactic cosmic rays to the inner part of the solar system. Then as the Sun cranks up it starts unleashing all of this material and high-speed streams, if you will, and they push that stuff away. It has a harder time getting in. However, when the Sun gets active it, itself, produces very energetic particles. These are the solar protons.

One of our colleagues was the principal investigator of the LEND [Lunar Exploration Neutron Detector] instrument[2], the neutron detector, Igor Mitrofanov from Russia. Somebody asked him, "Which is worse? The galactic cosmic rays that you get high intensity at solar minimum, or the solar protons at solar maximum?" His answer was beautiful. It was, "Both are worse." I've always loved that response. He's right, they're both worse in their own way.

Solar protons, you can more or less shield against those for the most part. They're episodic. You just have to be in a well-shielded place. But they're hard to predict. Galactic cosmic rays are always there, a little bit easier to predict. They vary over the course of the solar cycle by a relatively small number, but they're really hard to shield against because they're really energetic. They're different. They're different in different ways. You have to contend with them.

[2] LEND creates high resolution hydrogen distribution maps and provides information about the lunar radiation environment. It is used to search for evidence of water ice on the Moon's surface and provides measurements useful for future human exploration.

We were fortunate at the early part of the mission to watch the Sun turn on and go from that quiescent state to a more active one and be able to, at the Moon, see what the effects of those solar protons would be. That one particular event we were able to, along with LRO and other missions that were measuring the Sun and the particle environment, piece together a really interesting story about how the magnetic fields of the Sun connect up with different objects. As particles stream away you can almost get—I think we use the term curveball. The particles will follow the direction of the interplanetary magnetic field.

We were able to with this particular study show that pretty convincingly and have been doing that ever since. We went through a whole cycle. The Sun was quiet again, and now it's waking up. We're back to almost like we were at the beginning of the mission. That's actually really exciting for ESM5, the Extended Science Mission 5[3] I think we're in now. I've lost track as we keep going on. It's been really great.

We're now able to see how reproducible, was the last solar minimum the same as this one, and what will the rise to the next solar maximum look like for the particle environments. We do know from other records that that can be quite variable. Now we'll be able to do it with this particle instrument like it's never been done before, which is great, because that will, I think, help us understand going forward what the risks are for human exploration in the longer term.

JOHNSON: Do you know if there's anything that you've found as far as risk for human exploration and with that plastic that simulates human flesh? Do you know if anything that you've found with

[3] The Lunar Reconnaissance Orbiter Extended Science Mission 5 (ESM5) takes place from Sept. 2022 to Oct. 2025 during a period of unprecedented activity on and around the Moon including the return of humans to the Moon for the first time since Apollo.

CRaTER has already been applied as far as going forward for the Artemis missions and going forward for other exploration?

SPENCE: Certainly our measurements have been well incorporated into the community. We had one fairly recent set of papers that we did with colleagues at NASA Langley [Research Center, Hampton, Virginia] who again worry about things like what NASA calls permissible mission duration that is tied to how long can a mission last in light of different radiation environments. It varies as a function of gender; it varies as a function of astronaut age and some accumulated total risk.

We were able to use I think for the first time our full knowledge that comes from this particular instrument to make estimates of that permissible mission duration as a function of solar cycle for instance. I think that has helped put a set of boundary markers on what that looks like and how quickly let's say you have to get to Mars. The Moon is really a nonissue. It's close. You can get there quickly. You can get under shielding. It's potentially long transits to Mars where our data would suggest that you might start running the risk of violating your permissible mission duration. It's hard to say, but I know that teams are already thinking about faster ways to get to Mars in part just to mitigate against that particular risk. So yes, I think that first year of measurements that were exploration-minded really have become much more than that. It's become a solar cycle worth of exploration and science measurements. But that exploration aspect, I think we've never underplayed that. That is still at the core of the mission in different ways for different instruments.

For the imagers it's making better and more comprehensive maps. For us it's understanding the environment over a cycle. But all of those dimensions really add to our ability to safely send humans into deep space.

JOHNSON: As PI and working on an instrument like this, as you said you were inspired early on when you were younger and you had parents that exposed you to things that helped build that interest that you had. Let's talk about education and outreach as far as this type of work. How important do you think education and outreach, especially for a program like Discovery that is so heavily involved with the science community, how important do you think that is?

SPENCE: I think it's huge. I think there are so many bright lights that kids see these days. Some of those lights are maybe bright but not a whole lot of content. You're drawn over to a corner that looks great and maybe feels great but in the long run maybe isn't so fulfilling.

I think the kind of outreach that NASA does in particular provides that bright light that has a lot of content. I think making sure that whether a young person goes into a STEM [Science, Technology, Engineering, Math] career or not, just being mindful of what science is and how it works is good for everybody. That really doesn't stop at children. I think keeping adults apprised and outreach to that community is important too. We've really had some really great experiences with our outreach, the CRaTER team.

One of my team members in particular, Andrew Jordan, another former Ph.D. student of mine who's a research scientist, we worked to create a do-it-yourself cloud chamber that you can use to actually see cosmic rays on your desktop at home. It's a little bit more than at your home. You need some dry ice and you need some materials, but it's the kind of thing you can get together with a school group or so and make one of these. It produces this environment in a container that cosmic rays, which are around us on Earth all the time, they're passing through each of our bodies now, about 1 per square centimeter per second, so they're here with us. Fortunately they're well muted and moderated by the Earth's atmosphere and magnetic field. At any rate you can actually see the trail that these form in your do-it-yourself little cloud chamber.

It was our way of trying to bring to light something that's inherently invisible. It's a little bit scary too to think that's happening right now. Andrew is also a very good artist and so he made some cartoons of this that were really appealing to kids of all ages. They appeal to me too. I consider myself a kid. We've done a lot with that.

One of our really popular outreach events on LRO is the day at Fenway Park. We'll have a day where the LRO team and then a member of the instrument teams from the Boston area will descend upon Fenway Park during a Red Sox game, and before that have a big LRO day where all kinds of different activities are going on. In fact one of the project team members, the first event that we ever had, she played the harp, played the national anthem, and became the first person to play the national anthem on a harp at a baseball game ever or something like that. I never knew she played the harp and it was kind of cool.

Being able to connect people with the Moon, it's so easy. You can see the Moon. It's one of the easier things I think to talk about in astronomy with people. It's visceral. You can see it, can almost touch it. It shines a great light at times. Sometimes it's gone. Why? A lot of questions you can pose and think through with people. It's also kind of a romantic thing. I think there are many dimensions of the outreach that have worked. I think even just aesthetically the appreciation of nature and such. People I think really like what NASA does. It's exciting, and they want to be a part of that exploration.

Like I said, I think people are natural explorers. Even as some of us sit in our rooms during the pandemic and are confined to four walls, maybe even especially then, using NASA as a means to sort of really get out there if you will and feel like you're exploring. I think it has an important role to play beyond just doing the basic science. I think that engagement is pretty key.

JOHNSON: Let's talk about some of the lessons learned from your experience with CRaTER and on LRO; some of the things that you think are important going forward for NASA on these type of Discovery missions, with those instruments, or even things that you've learned that you've applied to other things you've worked on.

SPENCE: After LRO I've had a number of really great opportunities to lead other teams. I would say probably my greatest lesson carried forward is just the importance of a team and building a team that is functional and fun. I've been blessed recently with the selection of my latest mission called HelioSwarm[4]. It's a heliophysics MIDEX [Medium-Class Explorer] mission. Another really great team. A team that only has a few parts that really are carried forward from the last mission I was involved in, Van Allen Probes[5]. That's made it fun, starting with a different science topic and a different group of people.

What I really like is I like a team that has dynamic tension. When you have a scientific question it's great to have people with different viewpoints of that because that really allows you to, it forces you to consider as many different possibilities and keep open-minded. Ultimately let's

[4] The HelioSwarm mission is a constellation or "swarm" of nine spacecraft that will capture the first multiscale in-space measurements of fluctuations in the magnetic field and motions of the solar wind known as solar wind turbulence.
[5] The Van Allen Probes studied two extreme and dynamic regions of space known as the Van Allen Radiation Belts that surround Earth

let the data speak. What did we measure? What do we have to measure to differentiate between your idea and your idea or your idea or maybe none of you are right, we got something new.

I think having a team that has that sort of ability to create those dynamic tension moments, which can be a little bit intense, because people have strong passions one way or the other, but also to keep the eye on the prize and make sure people don't take things personally. It's an idea about how the universe works. It's not your idea. It's our—we're going to test it. Keeping teams moving toward that prize of let's answer the question. It's not who is right. Let's answer the question.

That can be really hard sometimes but it's also quite rewarding. Like I said, I've really been blessed with some great colleagues who get behind that kind of approach. Honestly, that's what gets you through the trials and tribulations as I mentioned before of a flight program. There are going to be days when things just go wrong, where you discover something that you've done months ago which was the right decision at the time like oh, boy, we didn't consider that.

I guess another lesson learned is assume every decision you make now may come back to haunt you. Think through all the different dimensions and that classic system engineering problem; I solve one problem over here, but by the way I've just created ten more problems over here. I love puzzles so I think that is what this is all about. How do you solve a puzzle that didn't come in a box so you don't know what the picture looks like? There's a whole bunch of pieces missing. Sometimes the shapes change as you hold the piece. It's like the trickiest puzzle but it's really cool. It's fun when it all comes together.

I think in terms of lessons learned for NASA and the Agency and humanity is maybe space is a harsh place but it's manageable. I think we more or less knew that in the Apollo era. I'm not going to say that CRaTER and LRO have overturned our thinking in dramatic ways in that regard.

Not at all. But we've certainly quantified that better than ever before in a way that is actionable. You should never sail out into the unknown until you know what the environment looks like. We've produced, if you will, the weather map for future mariners to use to get from place A to place B over some rough seas. I think that's a great legacy for the mission in general, not just CRaTER, but I think the whole mission, which is pretty exciting.

JOHNSON: Are there any decisions that you made while working on CRaTER that you might not choose to make again on another project?

SPENCE: That's a good one. I wouldn't say any fundamentally big ones. I really have to credit the mentors who've influenced me along my path, who I think for the most part transferred their collective wisdom and helped me not do too many completely stupid things on my own. We all stand on the shoulder of giants. I'm grateful for those who like I said were patient and gracious enough to help me along the way.

I think we always learn how to do things better. I don't know if it's wisdom of age or just getting tired with age or something. But I think I find that I don't overreact to situations like I did. Sometimes you can spend a lot of time and energy with every little thing that comes up. A lot of times that little thing really was a little thing. It wasn't worth overreacting to. That said, you also have to act. You can't just sit back. There is a happy medium there. Maybe there's a little bit of telepathy required. I don't know. Trying to figure out what's the real signal in all that noise sometimes.

JOHNSON: Let's just touch briefly on changes in technology since CRaTER launched on LRO. Technology changes daily if not hourly it seems like nowadays. But you mentioned your colleague that had an app on his phone that he created that he could actually see the changes in temperature. Have you been able to take advantage or has the team been able to take advantage of those changes in technology that they can't change on the instrument but maybe with the data that's being sent back and being able to use it more effectively?

SPENCE: Let me start with the technology because we actually have done that, and we continue to do it.

The CRaTER instrument, most of it was dedicated to taking the outputs of our six detectors and turning it into something that was a data product. That volume probably was two-thirds or so of the entire instrument volume. It took up several big electronic boards. The very next mission that we worked on with essentially parts of the same team, over the course of time, even in the short time between LRO's development and the development of the Van Allen Probes mission, which started Radiation Belt Storm Probes, there had been some breakthroughs in large part because another big mission, the Magnetospheric Multiscale mission[6], had invested in miniaturization of some of the electronics into ASICs (Application Specific Integrated Circuit) and so effectively we were able to essentially take that big volume and shrink it down to a single chip.

One lesson learned is if we were to fly a new CRaTER, a grandchild of CRaTER or something like that, it could be a much smaller instrument and be just as functional if not more

[6] Magnetospheric Multiscale mission investigates how the Sun's and Earth's magnetic fields connect and disconnect, explosively transferring energy from one to the other in a process that is important at the Sun, other planets, and everywhere in the universe, known as magnetic reconnection.

functional. Mass converts into dollars, and so it would be cheaper. Even in the short run of a decade technology has really allowed us to do a lot more with the resources we have and enabled science that even at the beginning of the Van Allen Probes mission, when we proposed some of these instruments, they weren't as capable on paper in design at proposal as they were as delivery and as operated. Those are really exciting moments when you realize wow, okay, we can really make a much better instrument, as reliable, maybe more reliable, cheaper, more functional. Cool, let's do that.

That's something that we always strive to. The tricky thing being of course that NASA doesn't like risk, and anything new you do is inherently risky. Again there's that balance between let's be zero risk and fly what we already flew, or at the other end we don't know if this thing is going to work at all, everything's brand-new. Then there's that happy medium of how do we assure that the new stuff we're doing is advanced enough and so forth. I think that process works pretty well and has worked pretty well recently. That's good news.

In terms of how to look at data more effectively, I think we're really now starting to get into that with this latest mission that I mentioned, HelioSwarm. That's a mission that's going to have nine spacecraft operating together as a hive mind. These nine spacecraft communicate with the central spacecraft and then those data come down. Again we're going to have a huge volume of data.

The worst thing we could imagine is a scientist at the end of the day making nine plots of wiggles on a page and then trying to figure out what that means. This mission inherently considers all of the data together to be the data product. How do you put that data together in a way that a mere mortal can ingest and understand? We're devising visualization techniques using some of the more modern approaches where we're thinking about how do you use artificial intelligence to mine the data.

I think we're at a little bit of a tipping point now in the discipline of borrowing some of these approaches that have been used for a bit longer in disciplines that have created these more complex datasets and so forth, medical imaging being one of them. We benefit from all of that past history that they brought. But I think we're going to find that our data are all as complicated, if not more complicated, because we're not doing a regular experiment in space in the sense that it's reproducible. We put spacecraft out there and nature comes at us. It's always a little different every time. I think that's an extra challenge to understanding what we're seeing. Finding that repeatability from the natural record that comes at us, then figuring out what are the tools we need to even be able to get to that point where we're finding that repeatability. I think it's a growing part of what we do.

I was telling a junior colleague that just in my career we've gone from missions that would generate data, those data would be processed from the spacecraft, it might take weeks or months, and then you'd get delivered a magnetic tape of just your data from that mission that you would have to read out and you'd make a plot. The way people did analysis back in the dark ages was people would say, "Okay, on your plot make every inch 1 hour, and then plot what you have." Then we'd all show up together and get a light table and put plots on top of each other to say, "Well, mine wiggled up and yours wiggled down. Okay, that must mean something."

Now you take your smartphone and you can pull up data that have all been incorporated. It's really been transformational in how we do what we do. The accessibility of that to not just the groups that built the instrument and not just the science community but really literally to the world. It's amazing. It's been really fun to watch and gratifying to see that change actually.

JOHNSON: What do you think the impact on the science community has been from this Discovery Program's missions and this model of getting things up and moving fast? Also the missions being PI-led instead of traditional NASA missions?

SPENCE: I think the success of the PI-led approach is really important. Not to say that community consensus missions can be equal and important and effective. But I think there's a place for that PI-led mission where an idea that's coming out of the community that maybe didn't come out of groupthink, I think this program really gives flight to those kind of ideas that are meritorious and win the day through the competitive process and peer review. Which is really really great, I think a hallmark of really good science.

I think the outcome of these missions has been really quite remarkable when you look at the missions that have been accomplished over the years. I guess 30 years now. It's hard to imagine. Just the discoveries that have happened, and what better word for the program. We don't know what's out there and we're going to send instruments that will give us that basic viewpoint. Or we kind of know what's out there and we're really going to send instruments that are going to figure it out with spacecraft that can do remarkable things. It's been a great program.

JOHNSON: Is there anything we haven't talked about that you wanted to mention before I let you go?

JOHNSON: I think, Sandra, that was fun. You caused me to remember some things that were quite fun, so I appreciate the opportunity to chat with you.

JOHNSON: Good. I'm glad.

[End of interview]