Jon Jenkins

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Interviewer

Q: Okay, here we go. I'm talking to Jon Jenkins of the SETI Institute virtually. Today is the 18th of June, 2024.

So, Jon, tell me a little bit about yourself. Where were you born? How were you educated?

Jenkins: Right. So I was born in Merritt Island, Florida. My parents both worked at Kennedy Space Center. My dad was an aeronautical engineer who started working for NASA in the late sixties, working on advanced missiles for the Army and then X-10, X-15, and then the early missile program. Then he worked Mercury, Gemini and Apollo and the Shuttle, made forays along the way to other states, but we always moved back to Florida because he always wanted to work in the space program.

My mom was a legal secretary, and they met on a blind date while they were both employees of Kennedy Space Center, so I kind of grew up in the shadow of the Vehicle Assembly Building. I was always interested in space science, read a lot of science fiction growing up, watched a lot of the launches, including Apollo.

Then I went to Georgia Tech on a scholarship after graduating from Merritt Island High School. In 1985, I was a little bit falling behind on my rent when I was a junior, and I had two roommates who were a year ahead of me in school and they'd met this electromagnetics professor who was doing research for NASA, and they introduced us and I was able to pay my rent [laughs] with the research assistantship that I picked up at that time as an undergraduate research assistant for him. Dr. Paul Steffes did planetary atmospheres research and we simulated planetary atmospheres in the lab and studied the microwave and millimeter wave properties of trace constituent gases in Jupiter's atmosphere, for example, and Venus.

Then in grad school, I started working on remote sensing of planetary atmospheres through the radio occultation method, where you watch what happens to the carrier signal on a radio transponder on a spacecraft as it goes behind a planet like Venus, and as the spacecraft goes behind, the radio waves kind of slices down through the atmosphere of the planet, and you can then invert that data to learn about physical properties of the atmosphere, like the temperature and pressure, for example, as a function of the height in the atmosphere.

In my case, my dissertation was on the abundance of sulfuric acid vapor below the main cloud layer, and I used data from missions like Pioneer Venus Orbiter, which was still flying when I was in grad school, and also Magellan. Because Magellan spacecraft was a biostatic radar experiment, it originally did not have a radio science component, but after one of the two identical and redundant tape recorders failed early in the mission, they decided to do some experiments. My advisor, Paul Steffes, proposed, "Hey, let's do some radio occultations of Venus with Magellan," and that was fantastic, because Magellan had a spare Voyager antenna, so it had a lot of power and we could see far deeper in the atmosphere, in fact, down to the theoretical minimum that you could actually see using this technique at about 32 kilometers in atmosphere, and that was phenomenal.

I came out to Ames Research Center on the Pioneer Venus Guest Investigator Program after I graduated in '92, continued the work, and then by 1994 [laughs], both Magellan and

Pioneer Venus were no more. I joined several Venus proposals. I worked with Kevin Baines, who had the Venus Environmental Satellite mission that was proposed, I think about four more times to Discovery.

And at the same time when I started working on Pioneer Venus, I met this very interesting and wonderful man named Bill Borucki. He was studying lightning on Venus. And first couple of years out at Ames, I'd met this astronomer Laurance Doyle, who also worked at SETI Institute, like myself, and he was interested in finding signatures of transiting exoplanets, and he and an international team of astronomers were focused on the CM Drac system. This was at the time the smallest known eclipsing binary system, and so one would expect if planets formed in eclipsing binary systems like this, that they would be in the same plane as the orbit of the stars, and therefore we would have a really good chance of seeing any reasonably-sized exoplanets that were orbiting these two stars.

So I designed detection algorithms for that group, and that work came to the attention of Bill Borucki, who then invited me to join the Kepler team. Actually, it was called FRESIP at that time, the Frequency of Earth-Sized Inner Planets. In fact, in my journal I can see in my first notes of the first science team meeting that we still were calling it FRESIP, and that was the year 1995, when we decided to change the name to Kepler. And I was hooked, so I worked for Bill Borucki basically doing laboratory-based demonstrations that we could reach the instrumental precision that we needed in the lab, and I also worked on detection algorithms and studying the impact of solar-like variability on our sensitivity to transiting planets like Earth. So I became the co-investigator for data analysis for Kepler and then led the design, development, and operations of the Science Operations Center for Kepler on the science side.

Q: Well, fantastic. One of my question was, what interested you in what amounts to signal processing, since you do signal processing for astronomy, but fundamentally you're pulling signals out of noise. What interested you about that?

Jenkins: Well, you know, at Georgia Tech I became an electrical engineer, was studying electrical engineering, and signal processing was one of the major disciplines, and I loved the math, I loved the concept. While I studied circuits and systems and control theory and electromagnetics, really signal processing was my passion, and so my work on studying atmospheres of other planets, I actually applied advanced digital processing techniques to more reliably pull those signals out of the noise. Anytime we're observing a system, we have noise in our instrumentation, and you're always fighting these fundamental limitations to your knowledge, but the most interesting ones tend not to be the fundamental limiting ones, but the instrumental systematics that fundamentally limit you if you can't learn enough about them, and so that proved to be the case on Kepler as well.

When we watched, we thought, based on the predicted performance of the spacecraft and the instrument, that we would be pointing-dominated; i.e., that is that we would be principally limited in our instrumental precision by the performance of the pointing system and how it behaved, and that absolutely proved not to be the case at all. It proved to be the case that it was actually the world's most sensitive thermometer that we'd launched into space at that time, and so even small changes in the thermal state of the instrument, the telescope and the spacecraft could cause perturbations to the measurements we were making. So, for example, early in the mission, we saw a sawtooth signature on many, many stars' light curves, and it turned out that there was a heater being actuated by a thermostat to control the temperature of the reaction wheel assembly. This set of parts was getting shaded, so it was no longer in the sun, it was cooling down, so this heater had to turn on to keep it nice and warm and happy, but that small change in temperature of this component on the spacecraft bus was enough to change the shape of the telescope enough that we could actually see a change in the position of the stars, and that was something that we had to deal with. Now, the engineers actually tightened up the deadband, and they tremendously reduced the amplitude of the effect, but it didn't completely go away.

And likewise, even other heaters onboard would change the shape of the telescope. The sun is rotating around the barrel by about 1 degree per day, because we're in orbit about the Sun and we're pointed in the same direction, and that would change the shape of the telescope. So, in fact, we could see up to plus or minus 1 percent variations in the apparent brightness of the stars simply due to the changing orientation of the Sun on the barrel of the telescope.

So to put that in perspective, the signatures of Earth-sized planets we're looking for are basically 1 part in 10,000, so 100th of 100. So some of the instrumental signatures that we had to fight against were 100 times stronger than the signals of interest to us, and I'd say that with respect to my interest in signal processing and remote sensing, these are the kinds of skills that I was fortunate enough to learn at Georgia Tech and then to extend once I got to Ames to help us deal with things like solar variability and stellar variability, for example.

Q: That's amazing. I knew you had to pull very small signals, and it amazes me that that could be done. Riley Duren had told me that there was something in the CCD electronics that also caused thermal changes and had to be corrected for. It's just amazing.

Jenkins: Right. Yes, we had some unintended features. There were some operational amplifiers being operated as unity gain buffers in the analog electronics, and about half a dozen of these parts, because they were being operated at the upper edge of their rated speed. A lot of op amps don't like being operated at unity gain. They want to be operated at a much higher gain like 100 or so, and you should de-rate the speed at which you operate these parts. Most of the parts were actually okay, but half a dozen or so would then go into oscillation, so we had this gigahertz-rate oscillations in electronics, and if those slewed through an integer multiple of the readout rate of a science CCD, we would see these rolling band structures that would move through the images and cause transit-like features. In fact, those created a huge pileup of transit-like events that we found near 372 days, the orbital period of the spacecraft, and so that was one of the most—it led to a good deal of consternation, because that's the period that is of most interest to us. Around 365 days, the orbit of a habitable zone, Earth-like, the inner edge is at 365 days around a Sun-like star. So we had a lot of work to do once we launched and saw the instrument in all its glory. [laughs]

Q: That's just amazing. Thank you. So you came on to the project, I guess at the second version of the proposal, still FRESIP, so tell me what—I talked to Bill Borucki about this too. Tell me what evolves in the proposal process. How does the design team structure, etc., change in response to the criticism from the selection committees?

Jenkins: Right. So I'd say that that was one of Bill Borucki's geniuses, in that he was very good at listening to the constructive criticism that we received. Some of it wasn't so constructive in intent. I think that Bill took it very seriously, and so I'd say that, you know, in the first several years after I joined the mission, we received a lot more rotten tomatoes in terms of the comments we received at conferences. In fact, the first conference I went to of American Astronomical Society was a meeting in 1996 on the Big Island on Hawaii, and there were no exoplanet sessions. My poster, which was about the CM Drac work, because that was what I could present at that time, was put into a "miscellaneous" poster session, where I ended up right next to a "Face on Mars" poster by a David Hoagland acolyte. [laughter] That tells you how fringe exoplanets were thirty years ago, nothing like today. Today you can go to conferences, and the last Astronomical Society meeting I went to would have as many as four, [or] so parallel sessions on exoplanets. So you can't today attend all the sessions and see all the papers on exoplanets because it's one of the largest and most energetic fields in astronomy and astrophysics today, as opposed to those early days when we were put into a corner, we were viewed as very much on the fringe, and quite rightly, you know.

So with Bill's genius, he basically was able to recruit a large team of experts who he recruited specifically to solve the problems that Kepler had, and he did an amazing job of that. So I worked with a lot of wonderful and brilliant people. Ted Dunham, expert on optics and electronics, is one of those; Ron Gilliland is another; Tim Brown; just so many people that were on our science team. In fact, in the last Discovery proposal, I joked with Bill because Bill had this way of, basically, he listened to people, he understood their problems that they were stating, and then he recruited people to work on those problems. In fact, sometimes he recruited the people who said, "Hey, this is going to be a problem" to his team. And we won over a lot of people that were skeptics at first, in fact, so that I joked with him, "Bill, if you keep on recruiting people from the community, there'll be nobody on the review panel who wants to do exoplanets." [laughs] He did such an amazing job in that regard.

So I'd say that the sensitivity of the CCDs was the big issue, and in fact, there was a key enabling opportunity that came into being in the mid-nineties, and that was backside-illuminated CCDs, charge-coupled devices, these light-sensitive chips that we have in all of our cell phones that we use to take pictures and make photos and videos.

Earlier, we had frontside-illuminated CCDs, and by thinning the backside of the CCDs so now you were illuminating the sensitive portion of the CCD directly rather than having the light have to travel through the gate structure that's used to read out the CCD, it essentially doubled the quantum efficiency of the device, and that's like doubling the size of the aperture by area. And, of course, when you're launching something into space, the size and the mass matter a lot, and so that was key enabling opportunity, without which I don't think we would have been selected.

The other was that we did have to demonstrate that we could deal with stellar variability, and that was my work, so I studied the behavior of the Sun using data from ACRIM at first, but then the best data I had, was able to acquire in those days was the SOHO spacecraft. It was a joint ESA-NASA mission. I was able to develop algorithms to deal with the fact that the stellar variability that we see is not a white-noise process. It has memory, it has a lot more power at long time scales, so when you're thinking about the problem of detecting transits of small planets orbiting the Sun and transiting the Sun, a lot of people say, "Well, what about starspots? What about sunspots?"

And the fact is that you can solve this problem by noting that there's a big difference in the timescale of these different phenomena. So, for example, the Sun rotates with an average rotation period of about twenty-seven days, and so that means that if a spot crosses the face of the Sun, it takes it about two weeks to do so, but a planet takes anywhere between typically an hour to thirteen hours in the case of the central transit of an Earth-sized planet orbiting at an Earth-sized distance a Sun-size star, and so it's kind of like listening to a marching band play John Philip Sousa's "Stars and Stripes Forever." Doesn't matter how loud the trombones and the tubas are playing, you can still hear the piccolo solo quite easily, because your ear naturally is able to filter out the pitch of the piccolos, which is well above that of the tubas and the trombones. So for us, this operates the same way as the signature from planets is on a much smaller timescale than the typical signature of star spots, at least for Sun-like stars, which are kind of medium-aged and they're rotating relatively slowly.

Q: So, a data point of one. [laughter]

Jenkins: It is, it is! So, yes. In fact, I'd say that the most fun I had with Kepler was all the things that we discovered that we didn't intend to discover. We had no idea. So when we were putting these proposals together, all of our yield predictions were based on the premise that every single solar system or planetary system that we would find would actually be the same as our own solar system, and that was completely wrong [laughter], completely wrong. Nature is much more imaginative than humans are, and I think that's one of the great joys and pleasures of seeing all these missions like James Webb launch. Every time that you create an instrument and launch into space that's much more sensitive than anything in its class before, you find things you had no idea were there to find, and so you push back the boundaries, push back the veil of ignorance to reveal things that nobody had any idea were there, and that's a lot of fun.

So, for example, I often got called by people saying, "Hey, we found this really strange signal. Can you tell us whether it's an instrumental artifact or not?" And one of those was brought to my attention by Saul Rappaport. He's a retired professor at MIT. He said, "Hey, Jon, we found this signal that you found, actually, and we're trying to interpret it. We think it's a disintegrating sub-Mercury-sized planet." This is the signature from KIC 12557548 (Kepler-1520). This is the first known example of a disintegrating planet. In fact, this is a planet that's smaller than Mercury. We found that every time we ran my pipeline, the problem was that it showed transits every sixteen hours most of the time, but the depth of the transit changed from transit to transit, from orbit to orbit. So the astronomers on our team and astrophysicists ignored it. "It can't be a planet, because planets can't change their size that rapidly over time, of course."

What it proved to be, though—and this was quite controversial at first—is an example of a small planet, a stripped core that's orbiting in a sixteen-hour period about a K star, and the K star is hot enough and bright enough so it can actually photoevaporate the surface of this planet, but it's not too hot to prohibit the formation of a comet-like tail. So the material evaporates, it blows off the planet, but then it cools and condenses and forms a comet-like tail. So it's this comet-like tail, this dust that we're seeing, not the planet itself. We're seeing the dust trail cross in front of the star. It turns out that the star is spotted, and the amount of photoevaporation that goes on depends on how hot the planet is, and that's dependent upon how bright the star is. When you have a lot of spots facing you, it's cooler. When they're not there, it's brighter. So actually it's the spots on the star modulating the brightness of the star from the planet's point of view that's modulating the evaporation. So that means that the comet tail is growing and shrinking, depending on how much heat and radiation the planet's receiving at any given time, and that explains why the signature was so variable.

But a lot of senior members on our science team were quite skeptical about it. We kind of soft-pedaled it. It wasn't till several years later when people went out and tried to make observations to prove that their pet theory as to why this was not a planet, all of those failed, and then a team actually made observations that actually showed that the brightness of the star from the planet's point of view was directly correlated with the strength of the transits, and that was the last nail in the coffin of that interpretation.

So we only have, I think, one or two other candidates like that. One of the things that Kepler did late in the mission was that we were able to find visible light signatures of transiting exoplanets, so, again, brought to my attention by Saul Rappaport, who worked with a number of people, amateur astronomers who were part of the Planet Hunters consortium on Zooniverse. These are amateurs, citizen scientists, who basically viewed Kepler-like curves and clicked the button "We think this is a planet. We think there's something interesting here." So it's amazing to me that the citizen scientists were much more curious about this object, KIC 12557548b, than the astronomers and astrophysicists on our team, but, of course, they were much more interested in the planets, not the things that kind of look like planets but weren't. In this case, they were wrong. It really is a planet, but a very special kind.

Q: It seems like quite an act of imagination to take your light curve and turn it into the disintegrating planet around a star that you just described.

Jenkins: Oh, absolutely, absolutely, and that was not my forte or my contribution. [laughs] Fortunately, we had astronomers and astrophysicists that could build models that predicted that this was what was happening and showed that it described accurately what was going on, and we had follow-up observations, were able to exclude other potential sources of the signal we were looking for.

Q: Right. I would imagine someone would be interested in doing follow-up observations with one of the ground telescopes.

Jenkins: Oh, absolutely. That's right. That's right. So astronomy and astrophysics, we usually have two kinds of people: there are observers and there are theorists. So the theorists wait until there's interesting and new data that can't be explained, and they get very excited, they work on it, and it's a strong partnership between the theorists and the observers in order to make many of these discoveries. Oftentimes, from an observer's point of view, we see something interesting, we don't know what it is, and we need the theorists to come in and help us out.

Q: Fair enough. Let's see. We should talk about, back in the proposal process and the iterations, at one point, you develop what you call the Vulcan prototype—

Jenkins: Right.

Q: —which I guess was at Lick Observatory?

Jenkins: It was.

Q: Tell me that story.

Jenkins: Right. Well, one of the early criticisms we got was that we had not demonstrated that we could perform differential photometry on tens of thousands of stars, and so Bill Borucki had this idea, "Hey, let's install a small telescope with a fairly wide field of view up at Lick Observatory." This was in the wake of the discovery of 51 Peg b. These are hot Jupiters, and that was hotly contested at the time for several years. But we should be able to find them.

So he had another NASA civil servant, Tim Castellano, put together and build a small telescope, and we operated it for several years, and then we upgraded the telescope to have a much larger-format CCD and much larger optics. In fact, a kind of amusing story was that Bill was very interested in getting this much larger optic. It was a lens that had been on a spy plane, and it was being offered on auction on eBay, and NASA can't bid on eBay auctions, but contractors can. [laughter] And so my friend Doug Caldwell, who was the Kepler instrument scientist, and I bid on eBay for this lens. We won. [laughs] And that's how we got the final lens that we used on the Vulcan telescope, or camera.

One of my jobs was to basically design and build the science pipeline, and so I wrote a package that was GUI-driven, allowed an operator to sit down once the data had been collected and process it from the first image calibrations that you do. We had issues with the telescope mount and the tracking, and so I had to be a little bit inventive in how I was able to register the stars' locations and then reconstruct the pointing so that we could then predict where each target star was in each frame. That was a lot of fun, quite challenging.

Then I wrote the code that removed the instrumental signatures from the light curves and then performed the detection of the transit-like signatures. Now, fortune was that we never detected outright or never discovered a transiting exoplanet. It seemed that all the ones that were in the fields of view we were looking at were just off the field of view we were looking at unless we knew of one and pointed the telescope at it, but we did demonstrate that we could perform ground-based CCD photometry of 10,000 or more stars simultaneously and attain precision limits that were pretty close to the theoretical minimum, given the conditions that we were observing under. So that was a project.

Then in the next go-round, they said, "Well, okay, so you've demonstrated that you can do photometry on tens of thousands of stars, so we can believe that you could be able to scale this up to 100,000 or more stars. Okay. But you haven't demonstrated that Kepler can achieve an instrumental precision of 10 parts per million in six and a half hours." So that was the next tentpole to knock down.

So we did get money from Headquarters, I think about—Bill Borucki would know better. I think it was about half a million dollars or so, and then we got money from Ames Research Center. Ball Aerospace kicked in money for the Kepler Tech Demo. This was a high-fidelity simulation of the Kepler photometer. We set it up in the basement of the Science Building in 245 at Ames, and there were several other people who worked on it. But we were able to demonstrate that we could achieve instrumental precision of 10 parts per million, and we simulated everything we could simulate in hardware. For example, we had PZTs that we used to control the pointing of the systems that we would actually jitter the images of the stars around. David Koch, our deputy principal investigator, designed this system. He had this genius idea that, "Hey, let's use a laser mill holes, rectangular holes in a stainless steel plate, and then we can shine a light through integrating spheres on this plate and illuminate and focus it on the CCDs, and that would be our star field."

So we had something like 1,600 holes milled in the star plate, and on a couple hundred of them we put these thin ribbon wires across them and put a milliamp or so of current through the wire, and then the wire would expand by about one atom and would be able to cause a change in the brightness that was the same level as you would expect from an Earth-sized transiting planet orbiting the Sun. So we demonstrated that we could achieve that, the instrumental precision, but we also demonstrated that we could actually detect signatures of Earth-sized planets using that system. So that was also a very important ingredient, I believe, in our final selection. That was the previous cycle.

And the third thing that had to happen technologically besides algorithms that I developed, also having computers that were fast enough and big enough for us to do this work, we had the CCD backside-illuminated CCDs came into being, we also had to have planets to find, back in the good ol' days when we were detecting these hot Jupiters that nobody expected to be there. We're still trying to answering the question how did they get there. There are a couple of competing theories for how Jupiters form and migrate inwards, and we're still puzzling that out, and the TESS mission is actually helping out a lot there. But the other thing we had to do was to know that there were planets to find. There was a lot of skepticism. Some people thought that the hot Jupiters were probably substellar bodies that were much more like stellar embryos than they were like planets. In fact, the CEO, David Black, of SETI Institute was one of those skeptics. But the thing that had to happen was that once you detect about twenty hot Jupiters, because each of them has a 10 percent chance of transiting or crossing the star from our point of view, you would expect at least one of them to do so, and that happened with HD 209458 b that was discovered in 2001 to be transiting. Dave Charbonneau and Greg Henry discovered that simultaneously. The transits had been actually detected in radial velocity first, like all the planets up to that point that were detected around main sequence stars, but now these were real planets and we had planets to find.

We still faced stiff winds, so Bill Borucki may have talked to you about this, but when we were selected in December of 2021 at the end of that cycle, early in 2022, they said, "Hey, good news. You're selected, but we're going to have to delay you by at least one year before we can give you any funding."

And Bill said, "Hey, I've got people on soft money."

So they gave us, I think, $2 million that year just to make sure we could keep everybody going and get started. And they said, "Oh, and Ames Research Center won't be allowed to manage this mission. Ames is in charge of small missions, and this is not a small mission, so you need to choose either Goddard or JPL to manage the mission."

We ended up going with JPL, and that brought down a lot of risk. In fact, that, I think, really helped us out, because, among other things, JPL had a really deep bench of technical talent that could participate on the reviews, could take a really good, hard look at things. Riley Duren was a major asset as our systems engineer for the project, and Nick Gautier was our wonderful project scientist from JPL as well.

Q: During development of the mission, I guess your job was really the ground system—

Jenkins: Right.

Q: —or the processing pipeline. Tell me where your challenges were in the ground system development, pipeline development.

Jenkins: Well, it was a much bigger job than we had appreciated, and so, in fact, the proposal itself significantly underestimated the scope and the cost of the pipeline, and that got addressed later in the mission. But I'd say one of the chief challenges for me was, in the early days I was able to spend most of my time on direct technical development, but then I had to build a team, so I had to recruit a team. I recruited a team of about half a dozen software engineers to work on the pipeline infrastructure. I recruited a team, about dozen data scientists, but then when we discovered these electronic image artifacts that we were talking about earlier, we had to divert a lot of our attention to studying these effects and also developing software that would help us during commissioning to analyze and try to characterize what was going on, especially before we took any data with the dust cover off.

And so we actually weren't able to complete the pipeline before launch. In fact, the data validation module, which was the module that, once you find transit-like features constructs, a suite of diagnostic tests that you apply to the signature in question to decide whether or not it's likely to be a planet, wasn't done. In fact, it took us about a year after launch. I guess—let's see. I think we finished in December of 2010, so it took us about six more months to finish that component, but about a full year to work out all the kinks before we had a fully functioning pipeline.

So I'd say that the chief challenge was the fact we were trying to do something that we didn't really understand fully how hard it was, and, of course, once we got up into orbit, it turned out that one of the things we learned was that the Sun is not a solar-like star. Turns out that the Sun-like stars we were observing were about twice as noisy on transit timescales than we'd expected, based on how the Sun behaved, and so we spent a lot of effort on the electronic image artifacts, we spent a lot of effort learning the intricacies of the instrument, also intricacies of nature, and the kinds of behavior that the stars evince when you couldn't know it beforehand.

So I kind of compare how we saw the stars before Kepler to, if you're swimming in Hawaii above a coral reef without a mask, then you can see that there are brightly-colored fish, you can see the coral, but it's very blurry. You can't see any of the details. But having Kepler in orbit was like putting on a good set of snorkel gear and having a really good mask, so now you can see every stripe and every spot on every fish and every color.

It was just mind-blowing to see how well Kepler performed. In fact, during commissioning, we had to collect a lot of data to get us set up to be prepared to execute the mission. One of those tasks was to collect a set of observations that allowed us to map the point-spread function of the instrument, and it was going to take us about a week to process that data. Also part of that was to understand more what the mapping is between sky coordinates, the pixel coordinates. We had to tune that up.

So during that week or so when we were waiting for that to happen, to be able to get our final target set up on the spacecraft, we conducted an experiment that was—I believe it was actually ten days long, where we observed 54,000 stars with fairly large apertures, and then when we got that data down, it was the first science-like data that we had acquired.

In fact, I got the email from the operators late in the evening that it had been fully processed and was ready for us to come in the next morning and analyze. I got up early and got to the office at 6:00 a.m. I was filled with trepidation. This was our first chance to see whether or not the mission was going to work or not. [laughs] So I actually washed the coffeepot, a little procrastination there [laughs] to settle my nerves.

Once I had my coffee, I sat down at the workstation, pulled the data over and started looking at it, and, *wow*, it blew the socks off of everyone. In fact, we identified our first *Science* paper that very morning. So one of the things I did was I took the collection of 54,000 light curves, I did Fourier transforms on all of them, and then I ordered them by how compact the information was in the frequency domain, and this would naturally order the stars according to how periodic their behavior was, so it was really easy to see the eclipsing binaries at the top of the list. We also saw lots of pulsating variable stars like R Lyrae stars. In fact, R Lyrae is in our field of view, for example. And it also [laughs] was a source of false positives, because it was so bright, it contaminated other stars, for example, so that was another wrinkle in that.

But the stars we were looking at, there were three planets that had been identified in our field of view prior to launch. One of those was HAT-P-7b. And one of the things that I'd worked on before launch was, could we actually detect planets through reflected light, because if there's a planet orbiting a star, some of the light will be reflected off of the planet and you'll see phases like the Moon, so you ought to see the sinusoidal rise and fall of the light from the planet, even if it's not transiting. In this case, HAT-P-7b was transiting, and it was easy to see in the seven- or ten-day light curve exactly where the transits were. I asked an astronomer friend of mine who was in the room—I gave him the Kepler ID number and said, "Hey, this must be a planet. Which one is it?"

"Oh, it's HAT-P-7b."

And then I zoomed in and I could see that in between the transits there was this bow, so light rose, but then halfway around, there was this little tiny 100-part-per-million dip or bite out of this bow, and that was the thermal signature of the planet disappearing when the planet went behind the star. So, yes, we were seeing thermal emission from the planet because it was so hot, and when the planet went behind the star, the thermal emission winked out and so we saw this 100-part-per-million dip in the light curve that was happening every three days or so. And nobody at that time had ever observed a secondary eclipse in an exoplanet, so we were very excited about this. In fact, the discovery paper for "HAT-P-7b" indicated that this was a wonderful target to see if one could actually observe the thermal emission from this planet like we had done.

I called up Bill Borucki, because he wasn't up in the lab with us where we were observing these light curves, and I told him, "I think I found our first *Science* paper." I told him what we'd found, and true to Bill's colors, he basically tried to throw up every strawman he could as to why this wasn't what we thought it was, and finally I was a little exasperated. I asked him, "Well, Bill, just come up here and look at the data for yourself." [laughter]

It was amazing. And the reason why that was so exciting was that we really saw that first day that we got science-like data down from Kepler that it really could work and that we really could find the signatures of Earth-sized planets which are 100-parts-per-million deep in the light curves of the stars we were observing.

Q: So you knew then you were going to have a pretty successful mission.

Jenkins: I knew it was going to be successful. Now, we also knew it was going to be very challenging, and indeed it was, for all the reasons that we've talked about. I wish we'd found some additional small transiting planets in long-period orbits. There are a number of people that are trying to do that in the legacy archive. In fact, I'm part of a team led by Steve Bryson, who was one of the data scientists I hired, to actually improve the Kepler pipeline and reprocess the data to see if we can push the sensitivity down and find additional small transiting planets over long periods so that we can get a better estimate of $\mathbf{H}_{\text{earth}}$. That's the frequency of Earth-sized planets in the habitable zone of Sun-like stars. And the reason we want to do that is that NASA wants to build the Habitable Worlds Observatory, and this will be a mission to characterize these planets through reflection spectroscopy, and we want to size it and scale it so it can observe at least twenty or twenty-five such planets, but you have to know how many planets per parsec there are, right, what the density of planets is in the universe in order to properly scale this mission.

So we've received a grant to do this, and we've just brought on our two postdocs who've gotten started on this work, so we're very excited to see this play out. But there are other people in the community who are also making similar attempts, and I think that it would be just really wonderful for the legacy of Kepler and NASA if people were able to be successful at this so that we actually got the answer to the question that we originally posed for Kepler to answer, namely how frequent are Earth-sized planets around Sun-like stars in Earth-like orbits.

Q: And the reason Kepler wasn't successful at that is just because the mission was cut short by reaction wheels, or was there some other issue?

Jenkins: Well, one of the primary issues was that the Sun-like stars we were looking at were much more noisy than the Sun is on transit timescales, so it was a much harder problem than we appreciated before we launched. In order for us to recover the original sensitivity of the mission, we would have needed to have observed for at least four more years, and so, yes, it's the loss of the second reaction wheel that cut short the extended mission, but had the reaction wheel not failed, we would have been able to observe for another five, six, eight years, perhaps. In fact, Ball Aerospace, for the repurposed K2 mission, where we actually had to use thrusters every six hours or so and burned a lot more hydrazine much faster than we did during the primary mission, was able to eke out another five years of data collecting with Kepler being operated for K2, where we observed in the ecliptic plane, but we couldn't go back and observe in the original field of view just because of the very unique nature of how we had to operate the spacecraft during the K2 mission.

Q: And the K2 mission was partly about understanding variability, I think. Tell me a bit about the K2 mission.

Jenkins: So there's a Ball engineer who came up with this brilliant idea that we could use solar pressure on the spacecraft to help stabilize the pointing, but you had to be operated so that the spacecraft was oriented along the ecliptic plane, and the spacecraft is roughly asymmetrical, and so if you put the solar arrays so that they were perfectly centered on the midline, the Sun was centered on the midline, then it would be somewhat stable, but it would kind of drift off, and every six hours you had to tilt it back. The fortunate thing was that we still had two reaction wheels allowed to control where we were pointed. We just couldn't control with reaction wheels the orientation. So we were able to observe each field of view for about eighty-five days or so, and it became a community mission. So, yes, a lot of people were still finding planets, but we were finding planets around the sky and not just in the Kepler field of view.

We also conducted some special-purpose campaigns, like there was a gravitational microlensing campaign where we observed the galactic bulge. The purpose of that observation was to help the gravitational microlensing community get ready for the Nancy Grace Roman mission, which was in formulation, but will be launched in just a few years, which is doing a dark energy study, but the other part of that is exoplanets, and it's going to be conducting primarily a gravitational microlensing search for exoplanets in the direction of the galactic bulge. It turns out that we predict that it's going to find hundreds of thousands of transiting planets orbiting field stars at other orientations.

So it's just amazing to me that if you think about it, Kepler was really a true Cinderella story. Most of the community was very skeptical. It took us years to win over people one by one, but if you're entering the field today, it seems like Kepler's a fait accompli. Of *course* it's a magnificent success, but in the early days, in fact even after we launched, a lot of astronomers thought that we would be finding a lot more eclipsing binaries than planets. Some people thought we would *only* find eclipsing binaries and would find no planets. But it's a *phenomenal* success, and I just feel so lucky and fortunate I was in the right place at the right time, with the right skill set to make a signal contribution to this mission.

I just remember when I was growing up, my father watched *Star Trek*. We watched *Star Trek* when we were very little. We'd go out into the summertime and lie in the grass, in the cool grass, looking up at the sky at night, at all the stars, wondering, you know, are those campfires and are there people about those campfires in the sky looking up into their night sky in our direction, wondering the same question.

And so Kepler is really the first mission to get us a far piece down the road to answering this question are we alone, and it's just been such a thrilling ride, and it's just amazing to see how big the field is now and how excited the community, not just the community, but the entire public is about exoplanets, because we all have the same burning question, you know: are we alone and where do we fit in the universe? What's our role, in some sense? And, of course, as a scientist, our role is to answer these questions, but it's really great that we're able to answer this question that we've been asking ourselves for thousands of years: are there planets orbiting other stars? We knew they probably must be, given the nature of our own solar system, but now we have proof, and we have proof that nature is much more wild and imaginative than we ever could be.

Q: Yeah, the hot Jupiter thing is still crazy to me. [laughter]

Jenkins: Yeah.

Q: What would you say are your kind of top two or three Kepler discoveries?

Jenkins: Top two or three Kepler discoveries.

Q: Or just your favorites. They don't have to be the most scientifically important.

Jenkins: [laughs] It's hard to choose which ones are the most important ones. I'd say Kepler-10b is the standout, because that was the first time that we found a small rocky planet orbiting another star.

Kepler-20 stands out. Nick Gautier, our project scientist from JPL, led that particular paper where we found Kepler-20e and -20f. Those were the first Earth-sized planets that we discovered outside the solar system. It also really was a lot of fun because we were able to reduce the instrumental systematics and we could actually recover the stellar variations of the star because it was spotted, and we could estimate the rotation period of the star, and that allowed us to estimate the age of the system. So that was really phenomenal.

Gosh, it's really hard to pick. I think KIC 12557548b stands out for me because it was just something we had no idea that was there to find, a disintegrating sub-Mercury-sized planet. And in the end, Kepler actually, if you look at the literature, about 60 percent of the papers that have been published about the discoveries of Kepler are not about exoplanets themselves, but about the stars. So one of the communities that was most vigorous during the Kepler mission and is now quite energized by the TESS mission is the asteroseismology community. They study the oscillations of stars. Stars are like bells, they ring like bells, and, of course, bells, the tone they ring at is dependent upon the mass and the size of the bell.

So it was just amazing to me that you can actually look at the changing shape of the star. As it changes the cross-sectional area, you get these small, like, 6- to 10-part-per-million changes in brightness that are sinusoidal, that are at typical periods of five minutes for the Sun, and then you can actually look at this comb of oscillation frequencies for the mass and the size of the star to within a couple of percent, and you can study the structure of the interior of the star. It's pretty cool, because there are disturbances on the surface of stars, starquakes. They produce soundwaves that then travel down towards the center of the star, but they get refracted by the changing density back up to the surface, and they get reflected off the surface, and they kind of tend to go around like a daisy chain. If they end up at the same place they started, they keep on going. So there are these quasi-coherent oscillation modes that allows us to learn about these stars in far more detail than we ever could.

In fact, one of the most amazing discoveries, I think, from Kepler was the fact that we could actually look at a red giant. Red giants at first are burning hydrogen, and it's just a shell of hydrogen that remains because the helium that's being formed by the hydrogen burning, of course, is at the core in the center, and so you have these shell hydrogen-burning stars and then there's a flashpoint where the core becomes dense enough to start fusing the helium together. But from the outside, these stars are the same temperature, the same color, and the same size, so if you're just looking in visible light at a snapshot, you can't tell what's going on, but the fact is, once the helium starts fusing, the core is dense enough, and so there are these gravitational or buoyancy waves that can actually leak out from the core that we couldn't see before, and they interfere with the soundwaves and they split the frequencies. So we can actually use Kepler as an x-ray machine to look deep inside the star to tell which stars are burning helium and which stars are still burning hydrogen in a shell around the helium. Moreover, you can actually look at the broadening of these frequency modes and actually measure the differential rotation of the core compared to the convective envelope of hydrogen. So that's really amazing, too, that you can actually reveal some of the dynamics deep inside the star from the outside. So I think those are some of the most fun and important discoveries I think we made with Kepler.

Q: You were telling me about the stars. That's knowable now because of Kepler's staring, essentially—

Jenkins: That's right.

Q: —because it focused on the same spot, whereas most astronomical observations are snapshots, right?

Jenkins: That's right. That's right. That's right. Kepler really ushered in time series photometry on large fields of view with lots of stars. TESS is playing a similar role. TESS is in a higher Earth orbit, so it's not driftaway orbit like Spitzer that Kepler was in. So we can only observe each field of view for twenty-seven days at a time. But Kepler enabled TESS. TESS' mission is advanced scouting for Webb. What we're trying to do is find planets that are transiting, that could be followed up and characterized with the Webb Telescope, and Webb isn't sufficiently strong enough to actually characterize a cool Earth-sized planet around a Sun-like star, but it *can* characterize hot Jupiters, warm Jupiters, warm Saturns, and I'm sure they'll push the size down. We'll discover things we didn't think we would be able to.

But TESS' primary mission was to find at least fifty planets smaller than Neptune, for which we can measure the masses using radial velocity observations that we would then have the size of the planet from the transit photometry because, of course, the dip itself, the drop in brightness is proportional to the ratio of the area of the planet to the area of the star to get the size measurement from the transit. You can get the mass of the planet from radial velocity, and now you've got the bulk density of the planet. You can start arguing what it's made of. And so Kepler is enabling so much science, present and future.

TESS would never have been selected had Kepler not been successful. I don't think the Plato mission, which is an ESA transit photometry mission that's slated for launch in late 2026, I don't think that would have been selected by ESA. The Ariel mission is an ESA mission to characterize exoplanets. I don't think that would have been selected. Webb has a very strong program for exoplanets.

So I think that despite all the difficulties and all the years of hard work and effort that it took to get Kepler selected and then to be successful, really what it's done is put wind in the sails of this entire exoplanet enterprise, and there's so much more to come. Back thirty years ago, I don't think I or anybody would have been able to predict where we would be today in this field, and I think there's just so much optimism, given the rapid progress we've made just over the last thirty years since 1995 when 51 Peg b, the first planet-orbiting main sequence star was discovered, that it's likely that many of us, even those of us who kind of started in this field before it was a field, may actually live to see the imaging and spectral analysis that the atmosphere of an Earth-like planet around a Sun-like star in just a couple of decades. So it's just amazing how this field went from zero to 60 in so little time.

Q: Yeah, that'll be amazing if it happens. Just need the budgets to accomplish it, right?

Jenkins: That's true. That's true. There are architectural studies going on now. NASA's certainly all in on the Habitable Worlds Observatory. I'd say that it has a really good chance of being both launched and then a reasonably good chance at succeeding. And the good news is that there's a whole new generation of astronomers and astrophysicists to help us make that happen, and we have much better tools now than we did before. Kepler really pushed the envelope in terms of the power of the computer. The RAD750 that we launched with, we could do things with that that we couldn't have done before. It had a fair amount of data storage onboard. We collected basically 1 gigabyte of data per day. And TESS, which was launched in 2018, we collect about 150 gigabytes per day.

Now, one of the things is that we have to compress the data because the actual raw data storage can't hold that much data. That was another one of my principal contributions was to design a compression algorithm. We actually got better than 6.5-to-1 compression onboard with Kepler, so we were able to compress each pixel measurement down to about 4.5 bits. Normally you represent a measurement with 4 bytes, so that's quite a lot of compression. And then with TESS, I was able to actually improve the algorithm and we actually reached compression rates of about 3.5 bits per pixel. So I'd say that from my perspective, being able to actually apply my engineering know-how to help enable these missions is one of the greatest joys of my life.

Q: We're just about out of time.

Jenkins: Okay.

Q: What haven't we talked about that's important? This is your opportunity to tell me something that I didn't know enough to ask about.

Jenkins: Wow. Okay. Well, you know, I'd say that I think I've learned, especially with Kepler, is the importance of persistence. Bill Borucki epitomizes persistence. And the fact is, the journey is going to be long and hard to do these very hard, difficult things, and it's the relationships that you build with the team that you've formed that really make it all work. I'd say that it's really just like with our own interpersonal relationships with our spouses, it's the challenges that bond you together and that make it such a thrilling ride all the way through. So we have to dare mighty dreams and then do our best to try to make them a reality, and Kepler epitomizes that, I think.

Q: Thank you very much. It's been really interesting. I will turn off the recording and then send this off to my transcriptionist. May be back probably within a couple of weeks. She's usually pretty fast now. Okay?

Jenkins: Well, thank you so much, Erik. It was a pleasure talking with you.

Q: Thank *you*. Have a great day.

Jenkins: Okay. You too. And I look forward to seeing the series when it's made public.

Q: Take care. Bye.

Jenkins: Okay. Bye.

[End of interview]