Key:

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I: Can you please tell us about yourself and your work?

R: Yeah, hi, glad to be here today. My name is John Zink, I'm a researcher at California Institute of Technology. I have a kind of unusual path into academia. I was originally born in the suburbs of Detroit, Michigan and I pursued a rock musician career which is not usually the traditional academic path. I played drums, we toured a bunch. It was a really interesting time in my life. After doing that for about five years and really struggling to make that work out I made a giant pivot in life and went from rock musician to astronomy which is kind of the backwards thinking of someone like, say, Brian May from Queen, he went from astronomy to rock, I went the other way around. He was obviously way more successful than myself but needless to say that's why I'm here today. So my work is really exciting. The goal is to really understand the origins and future of our own solar system. That's really the basis for my work. To do so, this work involves studying the orbital dynamics of planets in our solar system but also the dynamics and demographics of planets outside of our solar system, so planets that orbit other stars and these are known as exoplanets. By looking at the vast plethora of planetary systems beyond our own, we can really learn what are the important features that make our home system unique.

I: That is fascinating. Both your different career path and obviously your work. Thank you so much for being here today to talk about your work and to answer our pressing questions about the future of the solar system. So, the sun is a middle-aged star and we think it will continue to mostly placidly, ignoring the solar storm that happens once in a while, to just fuse hydrogen in its core for the next five billion years. Can you give us a bit of an abridged version of what we think will happen in the solar system during this phase of sun?

R: Yeah, so this phase of the sun is actually surprisingly boring. It's as you said, very placid, and the solar system is incredibly stable, like shockingly stable. There's actually a really interesting story about how our understanding of the stability of the solar system has just gotten stronger and stronger over time. So, if we think back to Ptolemy, the famous Roman astronomer, he made these really precise positional assessments of Jupiter and Saturn back in 220 BC and 240 BC and basically that was the original dataset for understanding the positions of planets in our solar system. So, lets fast forward 1800 years from there, Tycho Brahe jumps on the scene, he's again making really precise measurements of the solar system, particularly Jupiter and Saturn here and this really sets up Johannes Kepler, the famous astronomer that most people know who put together the heliocentric model. So, we have these two datasets, one from 200BC to 1800 years later with Tycho Brahe, so when Kepler is putting these two datasets together he is seeing that his heliocentric model works incredibly well but there's a few glitches that are hard to rectify and that's between Jupiter and Saturn. They don't seem to quite line up perfectly with his model. This 1800-year gap, somehow there's some offset and it appears that Jupiter seems to be slowing down a little bit and Saturn seems to be speeding up a little bit over this 1800-year span, which is kind of shocking and they didn't really know what to do with it. It kind of just sat there and was not really fully understood, some people make some guesses so Edmond Halley, the famous astronomer, Halley's comet was named after him, he made this logical leap that if these two planets are not perfectly fitting into Kepler's model, it must mean that they're migrating. So it seems that Jupiter would eventually migrate inward into the sun and Saturn would migrate outward into deep space. This was the assessment from Kepler in the era of Kepler and Halley. Now, enter Issac Newton. In his announcement of the universal law of gravity, he was able to explain these deviations by claiming that there was this mutual gravitational interaction between Jupiter and Saturn. Since these planets were not independently orbiting the sun but also interacting with each other there was this push and pull affect that was occurring. So that part seemed great but he wasn't totally able to rectify it and the math is really complex when you think about overall dynamics. It seems really simple but when you add multiple bodies in there it gets really complex. And so Newton's assessment was that, okay I think Edmond Halley is right, Jupiter is migrating into the sun, Saturn is migrating outward so there is this incredible instability in our solar system and lacking some divine intervention, in about a thousand years the solar system should be totally torn apart by these two planets' migration. This was the thinking for about a hundred years, people just sat on it and were like, we're got a thousand years to figure out our game, get off this planet or figure something else out. Fortunately, LePla steps on the scene in the 1800's and with that he brings this new game of mathematics and physics called perturbation theory and what it really does is it allows us to answer some of these challenging problems of the old-world dynamics by simplifying it and making it more accessible and on a small scale. What LePla was able to show is kind of what we know today, is that Jupiter and Saturn sit in a near 5:2 orbital resonance. That means every five times that Jupiter goes around, Saturn goes around twice but it's not exactly a 5:2 resonance. Saturn is a little bit too fast, so it's a little bit out of this 5:2 resonance and because it's just outside of this 5:2 resonance there are these periodic modulations that occur on about a 900-year span and that is exactly what we were seeing in these two datasets from Ptolemy and Tycho Brahe is we are actually seeing this modulation over this really long period of time and it eventually would course correct and come back together. This isn't some great migration outward and inward, but rather just an oscillation outward and inward in their orbits. Basically, this idea of perturbation theory solves this problem known as the great inequality and gave us a very stable solar system. So, with this idea of perturbation theory and all the great technology we have had since then, we are able to show that the solar system, as it stands today, ignoring any solar changes, would be stable on order of 10 to the 18 years, so it's an enormous amount of time. No divine intervention needed, it's just an incredibly stable system as it sits today.

I: That is fascinating. If the sun will not change or there were no other interactions beyond the solar system that the orbital dynamic of our eight planets plus all the other stuff that is around is so stable.

R: Yeah it's incredibly stable. It's kind of wild to think about. There are some minor caveats to this I should caveat. Mercury is a little strange, so Mercury being so close to the sun, general relativity has a major impact on it and it leads to a somewhat chaotic orbit and by chaotic I mean it's hard to predict. So, just fractional millimetre differences in the orbital measurements today, so with all of our great technology, if we are just off by a fraction of a millimetre of our measurements of the position of Mercury, we have really no idea what it's going to look like in a hundred million years. So, these minor offsets can lead to wildly different orbits over time. Given that knowledge of how chaotic Mercury is, there's an expectation that there's about a 1% chance of Mercury going unstable over the next five billion years. Also, I should note, Pluto which is not a planet, is also very chaotic given it's high eccentricity orbit and also hard to predict. So over the next 20 million years we really don't know what's going to happen with Pluto. So, possibly the planet Mercury and the dwarf planet Pluto may go unstable during the main sequence, but there is a chance they don't. It seems very likely that they stay relatively stable throughout the rest of the main sequence of the sun.

I: Okay, seven out of eight planets will be stable and we are not really sure about what's happened to dwarf planets but it seems that the next five billion years, not really that eventful.

R: Yeah, it's going to be rather boring assuming everything stays static, right. There's always this chance that something comes into our solar system and totally wrecks everything but given the current state it's going to stay really static.

I: Okay. Let's move on to the big change. The big change that we know will come. The sun will eventually run out of hydrogen in its core, it will leave the so-called main sequence. What happens next? What happens next to the sun and what happens to the planets?

R: It's a great question. So, as you pointed out, the sun is not static forever, things do change. Once it runs out of hydrogen a fusion really stops in the core and so the core starts to contract because there is no pressure against the gravity to hold it up. This releases a ton of heat which expands the outer envelope or the outer regions of the sun to somewhere around one to two AU in radius. That's an enormous envelope and in doing so it's going to certainly encapsulate the orbit of Mercury and Venus. The Earth and Mars it's actually a little bit less known whether those two will be encapsulated in this red giant sun but it seems likely that it's going to be large enough that there is some kind of tidal drag that's going to likely engulf earth. Mars may survive, I think the question of Mars' survival is quite uncertain still depending on who you ask, it may get sucked into the tidal drag, the forces kind of decaying the orbit and then allowing it to be engulfed in the red giant sun. So, it's possible that Mars survives but certainly Mercury, Venus and likely Earth are going to be engulfed in the sun. If you're thinking about Earth as a long-term planet, really our deadline to get off this planet is about 5 billion years, assuming it all goes right and we don't kill ourselves or do something else in the meantime.

I: Fair enough. I feel that a deadline of five billion years is a comfortable one.

R: Yeah. It's definitely an upper limit. That's kind of the expectation and many of the other… basically the other outer planets go unaffected. After some time, helium does start to get burning up in the core and so we reignite that core and the sun shrinks back down. So at this point a majority of the mass is still in the sun. In about a hundred million years, helium runs out in the core and the sun expands again but this time there is no next phase, it just keeps expanding forever and ever and about 50% of the sun is lost during this process. What is left behind is a white dwarf or basically just the core of the sun, the unfusing core of the sun is left behind and so we're left with a star that has 50% of its original mass.

I: How does losing the mass affect the other planets? I'm assuming it's come in a sort of very dense solar wind, more like a big… I'm imagining, and it might be completely wrong, but just big chunks of plasma leaving the sun maybe hitting the planets that are surviving, maybe Mars and the giant planets.

R: Yeah. What you can imagine is that you're losing mass in these spherical sheets, right, they're kind of being pushed out and so when you go out to these orbits of the outer planets the density of the mass loss is just so low that it really has almost no impact on these outer planets. There is no substantial mass gain because they are sucking up pieces of the sun or anything like that. So, they're actually quite unimpacted by this mass loss. They're just far enough away that the sun and the sheets of mass that are being excreted are so low in density they just don't impact them very much. But that's not to say that they're not impacted at all. They're not impacted by this loss of mass but they are impacted indirectly because the sun, in losing half of its mass, these planets have to maintain their orbital angular momentum and so now this star in the centre that's half of its original mass, the orbits actually expand outward by two. So, all of the orbital radiuses of all the outer planets that have survived somehow someway, they're now twice as far away from the sun as they originally were.

I: So, this is pretty much what happens to the sun and the planets after a red giant phase. So, as far as we can tell, several would survive despite the immediate changes to the architecture of the solar system. We have discussed this in terms of a solar system sort of away from the galaxies and other potential interaction but it's possible that the sun might encounter other stars. What would happen to the planets in those cases? What are the chances of being disturbed by such a close encounter.

R: There are a few things to think about here. As I mentioned, the orbital radius of all the surviving planets expands by a factor of two. The gravitational pull from the centre of stars is much weaker now, we have both a lower mass star in the middle and these planets are much further away. Passing stars in our galaxy can play a bigger role in impacting the orbits of these outer planets but I just want to give a general sense of how frequent these encounters, these close encounters from stars can be. So over the course of the next five billion years, so from today to five billion years, the expectation is that we should have one star that comes within .5 parsecs. The closest star to us is 1.5 parsecs away, so basically over the next five billion years there is going to be one star that comes between us and the nearest star. These aren't happening super frequently, they're pretty infrequent encounters just given the local star density and the velocity that these stars are flying about at, but it does happen. Needless to say it does happen. So, in about 10 to 11 years, this is an enormous amount of time, so the put the other side of the spectrum into play.

I: So that's one hundred billion years.

R: Yeah.

I: Ten to eleven you said, okay.

R: So, one hundred billion years we're going to have one star come within the solar radius, that means not just some distant perturber but actually something that is entering the solar system. So those are the limits, over the next five billion years, ones likely are not going to interact with us very much maybe a little bit, but over ten or a hundred billion years one will essentially just be within the solar system. But they don't necessarily need to come that close to have a major impact on our solar system. As I noted, after the solar mass loss occurs the remaining planets are orbiting twice as wide, they have a weakened gravitational pull from the white dwarf sun and the close encounters can really have a major impact on… in particular Jupiter and Saturn. So I talked about Jupiter and Saturn a bunch earlier with this historical context, the stability of the solar system and how they're kind of in this near 5:2 orbital resonance, so as a reminder that means that for every five times Jupiter goes around, Saturn goes around twice but its not quite there, Saturn is a little bit too fast, but upon this mass loss and this orbital expansion it gets closer to this 5:2 orbital resonance and a perturbation from a nearby star can actually push it into that 5:2 resonance and the reason that's important is because when you have these planets crossing from non-resonant to resonant, it's a very chaotic state and I mean chaotic in the sense that it churns up a lot of chaos into the system. So, by these planets wiggling around in this near or now in orbital resonance they churn up a lot of the outer systems and they actually increase the eccentricity or the elongation of the orbits of Uranus and Neptune so much so that over the next ten billion years these planets are completely ejected from the system and so is Saturn as well. It's such a chaotic process that all the planets just get flung around and get ejected from the solar system with the exception of Jupiter. So, Jupiter seems to hang on but we've now flung out all of the planets just because they've been perturbed a little bit by some close encounter and Jupiter essentially just orbits the sun by itself as the last standing planet for about 50 billion years. So now we have a sun and a Jupiter and then there's fifty billion years of time where the single planet is orbiting our solar system and eventually what occurs is that a star comes close enough to completely pull Jupiter off our solar system. So, putting this whole picture together, in about 100 billion years, our solar system will have no planets. It will no longer be a solar system, it will just be a white dwarf sun without any planets. It's kind of incredible to think that our system will be dissolved completely in a hundred billion years, despite the fact that it's such a stable system today and given a static condition, this thing would be stable for as long as anyone wants to run their computer code for. So, 10 to the 18 years and that's not the limit, that's just the limit anyone is willing to run their code for. So it actually could be much longer than that. In reality a hundred gig years or a hundred billion years is the real limit for our system.

I: Wow, that is fascinating that it's so stable now but then the changes to the sun and close encounters will lead to our solar system without planets, so just the sun as a white dwarf. Talking about the bigger picture, how has the galaxy changed over time? The milky way is certainly not static and so how is the galaxy changing over time and how will the change over time impact the solar system? What kind of changes have impacted in the past and what kind of changes might impact in the future?

R: Yeah, that's a great question. So, in the past the solar system was likely born in this dense birth cluster, so it was much closer to a bunch of nearby stars when it was born and because of that, we actually think that many of these stellar interactions early on in the origin of the sun may have shaped the outer parts of our solar system, particularly the Oort Cloud. So the outermost region was likely shaped by these nearby interactions at the very early stages of the suns history. But the sun has moved about the galaxy and we don't really have a good sense of you know, radially, whether it's moved inward or outward but we get a sense that its moved, it's not in this birth cluster anymore, it seems to have moved around a bit. So, our current state is not essentially it's originating state. Fast forwarding to the future expectations of how the sun may interact with the galaxy, in about ten billion years there is this expectation that the Andromeda galaxy will actually collide with the Milky Way and so once that occurs there is likely going to be an increase in stellar density in the local region, so the number of stars around us will likely increase. That means there is a higher chance for potential interactions of these close encounter stars and that could actually speed up this process I talked about. So, all of the mechanisms I mentioned are assuming that the current stellar density stays static but if we dump a bunch of stars into the region we can actually speed this up. So, a hundred billion years is kind of an upper limit, it could actually happen much faster. That's really interesting to think about, but the galaxy is always evolving, so this is some external factor and when we think about the galaxy it's important to remember that the chemical composition of the milky way and the stars within it are chemically unique from the stars born at the time of the solar system. Thus when we think about planets that are forming right now, one thing that is really important to think about is that these planets that are forming today are forming under distinguishable conditions from that of our own system. So, it's interesting to think about the solar system and we like to think about are there other habitable planets out there and there may have been some habitable planets that formed around the same time as the solar system, but we're not confident that the planets that were today may be habitable. There may be some goldilocks time at which habitable planets formed and that may not be today or it may be today. So the galaxy is certainly changing, it has certainly shaped the solar system that we see today and it maybe shaping the other systems that we're seeing forming right now as well, but its really important to keep the idea that our system is not isolated but it's actually in a grander, both galaxy and universe that are going to impact it and may have impacted it in the past and in the future.

I: Well thank you very much John, this was fascinating. So good news, we have a pretty stable solar system for the next several billion years and there is after that a lot of chaos ahead with very few planets if just Jupiter is surviving for a little bit longer and then nothing of the solar system but just a little reminder of what the sun used to be in the middle.

R: Yeah.

I: Thank you very much for telling us and taking us on this fascinating journey.

R: Yeah great, thanks for having me, it was a really fun time.

[END OF TRANSCRIPT]