

Episode 73: An Episode with Glass

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Ben: Never be afraid. There's nothing which is known which can't be understood. And there's nothing which is understood which can't be explained. For over fifty episodes now my team and I have brought you to the very frontier of knowledge in physics and astronomy. And still our mission goes on: to present you with your birthright, an understanding of the universe. I've traveled the world seeking out a certain type of genius, masters of not only their academic disciplines but also at explaining their research in understandable ways and I've bestowed upon these women and men the title of Titanium Physicist. You're listening to the Titanium Physicist Podcast and I'm Ben Tippett, and now allez physique!

1:49

Ben: A scientist must have humility and not for any honorable and virtuous reason either, it just comes with the job. See, being a scientist means that you need to both believe in an idea with your whole heart and all the while you have to expect that it will be proven wrong. In a week, in a year, in a decade, you have to do both. If you truly believe that you were wrong the whole time you'd have no motivation to spend any time working on the idea in the first place and so you have to fall in love with this idea. Only when you put your whole weight into it can you properly explore it and all of its possible consequences. And, on the other hand, if you truly believe that you were infallibly right, your thinking would become brittle. You wouldn't be able to abandon incorrect ideas and you wouldn't be doing science anymore. So, a scientist has to know deep in their heart that their ambitious projects, in spite of anything they do, in spite of their diligence and effort, will probably end up failing. It's something you learn from

failing over and over and over in the course of your training and in spite of it never giving up on the dream of being right. First you hear an idea and its evidence and then you lean into it and then you discover new, contradictory evidence and you have to cut out your own heart and abandon your original picture and that's how you get better. Who cares if it means you have to admit to yourself and others that you made a huge mistake. You don't let your self image get in the way of the pursuit of good work. You have to start thinking of yourself as fallible by default in spite of your degrees and knowledge and title and reputation and accomplishments. Like I said, humility. Let's give you a sample of how it feels. Consider the proposal that glass, the stuff our windows and bottles are made out of, is a liquid. It's a very, very viscous liquid. I started hearing this idea about 20 years ago and it changed my world. Start by imagining bitumen or pitch. It's the black sticky stuff we use to fill cracks in the road. If you heat it up it flows faster. But at room temperature it flows so slowly that it appears to be a solid. Now, Thomas Parnell's famous pitch drop experiment he filled a cone, like the kind you drip coffee out of, with this stuff, and he showed that it flows but very, very slowly. It takes a decade or so for each drop to form and drop out of the bottom. So yeah, this idea that glass is just like that. We know that if you heat it up it flows and if you cool it down to room temperature it seems solid but is it solid? The molecular structure of glass isn't crystalline the way we'd expect it to be. The way ice is, for instance. I mean, solid glass can't make the glass equivalent of a snowflake and, if you go to a century old cathedral with glass windows you'll see that the glass in the windows must be flowing downwards because of the pull of gravity. The bottoms of the windows are noticeably thicker than the tops of the windows. And this idea is fantastic. It makes intuitive sense and there's evidence supporting the principle. Now, feel how good it is to know things. Think of all the glass objects around you slowly flowing towards the ground. It's mind blowing. But it's wrong. The whole thing about glass warping over

time is a misunderstanding. Humans have known how to make glass for thousands of years but have only in the last hundred years have learned to make the type of glass we're used to. Glass that is really flat and really even. And before then, if you wanted to make a glass window you'd have to cut your window pane from a larger piece of glass which was only fairly even and then you'd put the thickest side facing down so the window pane wouldn't be top heavy.

5:02

Now, old windows look the way they do for reasons that have to do with the history of manufacturing not the properties of glass itself. And furthermore, we've discovered that glass historical artifacts which are thousands and thousands of years old. And if the cathedral windows were viscous enough to slouch this much in just a few hundred years, then 2,000 year old bottles would be puddles by now. So all this stuff about glass being a very, very viscous liquid, it's not right. When you discover new information or a broader context you have to throw out the old understanding no matter how much sense it made to you. Getting it right in the future is more important than the feeling of understanding you had in the past. And at this point in the game I'm going to guess that you're tired of listening me sermonize. All this talk about glass. You probably just want to know more about glass instead of science and the society. Well, guess what Ti-phyters, today's episode is about glass. What it is and how it breaks.

Now, our guest today is an icon and he's super good looking and I'm super excited to meet him. He's captured the hearts of fans of NASA and gotten shoutouts from presidents. He's a systems engineer at NASA's Jet Propulsion Laboratory and he's worked on the Cassini-Huygens mission and the Curiosity mission and you remember his famous face from when the Mars Curiosity Rover landed. Welcome to the show Bobak Ferdowsi.

Bobak: Thanks.

Ben: So, Bobak, for you today I have assembled two amazing Titanium Physicists.
Arise Jessica Rimsza!

Jessica: Dah, dah, daaaaa!

Ben: Dr. Jessica got her PhD from the University of North Texas in Materials Science and Engineering. She's currently working at the geochemistry department in Sandia National Labs on glass and oxides and fracture. Now, arise Jane Cook! Dr. Cook got her PhD in metallurgical engineering from the University of Wisconsin Madison and after working for six million years in research and development she's currently the chief scientist at the Corning Museum of Glass in Corning, New York. Okay everybody, let's talk about glass.

So, should we start talking about what glass is, deep inside of its guts?

Jane: As a good materials science exercise we always like to get into what we call structure property relationships. With this idea that the behavior you see in mass when you have, you know, a couple of centillion atoms in your hand, that that behavior is somehow predicated upon the atomic bonding and the larger mesostructures. So, I think understanding what that nature of those structures are as we begin to interpret things like what you were saying about flow rates and viscosity and shear stress and things. That's a good place to start, yeah.

Ben: Alright. So, glass isn't crystal, huh?

Laughter.

Jane: Nope! Yeah, there's a couple different ways that something can go when it cools down from its liquid state and most things in the Universe are perfectly happy and, given the time, to nice and neatly arrange themselves according to the rules of inorganic bonding, to assume a crystal structure. So, some sort of structure where you can define a repeat unit that will propagate itself and fill space and that's a crystalline

material. But glass gets in its own way. The proto-structures that glass begins to form as it begins to cool down while it's still a liquid forms the materials that will form glasses, frustrate themselves and that is, literally, the term that is used, is a glass is a frustrated material. It's a frustrated solid because it couldn't, in the time that it was given to change from a liquid into a solid as the heat was extracted and the atoms slowed down their vibrations, the atoms just didn't get a chance to find their way into those nice, neat repeating positions so they became a disordered solid instead of an ordered solid. So, it's a class of material, it's a subtle distinction from most of the other materials in the universe that do crystallize. But glasses don't.

Jessica: And an interesting thing, that I think, about glass is that it's not like a truly randomized mixture of atoms because there is some extremely localized units. Um, which are like the silicatetrahedra with the silica bonded to four different oxygen and you know, there's also boronoxide, it's kind of a base unit and then aluminum oxide as well. And so there is, kind of, I don't want to say molecular structure, because that's obviously very wrong, but this bulky formation of atoms and that's part of the reason why glass get's in the way of itself. If it had more flexibility and wasn't so thermodynamically driven to form those base units it would more easily crystallize. So, it's kind of interesting mixture of things where it has this extremely structured, local kind of unit, right, versus, it has this overall, long-range disorder which is a part of what makes it so frustrated.

Jane: And another aspect of it, as you begin to classify what glass is, just like you can with people, right. You ask a person who they are and they can give all sorts of specifications for themselves. Like glass is a solid, glass is a disordered solid, but in its most refined form glass is actually a disordered solid solution in that it is made up of things that a solvent base material that other solutes are dissolved in.

9:58

Jane: And it's the combination, it's the action of these solvents acting with the solutes that creates this material, I mean, from the point of view of industrial applications and also you see it in geophysics and petrology and vulcanology and beyond, this amazingly accommodating material that you can just keep throwing things into and it just dissolves them and sucks them up and brings it into this flexible, disordered structure and change its optics, change its viscosity behavior, change its mechanical properties. It's a highly tailorizable, adaptable material for technology and industry and beyond.

Ben: Okay, Bobak...

Bobak: Yes...

Ben: You have an engineering background, right?

Bobak: Right.

Ben: How much of that did you get?

Bobak: I got some of it, ah, not all of it.

Ben: Okay, so, first, let's talk about crystals. So, the idea here is that glass isn't a crystal and to distinguish what we mean we have to talk about what a crystal looks like. You know what a crystal looks like at the molecular level.

Bobak: Yes.

Ben: The repeating pattern. You think of a salt crystal, it's like, alternating and NaCl, NaCl, attached next each other in three dimensions making a lattice structure, right?

Bobak: Right.

Ben: So, what they're saying is, that this type of solid, glass, doesn't have a lattice structure. So, it's solid as in all the atoms are stuck to the atoms adjacent to them, but it's not in any type of pattern. So, you don't get this nice lattice structure. So, what

does it do instead? This is the cool bit. Okay, silicon oxide, is that what it's called? No, it's called...

Jane: Silicon dioxide...

Ben: Silicon...

Jane: Silicon dioxide is the basic repeat unit of a silicate. For folks who might be more familiar with organic polymers, it's essentially, like, the idea of like a "mer", like in a polymer. And there's some people who describe glass, actually, as a polymer material but instead of the carbon hydrogen units as being the backbone of the plastic, the silicon oxygen units are the backbone of the silicate type polymers. It's not a great analogy. It begins to break down, just as a visual for folks who are more familiar with plastics and polymers, it's a bridging idea.

Ben: Right. So the basic unit of our glass is silicon dioxide. For every one silicon there is two oxygens, right?

Jessica: MMMhmmmm.

Ben: But it's more complicated than that. You get a silicon and then it will grab four oxygens around it in a tetrahedron. So, you get this triangular base pyramid with a silicon atom in the center of it. Okay, so we have these little tetrahedrons, okay. Two silicon oxide tetrahedrons are going to share corners, they're going to share their oxygen molecules adjacent to each other. And so, there's two aspects to this, the first one is what Jane said, that glasses start off as a solvent, right. So, if you heat up this batch of silicon dioxide it's going to be really, really corrosive. The oxygen molecules are just going to grab and rip apart anything they touch and so the system can dissolve a whole bunch of other materials into it.

Bobak: Mmmhmmmm.

Ben: So, different types of glass, you've heard of uranium glass, right? Or lead glass, ah, there's all sorts of different types of glass that has different macroscopic

properties, different colors, they're shaped differently, you know. Lead glass you can make nice curves with, is that the thing? So...

Jane: Yeah, lead glass has a lot of, it has what we call a long working range. So the temperature range over which it has a viscosity, so, a flow behavior that is commensurate with sort of human scaleability to apply a force and stretch it and push it and move it around. With a lead glass where you dissolve 10, 20, 30, 40, 50% by weight, lead oxide, into a silicate, ah, that creates a glass that's very, very long and workable so you can make some really lovely shapes with it. As well as getting the refractive index behavior because of the big sloppy electron behavior of a lead atom, lead ion dissolved in this stuff, but that's another story.

Ben: Fantastic. So, long story short, you take your silicon dioxide and you heat it up till it melts and then you can put whatever you want in it. But, the tricky bit, the thing that makes it a glass instead of a crystal, is, when you let the temperature drop down from being really, really hot to cool.

Bobak: Yeah.

Ben: So, what will happen is, as you cool the liquid, instead of being a free floating silicon dioxide, ah, tetrahedrons bouncing all around, these tetrahedrons are going to grab each other and they're going to grab the things around it. But if you cool the system down quickly enough the system won't end up ordered. It's kind of like moving, you know, like when it's moving day and you're supposed to pack all these boxes but you've been procrastinating so instead of, like, wrapping everything nicely and, like, nesting all the bowls in each other, you're like I'm just going to wrap this bowl in a sweatshirt. I'm going to wrap this cup in a sock, right? And you just throw it all in a box and it's not packed in the box efficiently.

15:02

Bobak: Yeah.

Ben: Essentially, the silicon dioxide tetrahedra don't stack efficiently. They just kind of grab each other so instead of getting a nice lattice you end up with weird chains of these tetrahedra stuck together and in between them and around them are whatever else you've dissolved into your silica dioxide liquid. So, overall, the glass is a solvent which has dissolved other random things that we decided to put into it. But then the other defining characteristic is that inside of it it's not a nice lattice of these atoms. Instead it's made of these long chains that are attached together in weird ways. So, it's super, super disordered at the molecular level.

Jane: Nanoscopic.

Ben: Nanoscopic, yeah, you can't see it with a microscope.

Jane: I, actually, I was just reading a paper a couple weeks ago from a researcher over at Berkeley who has been doing some high resolution electron microscopy of different glasses and has been able to show, at least in certain processed glasses, in either high silica glasses or, sort of, the common glass like I've got my scotch in here, the soda lime glasses and pyrex, the bora silicates as well. That, when you properly set-up your electron beam in your microscope and illuminate your materials properly, you can actually begin to see some, not ordering exactly but certainly structures that are occurring in what we call midrange order. Sort of the range of maybe tens of silica tetrahedra units and the associated solutes in between each of those units. Something funny is happening that they are beginning to see with the electron microscopy. It's not exactly ordering per se, but it's sort of suggesting that given the opportunity the drive for things to crystallize is an extremely powerful force in the universe which is why glasses are so rare overall.

Jessica: Yeah, so in glasses, so, saying that like, I do atomistic modeling right, and when we analyze a structure we do a lot of analysis of the extremely local structure so the specific Si tetrahedron, SiO tetrahedron. But actually we can look at the intermedi-

ate range order and you said Ben, that it's chains and it can be chains, but in pure silica we see a lot of rings which contain ten or twelve or you know eighteen or even larger numbers of atoms. And we can analyze that ring structure and what we see is even in amorphous silica, the most common ring we form is the same one that you would see in quartz or cristobalite which is the crystalline forms of silica that you would get if you cooled the system really slowly. So, even in the pure glass, we're seeing that there is the thermodynamic drive to form that more stable structure that you would see in a crystalline system. And on a macroscopic scale you would see the same thing in the formation of glass ceramics which is essentially amorphous silica. And then you can heat it up again and you give the atoms the thermodynamic drive and energy that they need to overcome some energy barriers and you can actually form extremely localized kind of nuclei of crystalline material embedded within the glass. And so that's called like a glass ceramic and there's a whole other field of glass science which is focused on making these hybrid materials where if you provide enough temperature or even time or compositional differences or pressure you can actually start to form these separate embedded structures and that can provide some more strength and stability to the glass or really interesting optical properties because you have a two phase material and so that kind of shows that glass at its deepest, you know, core, wants to be crystalline. That's the lowest energy state of it and it's kind of stuck in this metastable environment and it's always kind of searching for a way to form a crystalline subset, um, so that it can be the lowest energy state.

Jane: Because of the work that I do at the Corning Museum of Glass I work a lot with artists who work in glass in different ways. And there's many, many, I mean, everybody's familiar with glass blowers because that's very sexy and flame workers because you see it at fairs, but there's other ways of working with glass that are really quite common and really quite lovely that involve casting glass or fusing glass. So, taking it

in its solid state, cutting it into different shapes and then putting it into a furnace that doesn't get hot enough to totally melt the glass back, but just enough to get it to flow a little bit so that it starts to stick together. And you can make some really lovely sculptures but what artists find is that in heating the glass back up into that range where it begins to just sort of stick together or to begin to slump under gravity slowly enough in different forms and to make different castings that that range of temperature where the glass is beginning to move and these are viscosities in the sort of hundreds of millions to tens of billions type of viscosities, that's also the range where the glass can begin to rearrange itself and begin to crystallize. So, artists are constantly fighting the tendency of the, what's called the devitrification, stopping being vitrified, stopping being glass. There's lots of folklore around it and there's lots of really sort of strange techniques and little chemical tricks that they use to try and prevent the surfaces from crystallizing in their sculptures or in their sun catchers or their fused windows or whatever they are making.

20:09

But it sort of highlights, to me, that on a daily basis, in a highly nontechnical but very expressive basis, that tendency of glass to revert or to continue to drive itself to that structure that it really wants which is to be crystalline but if you give it that extra thermal boost by putting it into a kiln at 600 or 700° C and that's enough in a typical soda lime glass to get things moving again. Enough that the structures that were frozen in can sort of begin to wiggle around and find their way into a lower energy, more thermodynamically favorable state.

Bobak: I mean, and I think you guys are hitting on, the question that I kind of had, right, which is, I want to understand what then defines glass versus a crystal because you know, the constituents are the same. You are telling me, but at some level, is the lower energy state mean it's no longer glass? Is glass just a local minimum?

Jane: Yeah, that idea of local minima gets into a relatively new field of theory of understanding the nature of glass. With the idea of actually defining within the structure of glass. The term that is actually used, is landscape. You look at this landscape of enthalpic minima and you can see where the energies were low enough for things to sort of lock themselves down in the solid given the fact that they have no other options. Because you've removed the thermodynamic drive and of course they can't get out of those potential wells in order to move on to another more thermodynamically stable configuration. And they're also locked in topologically, geometrically, they may find themselves in an environment that will require tens or hundreds or even thousands of other atoms to move in some sort of sequence in order to jimmy things free so that some new structure can form. And this is why for many, many years the idea of glass of being, of not being a true solid, but of being like a fourth state of matter was put out there. Because typically folks were used to looking at doing what's called calorimetry where you were looking at the amount of energy that's given off or taken up by a solid as it transforms from a liquid to a solid and glass didn't seem to show a distinct peak of that moment in time when all the atoms said, I am home and lock themselves in this nice, low energy state. What you see is more of a distribution as locally, every atom sort of picks its moment to say, you know, based on who's hanging out with me, this is where I want to live and they all sort of sit down and and get comfortable with what life has given them, if you will. And that's sort of manifested as, instead of this primary, deep expression of energy absorption of a first order phase transformation. They started defining something they called the second order phase transformation. Which is more this slur, this distribution of energies as everybody just sort of figured out what they were going to do for the next, you know, few hundred trillion vibrations.

Jessica: And I think part of that interesting feature is that part of what makes it so hard for glass to crystallize is actually the strength of the intrinsic SiO bonds themselves, right? So those bonds are so stable as is the silicon oxygen tetrahedron that form. And it's kind of a big unit, right, and you're talking about a lot of rotation and you need that whole, you know, the oxygen bond is so unwilling to break away from its silicon to you know, form a new tetrahedron, that you need the whole tetrahedrons to kind of rotate and move and rearrange themselves to form the crystalline structure. But, at the end of the day if what we're talking about is a glass versus a crystal, and in my mind it all comes down to the lack of long range order. So, once you have any sort of long range order, once you know where one atom is and you can say, where you know, an atom eight atoms away, is with certainty, then you're a crystal, right. So, even though we have this local, kind of structure, because you're lacking the long range order and realistically a ton of intermediate range order, that's when you've officially gone from, like a crystalline material to an amorphous material, in my mind.

Jane: Yeah, and this is where, I think, a lot of the solid state physics comes in. The mathematical definition of a solid, that this idea that order versus disorder is something that can actually be quantified. I mean, you can do the calculations on structural entropy to decide what is the actual number of joules required to move a structure from its nearest ordered structure to a disordered structure so that's going to be quantified. You can also quantify what's called the ergodicity. Glass is a non-ergotic material. You can't define ergo, meaning like therefore. I can't say if I am here therefore there is going to be something like me a certain distance away. The deviation from ergodicity is actually definable and quantifiable as well. So, we talk about glass very specifically as being a disordered, non-ergotic material.

25:01

But still being solid because it still has that definable structure at any given moment where it's not flowing, it's not moving under external forces, it does sustain shear stress as opposed to a liquid. There's this curious semantics around the idea of a solid versus a liquid and that has to be plowed through. In terms of the sorts of discussions that are still going on in solid state physics and non-crystalline materials physics, it really becomes a, the idea of what glass is, is locked down right now in discussions of subtlety and relaxation and the sort of local reorganization that Bobak was talking about. Of, is it just, this sort of, things just sort of shimmying themselves around to find their way to a more comfortable place in the absence of what we would think of as a thermal process that actually gives things enough juice to actually move around.

Bobak: I still, I guess I'm still trying to understand if this is sort of a spectrum of things because you're talking about ergodicity and then I want to, is there a threshold at which those things just kind of, like a perspective, let's say, something I'm familiar with, planets right? We define a set of rules and we say, if you are spherical, have a certain size you are a planet. If you're not, then, you're a dwarf planet. If you're smaller than you can't pull yourself into a ball then you're just an asteroid. Is that the same case here? Is that what defines a crystal or is a crystal always perfectly something?

Jane: So, within crystal chemistry there's the idea of the defect. Crystalline defects are thermodynamically driven. The number of defects that you're likely to find are a function of the Boltzmann constant. The more you heat something up, the more thermal energy you provide the more defects that you're going to introduce. So, you can get to a point where the number of defects that are present, so, the deviation from the known good crystal structure actually sort of cross over into a realm where the dynamics, the kinetics that are driven by the presence of defects seems to begin to override the, just what you would define as, just what's going to happen because the crystal is a crystal. That's that transition from order to disorder or ergodicity to non-ergotic. But

what ultimately defines the fact that something is a solid and this is my own point of view and this is a subject of some controversy. To me, ultimately the word solid, and this is because I work with artists, a solid is, if I drop it does it break or does it splat. Does it fill the container in which it's in in some sort of reasonable time frame or does it not. From that point of view glass is most definitely a solid and it's solid over lifetimes of universes, right?

Jessica: Yeah, so people are always trying to argue about the flow and viscosity and stuff. And there was a French group that did some calculation to try to figure out, can we calculate the viscosity of glass? And they calculated it and they found that it was, in fact, so large that if you were ever going to see it, an affect that was ever going to affect your calculation or your engineering structure or anything it would take like tens of thousands of years. So, at the end of the day, if the question is, is the glass a solid or liquid, perhaps the answer is it doesn't matter. For the purpose of what we're doing today, in our lifetimes, glass is a solid and that's what we need to know about it. Right? And the semantics of how liquidy it may be at room temperature is just worrying about something that's just not going to factor into the safety, you know, or the reliability of anything that we are going to make in our lifetimes.

Jane: And the specific sort of physics questions that you'd be after such as local relaxation or things like that, are esoteric enough that it's perfectly fine to consider those within the context of a bulk solid and then just add them onto just atomic motion under local chemical potentials. it really gets away from the real practical definition of if I hit this it's going to break. Or, if I heat it up it's going to crystallize. So, the silicon tetrahedron is on the order of, what is it, .7 engstrom or so. So, that's short range order, that's SRO in glass parlance. MROs or mid-range order, starts to be, sort of from 2 to 10 tetrahedral units so getting on the order of a few nanometers. And this is like that work we were talking about earlier, out of Berkeley, what you can see under a

transition electron microscope with good contrast imaging. And there you can begin to see that oh yeah I'm making rings or I'm making chains or double chains or something like that that's going on. But I can see those mid-range order units themselves are isolated islands that then have a certain bend or twist or something that's going on that causes a non-continuity. Ah, you can see that there is a boundary layers and so those then begin to get on the order of tens of nanometers and beyond.

30:03

Silicate glasses and by that I mean glasses where the silica solvent that are then modified by the addition of particular elements or ions such as sodium or potassium or lead or boron or aluminum, those sorts of structures all tend to fall on this local order, on the order of a few angstrom to midrange order on the order of a few nanometers and then longer range order beyond the nanometer, beyond that nanometer type scale. And at that point you start to get also also on the order of crystals, of crystal grains that would begin to populate ah, a particular material. So, that's the range of orders that we're talking about.

Jessica: Yeah, and that's a part of the reason that we use, ah, modeling a lot, to look at it. Because if you're talking about nanometer, you can be talking about a few thousand, ten thousand, fifty thousand, a hundred thousand atoms, and that's certainly something that we're capable of simulating these days. So it's really interesting to look at the inconsistency and the different structures that you can form inside the glass.

Jane: I mean, people think of glass as a material of commerce or of cultural importance, goes back about 3,500 to 4,000 years. Honestly it's really only been in the last hundred years that we've had the tools, say, of X-ray diffraction, to begin to probe the structure. And only in the last, like 20 years, really powerful, say, synchrotron x-ray sources or electron diffraction sources to go deeper and then the type of stuff that

Jessica can do, these molecular dynamics simulations is really only a few years old that can actually handle, I mean, it takes tens of thousands, hundreds of thousands of atoms in order to actually simulate a structure that lacks a crystal structure. You can get by with, you know, a few hundred atoms if you know that you've got a defined crystal structure, but if you lack one you are into statistical gray areas if you're under a hundred thousand atoms. And frankly, that's new, that's brand new.

Ben: Incidentally, if get one of these crystallizations, is the crystal noticeably different than a glass in terms "of, oh no, I cooled it too slowly, now it's a crystal!" Would it look differently?

Jessica: Do, you mean, like, physically? Like if you do any sort of characterization you'll get a distinct peak associated with the formation of the more ordered structure. So, any sort of diffraction based characterization technique would pick it up in a hot second, right? And Jane might know something more about this. I think in some cases with the glass ceramic you actually get a little bit of a change at the interface which can affect the transparent properties. So, in most cases, the examples I've seen of glass ceramic have been opaque compared to being clear. Usually the glass ceramic has a lot of interesting constituents in it that might be impacting the transparency.

Jane: Exactly. As you go from a truly, like, extended non-crystalline material, it's also extendedly isotropic, right, it has the same properties in every direction. And as you begin to create interfaces and boundaries as your crystalline, ordered areas get to on the order of quarter to half wavelength of light, say a hundred to two hundred nanometers, you'll actually begin to see structures and you begin to see an optical representation which often comes in as dichroism. You'll begin to see scattering off of these pieces and it can be really quite lovely and some artists actually shoot for this sort of long level, crystallization type behavior because it, essentially, recreates the scattering. I mean, why is the sky blue and the sun-set orange? You begin to see that in

pieces of glass that you look through them and they're orange. And if you just looked at the reflected light they are blue for exactly the same reasons as the sky. So, you do get to a level where' as the crystallization progresses, you create domains that are on the order of quarter to half wavelength of light, you actually do begin to see with your eyes, effects that are related to that domain size.

Ben: Okay, so let's imagine that we are, like, glass artists and we messed up. We heated up, but then didn't cool our glass fast enough.

Jane: Glass artists never mess up.

Laughter.

Jane: It just becomes a new expressive mode.

Ben: Okay, I see.

Jessica: Exactly.

Ben: So, we're creatively failing.

Jane: Yes, yes.

Ben: So, instead of cooling it down fast enough so that you get these weird, frustrated systems inside it, you get little pockets of crystal. Little crystal seeds and the slower the system cools, the larger the seeds will be until the point where they can interact optically and at that point it will get all scattery, it will be shimmery and rainbowy.

Jane: Right, eventually it will become opaque, eventually. White glass is just glass that is shot full of crystals. White isn't a color in glass, it just means that it is incoherently reflecting back at you whatever you are throwing at it. For example, if you're going to make a white glass you dissolve into that silica solvent things that, as you cool it down would preferentially form lots of small crystals so you'd put in phosphate ions or fluorine ions for example that would make calcium fluoride or magnesium fluoride

crystals at the hundreds of nanometers type size and that would make a very lovely white glass.

35:05

Or phosphates or titanium oxide, things that, as your cooling down will rapidly loose interest in the silicates around them and pull together and make lots of tiny crystals leaving the silica glass behind. It's a mixture, it's a precipitate, it's just like if you make a sodium chloride in a calcium carbonate solution, you mix them together and all of the sudden the calcium carbonate falls out. It's solution chemistry, but instead of an aqueous chemistry system, it's a silicate chemistry-based system. So, all the sorts of rules that you learn in freshmen chem, doing the little chemistry magic trick type experiments, it happens in glass, it's more complicated but it's still a matter of, well, does it want to stay in solution or does it want to crystallize and fall out of solution. The good news as that you can use sort of standard solution chemistry methodology to analyze it. The bad news is that the more that you put things into the solution, the more the solution itself becomes the solvent. This is why you don't learn about glass chemistry in freshman or sophomore level, you have to wait till you're like a senior and you've taken three semesters of physical chemistry before you can actually understand what we call strong electrolyte solution which is what a glass solvent combination is. I mean, it's beautiful, it's logical when you understand the foundations of it but you can't get to those foundations until, until you've been whipped to a pulp by various chemistry professors.

Ben: Okay, so, now we have at least a sense of what makes a glass a glass on the microscopic scales. Suppose somebody comes into your lab and they give you a shiny rock. How can you tell, based on the macroscopic properties or any test you can do, whether or not they've given you a glass or not.

Jane: Working at a museum, the question then immediately becomes, can I do destructive or non-destructive testing.

Ben: You ask the person and they say yes, whatever you want, I just want this rock out of my house. My husband is obsessed with this rock, it needs to go. Do whatever you want, tell me if it's a glass though because we have a bet.

Jessica: Well, the first thing I would say if someone walked into my lab and said that, they said, I found this rock and I want to know if it's a glass or not I would say, well, there's a 99% chance that it's not a glass because glasses just don't form that often in nature, right? Like, there's essentially, I can think of two main ways, one main way and one slightly less popular way you can form a glass. And the most popular way would be, like, a volcano, right. When a magma can cool fast enough to form a glass called obsidian. Or, if you have a really dry environment and you have a lightning strike on a sand you can form a very small, kind of glassy structure.

Jane: Or a meteor impact.

Jessica: Or a meteor impact. So, it's just not that common to form naturally in nature. So, the chance of someone walking up to you and saying, here, I have a glass. I'd be like, probably not. But, you could test it in a few different ways and probably the easiest way to tell would be to see if there's any dependence, like, ah, in a crystal system system or a fracture, will react differently depending on how you crack it. So, if you apply force along a specific plane of atoms it will fracture more easily than in a different direction. But, because amorphous systems have this kind of random mixed up frozeny liquidy, kind of complex structure, then they have isotropic properties. Which means that if you fracture the system um, from lots of different directions it should fracture consistently throughout the structure. And then, um, if you do the characterizations, if you do any sort of magnetic resonance or x-ray de-fraction or anything you get one really broad peak indicating that there's no consistency or repeatability in the

base units. So, that's how I would go about trying to decide if I had a glass or not. Even though the answer would be, probably no.

Ben: So, the first one definitely makes sense. So, if you have a crystal and you hit it with a hammer it will break differently depending on how you hit it but if it's this glass at the molecular level, there's no special direction, there's no, and so, if you can't split it in half easily.

Jane: Yeah, the term that gemologists use is cleavage. Say you have a salt crystal, you can very easily break that into nice, perfect cubes with a razor blade because it likes to break along those nice, clean lines of bonding. Glass doesn't have that so that type of cleavage is a really good indicator. If you're a geology person like me and you happen to have a hand lens in your pocket at any given moment you can even look at the breaks and even if they look sort of glassy or what we call conchoidal fractures, you can look at those pretty carefully and see if it's actually breaking a more discontinuously as the crack finds its way from grain to grain. Some crystalline materials break in a way that it looks a little bit like a glass but when you're trained to the eye you can actually tell the difference between a true glass breaking versus just a fine grain material breaking.

39:52

Ben: Hmm. And the second one Jessica listed, you know, you can use x-ray diffraction or one of these other analytical tools. In x-ray diffraction, what you do is you shine x-rays through a crystal, through the solid object and then you turn the object and so x-rays, the wavelength of the light wave is about the same size as the distance between two atoms in your solid. And so, if you turn it, ah, the way that the x-rays are reflected through your crystal will depend on how all the atoms inside the crystal are lined up along planes or in patterns. The way the x-rays reflect through your object is going to um, indicate what this internal repeated structure is. But, if you take a glass

and you shine x-rays through it you won't get this patterned reflection. Instead it will just kind of do whatever it does and it won't give any indication of internal structure.

Jessica: Essentially, like, you're looking for, like, a kind of, ah, a consistency, a repeatability, you cancel out when multiple atoms are lined up so that you get this distinct difference between the planes of atoms, right. But there's no planes of atoms in glass so there's no canceling out, it's just kind of a random mixture. I mean, usually you get something, you can get one kind of huge broad peak and you look at it and you say, well, I don't know how far the planes of atoms are, I can't index this crystal structure, it's just stuff, right. And so that's essentially what you're getting. And that comes up, I think we discussed that, MMR has the same kind of characteristic because the local structure is so disordered, it's disordered enough that you can't index it and that's really what kind of breaks down. So if you're looking at something and it's too broad, it's all mixed up and disordered, you're like, oh, it must be a glass or you know, some other mixed, complex mixed material, so.

Jane: There's even courser methods because of the way that glass cools down and the structure that it forms, crystalline structures tend to be more packed. The atoms bring themselves into positions of higher density whereas with a glass they get locked into more extended or expanded structures. So, in most cases the density of a crystal or a mixture of crystals that forms from a glassy liquid, will have a higher density than the corresponding glass. So, for example, if I have an obsidian which is this black glass that most people are familiar with that forms in volcanic eruptions, ah, that has a density of about 2.5 grams per cm^3 but if the liquid that was going to form obsidian cools more slowly, say, at the center of a lava flow or even below the surface of the Earth and forms granite instead of obsidian, then it has a density on the order of 3. So, from 2.5 grams per cm^3 to 3 grams per cm^3 , you notice this when you've handled a lot of glass samples. Someone can hand you a piece of material and you immediate-

ly sense that it is lighter than would be if it was crystalline. It's sort of one step beyond when someone hands you something that looks like it could be glass and it's plastic and you notice that it's much, much lighter than it should be. So, which a sort of, you can very quickly determine, also glassiness versus crystallinity often just based on a gross density calculation. Another way that you can get at it is also thermal conductivity. Glass, because it lacks a crystal structure, it also lacks coherent phonon motion, phonon vibration or the motion of the atoms as they vibrate in response to temperature, isn't coordinated. So it has low, in the same way glass has low electrical conductivity, it has low thermal conductivity. So when you pick up a piece of something that is glassy, again, when you're sort of sensitized to this type of affect, you notice that it doesn't suck the heat out of your hand. It feels warmer than a crystalline material that immediately pulls the heat from your hand, it feels colder. And there's actually tools that you can buy that will zap whatever material that you're interested in with a low power laser and then has an IR camera associated as well. And so you look at the thermal bloom as the heat impinges on the surface of the material. If it has very low thermal conductivity you'll see that the heat will stay isolated but if it has high thermal conductivity the IR camera will see the thermal spread much more quickly. So, it's a very quick, non-destructive way to look at the difference between an inorganic glass and a crystalline inorganic material.

Ben: Oh man, that's fantastic. I was going to say that the, the ah density thing is like how you can tell that the person who's boxes you're moving, if they're moving house, is like really poorly assembled because like, if they haven't done a good job packing their boxes will be poorly assembled and they'll need more boxes to carry less stuff and so each box.

Jane: Are you moving? This is the second time that you've gone to a moving analogy Ben.

Ben: It's the best metaphor, I have keep going back to it.

Jane: It's really good.

Ben: The second one is really neat.

45:00

Jane: Yeah, like I said, it translates to electrical conductivity as well. I mean, one of the major uses over the last century, of glass, industrially is as an electrical insulator. There are, actually, societies of people that collect electoral insulators from utility poles.

Bobak: They're beautiful. I mean, in their own way. There's a collection here at the Huntington Library right now.

Jane: Yeah. There's beautiful examples of glass formulation, glass color, also there's stuff with glass insulators that have been sort of out in the sun for decades or so and you can actually see solarization. You can see the effect of ultraviolet exposure on glass structure in the way that the colors change in the material with knock-on damage from UV radiation on the transition metals that are dissolved in the glass. It's really lovely.

Bobak: Another nice thing about this, a number of techniques that you guys are discussing are, not surprisingly, techniques that we use in space exploration, right, to also understand mineralogy and chemistry of what we're looking at on Mars. We also look at thermal conductivity, X-ray diffraction where we have an instrument for diffraction as well on Curiosity. So it's kind of a fun thing to be able to understand. So, you know, you made the comment earlier that glasses are exceedingly rare in nature and I'm really curious about how we know so much and how we got to this state of knowledge and then I really want to hear about where it's going, too. To me, I think about so much that we know is inspired by what's around us and if glasses are not very common I'm kind of curious how we came to where we are.

Jane: Actually, before I get to glass for humans, let's talk about glass in the universe. So, even though we say that glass is very rare, we're really specifically referring to glasses based on silica backbones. Sort of, one of these factoids that you can win a drink at a bar with, I suppose, is that the most common type of glass in the universe is actually water. That most of the interstellar water that's crystallized, recent results from radiotoloscropy is actually showing that it is amorphous. So, it, the water itself, if it crystallizes very, very rapidly as you'd expect in a 3k environment will not crystallize but solidify in a way that is amorphous. So, the glasses themselves, writ broadly, the phenomena, the kinetic conditions necessary for things to come together and solidify without crystallizing is certainly possible. When we say that glasses are rare, it's more in the lithosphere of Earth or Mars or the Moon, those conditions necessary, that, the chemical conditions. The composition space of the combination of atoms that will actually create a solution that will self-frustrate on solidification, that's a very small subset of all the possible things that silicates in various lithospheres will do. Um, humans really discovered the ability to make something interesting that was glassy only about 3,500 years ago. Even though they were making things that were, at least partially, glassy well before that as a part of either glazes on pottery or slags in early metallurgy. Anytime that you had the temperature to get up hot enough, and this is like, above, say 700 or 800° C, that the solution chemistry would begin to run. At that point, you begin to make things that when you cool them back down, whether they were glazes on pots or fused sands for amulets or beads, you begin to make stuff that was at least partially glassy. But it was only about 3,500 years ago that the right formula, the right temperature ability and someone being smart enough to recognize that it had happened, that people began to make stuff that was predominately glassy that didn't need a backing structure in order for them to stand alone. So this is an object that is entirely based on glass that doesn't need a pot and it's not floating on top of molten

metal. And so this happened in Mesopotamia. It was quickly picked up in Egypt, between 3,200 and 3,500 years ago. But they didn't know they were making glass. What they thought they were doing was doing magic to make semi-precious stones. Because of the types of materials they were working with, the first sort of colors that they stumbled across were very similar to lapis lazuli which was a very valuable stone in both Egypt and Mesopotamia. They thought they were making fake lapis. Or, they thought they were making real lapis actually and if you look at the linguistics of it, they honestly thought that they had figured out how to cheat nature. And they were making it near net shape, that was the brilliance of it. Instead of having to, like, mine a rock from a certain mountain and then hand it to a lapidary artist and have them grind it into some sort of a shape, now they had something that they could mold and squish and shape to get it to this near net shape engineered object that they could just hand to the lapidary for a little finishing work and then they were done and save, you know, six months of work.

50:07

It was absolutely an engineering and economics type of discovery that really led glass to become more valuable. But it was almost a thousand years before that glass changed from these sort of opaque, deeply colored objects into something that was transparent. And there again, though, the value was now, okay, we went from something that looked like lapis or jade or cornelian and now it actually looks like quartz or it looks like diamonds. So, glass' value for thousands of years was really in its ability to look like something that it wasn't. It's memetic properties, petramemetic properties, that it was a shapable rock that you could put into some sort of a form. Once you understood the solution chemistry you could make it orange or red or green or yellow or blue or whatever you wanted it to be because you knew what to add into and maybe what prayers to utter in order to get just the right color. But that was history of glass

for many, many years. It was about the optics of it, and certainly its appearance. But much more it was about its formability, the fact that it had a working range. Because most materials, when they're a liquid and you cool them down, they go from being this centipoise liquid to suddenly freezing and becoming a rock. The fact that you had something that would go through this long transition of workability, of viscosity from a billion poise to a thousand poise that you could control if you knew what you were doing, if you had a skill set and you could almost throw it like a pot but at the end of an iron instead of on a rotating wheel. That was a huge engineering and materials processing innovation that, ah, really held sway for thousands of years. It was only, really in the last 150 years with the advent of intentional chemistry and the discovery of the periodic table and reclaiming from alchemy the solution chemistry of if I put this in, it changes the properties in such and such a way. That's a good thing so I can put in the uranium and it makes it look weird. I can put in the lead and it makes it long and high diffraction and high dispersion. That sort of understanding is really only about a hundred years old.

Ben: Any other questions, Bobak?

Bobak: Well, I was curious where it's going. I mean, like, what will that, so, for example, the computational physics of glass, I'm curious what, Jessica, you think that is going to lead to.

Jessica: Well, improvements in the ability to simulate, you know, the structures and properties of glass and stuff is really kind of designed so that we can identify specific structural elements which are the strongest or have the best optical properties for a certain application. And then, essentially designing, you know, experimental glass systems which take advantage of what we identify computationally. So, it's sort of this idea of building and designing a glass from the atoms all the way up. And that way we can investigate, you know, a large compositional range or glasses with unusual puri-

ties that would be difficult to create experimentally before we go through the effort of figuring out all of the different processing details. First we can see if we want the glass and if it's useful and if it meets our needs and then we can start to create it in and of itself. So, that's kind of the future is trying to combine, my opinion is, the combination of the computational and experimental methods to really have precisely tailored glasses which can meet a lot of different engineering needs. So, when Jane talks about, like, the ability to put all sorts of different elements inside the glass, that's really, kind of, really the power in specifically getting a glassy material that you want. I mean, as long as the system remains, you know, vitreous or amorphous, you can put a lot of weird stuff in glasses. And that means that you can get a lot of interesting properties that can fit a lot of different applications. You know, I think the development of Gorilla Glass is an example, ah, on the surface of, you know, phone screens and stuff has really highlighted that glass can fit in a lot of places and be a very reliable, you know, material for a lot of optical applications and stuff and we're only getting better and better every year. So, the more we can tailor glasses the more, I hope we're going to see, a lot more glass in a wider variety of you systems and engineering applications where before, you know the brittleness of glass or issues with reliability or, you know, developing glasses, hopefully we're going to see a lot more glass in a lot more interesting places.

Bobak: Well, it was really interesting that you mention Gorilla Glass and I was reading an article about that recently. And what was really interesting to me is the fact that there is still very reliant on trial and error. That it wasn't a clear, like, oh, you know, I run this equation, I do some analysis and then I figure out the exact ratio of things to put in there and I follow this process and it's done. I mean, it is for the ones that come out of, but, to figure out the next generation of that glass, so much of it was still trial and error, that was kind of fascinating to me.

54:52

Jessica: Yeah, I've heard it been said that the development of specific glass compositions for many years and decades and generations has been more of an art rather than a science. So, it's kind of, you know, someone has a feeling or they noticed a trend, so they're trying to incorporate that and that still, because glass is so complicated, I think we're a while away from being able to say, no, it's all completely scientific. But, especially with computational ability to look and see, okay, what is it about this glass that's giving us a property we want and how can we exploit that to its fullest extent, right? So, I think eventually, now that we have the tools to analyze the glass on such a fine scale we're getting closer and closer to a point where we can actually use science, you know, combined, of course, with scientific discovery and all those wonderful things that Ben was talking about at the beginning. Um, in order to come up with glasses that are exactly what we want rather than having to kind of wait for a mixture of fortuitous ideas and everything to come together to create just the glass that we want.

Jane: Yeah, I think that there's an angle on that, especially, like related to the current generations and next generations of Gorilla Glass, as an example that you might be able to predict that, okay if I put this much, of different constituents into that glass, I'm going to make such and such a structure but the reality of how that particular structure is going to respond to an extended stress field, if I push on it in a certain way or I drop it in a certain way, that's very difficult to predict. Jessica, you can go into this a great deal I know, what a crack is and how a crack actually interrogates a structure bond by bond as it moves from one side of a material to another is an enormously complex decision making process that those atoms have to make.

Jessica: Yeah, so, in the case of a glass, because you have so much interesting and variable local structure, it's not as though all SiO bonds are exactly as stable, right. It

depends on how many oxygens a silicon has bonded to. It depends on what other atoms are nearby, you know, how much modification the structure has, if there's any other network forming units if there's only boron oxides or aluminum oxides or anything else that's going on. So, even just trying to figure out like, what's the weakest link in this glass structure, that's something that we're still investigating, right, and if we can figure out exactly what the weakest or the strongest is, we can create glasses which are, you know, more or less stable. Are stronger, more resistant to fracture and can heal themselves and that's kind of a part of the area that I'm looking at, is trying to figure out within all this variability, that just provides a wonderful opportunity to exploit that, to make stronger glasses, more reliable glasses or perhaps the opposite. Maybe you want a glass that fractures easily for whatever reason. That's just another opportunity that we can exploit.

Bobak: Yeah, I mean, that makes sense. I mean, I think about car windows, right, they are designed to shatter in very specific ways so that they break away from you, right, and things like that. So it makes sense that there might be ones that you do want to have predictable failures I guess.

Jessica: Yeah, so in my case that ties a little back to the fact that I'm in a geochemistry department now, so, in terms of fracking, they are really interested in being able to predict how systems which contain silicon and oxygen, you know, how they break specifically. So that we can predict, you know, what fracking is going to do when it is performed in the subsurface and making sure that we are doing that as safely and as economically as possible. So, that's a case where you really, kinda want to promote a very specific type of fracture while avoiding other types of fractures. So, even when we're talking about the stability of different SiO bonds, their structure and their variability, etcetera, etcetera, there's a whole other aspect that can really affect the stability of the system itself and that's the environmental factor, right. So, none of the glass

that we're talking about anywhere exists isolated from the surrounding environment. In some cases, even just the presence of mere water, or like a human environment, can have a huge impact on how the glass responds. So, if you imagine, you know, you have a fracture and you zoom all the way in to the very tip, where it, you know, you are looking at an individual broken bond. If you introduce water into that system it can react and it can promote the fracture or the breaking of different bonds, right. Because the water wants to form SiOH system and under high stress it can actually promote the, you know, the movement of the fracture, the crack propagation rate through this system. And then the question becomes, okay, so that's just water and let's just say pure SiO₂, what happens if the water has sodium atoms in it, right? What if the water has sodium and so does the glass? Do they exchange back and forth? How fast do they exchange? Do they promote breakage or not promote breakage? And that's another kind of tool in our toolkit that we can look at to see, okay, what is the affect. And if we know what the affect is of different compositions of both the environment and of the glass, can we use that to design even more specialized systems or to understand what happens in even more extreme environments. And if we know what happens in extreme environments then we can design glasses which can be stable and we can, you know, introduce them into another use, engineering application, essentially.

60: 03

Jane: Such as nuclear waste disposal, for example.

Jessica: Yeah. So, nuclear waste glass is a fantastic example of a case where they just put everything and the kitchen sink into glass, right. So, it's sodium borosilicate but then they also put in, like, 28 or more, a lot of these are proprietary stuff and I don't know what they are. Um, but they just put in an immeasurable number of things in it because they can. It's a great way to take, you know, an actinide or something radioactive and just kind of lock it away because it finds a, you know, "happy position"

or you know, local equilibrium where it can just sit then it's very, very stable. So, you know in some cases we want to pick what we want to put in it and in other cases we just want to put everything we can to keep it kind of locked away in this stable, silica backbone type structure, so...

Jane: In an industrial setting, say, for making window glass or cell phone cover glass or whatever it is, that question of reliability becomes paramount where you're essentially selling reliability. And so being able to quantify, what's the likelihood that an impact of a certain level is going to cause the glass to fracture or not fracture. Being able to quantify that is very important and then being able to, after the fact, to be able to look at what actually happened and say, that's my fault as a manufacturer or that's your fault as a consumer, can become a very important thing as well if you're testifying as an expert witness, for example, in a fractography, to be able to say that this is your fault, this is my fault. That discipline is very important. But then also, then looping that back into glass composition and glass processing research and manufacturing development to make glasses that are as reliable as possible because of their formulation or the uniformity with that they manufactured, that can be a big thing as well.

Jane: So, when I worked for Corning, the gentleman who ran our mechanical properties lab, his job was to direct people to break things. The quote that he had up on his door was the motto of the American Paleontological Society, which, in Latin, if I, fake Latin but still Latin, "Frango ut patefaciam" which translates to I break in order to reveal. So that idea that fracture or the way that any material breaks is kind of going back to what we said at the beginning, this idea that the fundamental principle of materials engineering of structure property relationships that I can understand what's going on at the atomic, molecular, mesostructure level by how the mass of quintillion's of atoms behave together. If I break something in the right way I'm paying attention, I've

got it well instrumented, I can actually understand about what it is that I've broken. Even though I've broken it, oops, but at least I've learned something, right? And it's always important to learn things if you're going to destroy something in the process.

Jessica: We had a speaker just a few weeks ago, from NASA, and he was talking a lot about the reliability of the windows on the International Space Station which is obviously a case where you want extreme reliability. Which brought up an interesting point that because it's such a large piece of glass it's really hard to predict the reliability because the glass will always fail at the weakest point. So, it's the weakest link theory. So with the super large piece of plate glass it's really hard to say what the biggest flaw is and to keep it as small possible. And so that made a particular challenge because you're in an environment where the stakes are so high, right, and you need such a tight seal but obviously, you know, astronauts want to be able to look out of the space station because that's a part of the fun. So, you want to use a glass and so I thought that was an interesting thing that they, you know, you really need to have something so perfect and so pristine and the margin of error is so low that it makes a challenging environment even if you're just making a window. So, I thought that was an interesting thing that I hadn't considered.

Bobak: Yeah, and they finally found the first damage to it with a micrometeorites that had smashed into it. So I'm, I'm very curious now if they've done any sort of testing, obviously it would be non-destructive testing of that plate of glass, to see how it started failing and if you know anything else that would come of it. I mean, they have windshields as well they can use to cover it but you're right, nobody wants to leave those closed all the time so they can't look outside.

Jane: And you can't call the local AAA glass service to come and change out your front window.

Bobak: One day, one day.

Jane: One day we will. I know that at least some of those windows are actually made out of pure fused silica. Corning Incorporated has made a number of windows actually going back to the Gemini project of a lot of the early spacecraft.

65:00

So, one way that they get around the liability issue is to get rid of anything but silicon dioxide. So that you have, essentially, the strongest most reliable, least opportunity for any sort of process deviation to introduce any risk into the material.

Bobak: Yeah, that's an interesting trait, that, you know, you could say applies maybe in a lot of what we do which is to think about not necessarily the best solution but the most predictable and understandable solution is often the winner. Our wheels, for example, on the rover, come from a solid block of aluminum in order to insure that there is no, you know, welding or any other things. But you could certainly consider going to a much fancier things or doing other things that might be stronger but would have some unpredictability in the process or some failure mode that you hadn't really fully considered.

Jane: You want something that is as simple as possible that references as much as possible, just the fundamental physics of atomic attachment. Right...

Bobak: Right.

Jane: The thing that we studied the most, that we understand the best with as little human intervention between you and those bonds as possible.

Bobak: That's right. It would surprise me that some of the facilities that they have up there that they wouldn't be looking at other materials for the future right, that are still, I'm still waiting for the transparent aluminum revolution, guys, that I saw in Star Trek 4, so...

Jessica: I wouldn't hold your breath on that one, but...

Laughter

Jane: Yeah. Let's talk about quantum mechanics. Inherent electrical conductors are a problem.

Laughter.

Bobak: Do you guys know of any testing. I know that they've done testing of formation of crystalline structures in microgravity but I'm not familiar if there's any similar such tests for glass. And if not, let's propose one guys.

Jessica: Yeah.

Jane: So, there has been some on orbit studies of glass formation but they've been directed toward this point that we brought up early on about glass' corrosive nature that whenever you melt glass typically it has to be in something and if it's in something chances are that it is interacting with it because glass is such a corrosive material. And actually, this gets back to my space cred, my doctoral dissertation was actually done under NASA graduate research fellowship through the microgravity program down in Alabama, nominally to study glass formation done in, ah, containerless. So, floating, like laser heated, floating globules. So, if you remove that container, if you remove that surface contact in terms of both contamination but also the geometrical contributions to crystallization that the surface of whatever it is that you are crystallizing and can actually promote nucleation and crystal growth. So, if you can do it as a floating globule then that's a good thing if you're trying to make a more stable glass, a cleaner glass, a more uniform glass. So, some resource has been done on that and it definitely points to validating the hypothesis that cleaner glass, less contact, definitely makes for a more stable and really curious structures. We talk about these mesostructures, things can be different depending upon whether it's had that templating possibility off of whatever it is that's inside of. You can actually get different types of glass structures. They're still glassy, still non-crystalline but different meso structures developing, mid-range order structures developing.

Bobak: Not as a catalyst you mean but as from the interaction with a solid surface.

Jane: Yeah, it's not exactly a catalytic reaction it, geometry will promote crystallization. Anything that gives a little bit of a push out of that potential well, toward the ordered state, exactly, you can see it in, ah, you pour soda water into a dirty glass and you get bubbles streaming off from the particular dirty points.

Bobak: Yeah.

Jane: The carbon dioxide is nucleating and precipitating at the dirtiest parts of the glass. So the glass itself will crystallize at the points where it has the sharpest points for example or where the chemistry is favorable. It's not exactly catalytic but it's certainly is ah...

Bobak: Champaign glasses, right, where they etch on order to create the bubbles...

Jane: Yes.

Bobak: Great, okay.

Jane: Yes.

Ben: Hey Jane, if I had a glob of molten cooling glass and put, like, a source of ionizing radiation near it, would, like, the nucleation form on the, ah, trails of...

Jane: Ooooh, that's a good question.

Ben: Like would you get, like, little beans of crystallization in your glass.

Jane: I don't know if you'd get crystallization or if it would actually deter it. It's a relatively rare form of natural glass but the term is metamict. So, you can actually amorphatize a crystalline material by doing enough knock on damage with, like, alpha particles for example.

70:01

So, you can get in there and like, disrupt the structure so much with momentum damage by particles that you can amorphize it. So, you're sort of saying, kind of boosting the local amorphitization with momentum.

Ben: That would do it, yeah.

Jane: Yeah, I don't know. That's kind of cool. My son plays with technetium a lot in graduate school and maybe we could get him to do something.

Ben: Um, what else is there to mention. Let's see. Is there more glass blowing space to talk about?

Jane: Only that no one's done it yet.

Ben: Oh, yeah, I suppose.

Jane: But, it's kind of an interesting fluid mechanics problem I suppose. You start getting into what happens when you have this high viscosity material, very high surface tension material but then you turn off density, right. You turn off a directional gravitational field, how does that change the ability to form the glass. All your dimensional groups that are dependent upon some sort of a g-term, if you remove that, how does that change heat flow, convection, convective currents, ah, glass flow. It's something that some of us will, we'll definitely start to talk about around a bar...

Ben: If you have another glob of cooling glass and there's little crystallization nucleus' in it, will, the crystals, like, sink to the bottom over the course of it cooling. Do you end up with a gradient?

Jane: No, because that gets into, sort of, stokes type of relationships. The density of an individual crystallite and how it's to move in a gravitational field, like, that force compared to the viscous resistance is minuscule. So, settling over industrial type timescales is minimal. But you actually see it in geological systems. You'll actually see, in say, like a large, um, molten intrusion ah, below the surface that maybe cools off over several hundreds to several tens of thousands of years, you'll actually see the first

things that will crystallize out of that are like the quartzes and the zircons. The high temperature, high density things will actually fall to the bottom of the magma chamber and then the crystallization will kind of go forward from those pieces. But, in like an industrial scale you'll make these little, tens of nanometer micron type crystallites, they're so small, they are essentially colloids at that point. They tend to stay in suspension, they don't have time to move under gravity. So, that wouldn't be a huge advantage or disadvantage to blowing glass in space. It's going to be more that a typical glass blower or flame worker, they rely on gravity a great deal. They fight it but they also use it as a way to elongate the material or as a way to change the shaping of things. So if you suddenly turned off gravity or turned down gravity it would definitely change the way that a glass blower manipulates a bubble or a gob of glass at the end of a blowpipe.

Ben: Holy crow. So many things I don't know.

Jane: And nobody knows. I mean, who the heck is going to let somebody blow glass on the space station?!

Laughter.

Jane: Here, I've got this gob of glass at a 1100° C, let me just sort of spin that around a little bit, okay? You worry about M&Ms getting into the works, imagine that.

Ben: I would watch that. I would show my physics classes that video. That would be fantastic.

Jane: Oh, absolutely. It will be very interesting to see, you know, in the next hundred years or so, if we start colonizing the Moon or Mars and working at 1/6 or 1/3 gravity and people are going to need to make stuff out of glass. How are they going to accommodate that will be very interesting.

Ben: Well, that was fantastic. Good work everybody. Thank you Jessica, thank you Jane. You have pleased me. Your efforts have born fruit and that fruit is sweet. Here's some fruit. Jane, you get a plum.

Munching sounds and laughter.

Ben: Oh gross. And Jessica, you get a pear.

Jessica: Crunch, crunch, crunch.

Ben: Alright, I'd like to thank my guest, Bobak Ferdowsi, thank you for coming on our show, I hope you had fun.

Bobak: Thank you guys, that was super fun. I appreciate it and thanks for answering my questions.

Ben: Alright.

74:02

Ben: Well, that was really fun. So, it's announcement time. First announcement, please give us a review on iTunes. Or, tell your friends online about us. On another note, we're still humbly soliciting your donations. Your donations go to paying our server fees and our project to transcribe all the episodes when they come out and our sweet project to buy people microphones. All of those are going super well.

You can send us one time donations through PayPal off of our website or you can go to our sweet Patreon site and give us a recurring \$2 donation. This particular episode of the Titanium Physicists has been sponsored by a collection of generous people. I'd like to thank the generosity of Paul Mans, Hierus Ascar, Simon Lunt and Robert Brooks for their donations. I'd also like to thank our emperor Courtney Brook Davis, Mr. David Lindells, Mr. Carl Lockhart, our eternal friend B.S. and Randy Dazel. A Miss Tina Roudio, the enigmatic Ryan, a gentleman named Crux, and Gabe and Evan Weans, David D and Dan Vale, a Mr. Alex, WTL, Mr. Per Proden, Andrew Wattington, Mr Jordan Young and John Bleasy. A Brittany Crooks, James Crawford, Mr. Mark Simon,

Two Songs Gang of One, Mr. Lawrence Lee, Sixton Linason, Mr. Simon, Keegan Ead, Adrian Shonig, Andreas from Knoxville, Cadby, Joe Campbell, Alexandra Zany is great, Weena Brett, Eric Duch, Atein Raymond, and a gentleman named Peter Fan, Gareth Easton, Joe Piston, David Johnson and Anthony Leon as well as Doug Bee, Julia, Nora Robertson, Ian and Stu. A Mr. Frank, Phillip from Austria and Noisy Mime. Mr. Shlowmo Delow, Melissa Burke, Yaseem Omarasazee, Spider Rogue, Insanity Orbitz, Robert Johnson, Madam Sandra Johnson, Mr. Jacob Wick, a Mr. Jon Keyes, a Mr. Victor C, Ryan Klaus, Peter Clipsham, Mr. Robert Haupen, Elizabeth Theresa, and Paul Carr. A Mr. Ryan Knewl, a Mr. Adam Kay, Thomas Shiray, a Mr. Jacob S, a gentleman named Brett Evans, a lady named Jill, a gentleman named Greg, thanks Steve, a Mr. James Clausen, a Mr. Devon North, a gentleman named Scott, Ed Lowington, Kelly Weiner-smith, Jocelyn Read, a Mr. S. Hatcher, Mr. Rob Arizato, and a Mr. Robert Stietka. So, that's it for Ti-Physicists this time.

Remember that if you like listening to scientists talking about science in their own words there are lots of other lovely shows on the Brachiolope Media Network. The intro song to our show is by Ted Leo and the Pharmacists and the end song is by John Vanderslice. Good day my friends and until next time, remember to keep science in your hearts.

77:38

Ben: So, to start us off Bobak, do you have any general questions about glass?

Bobak: Well, I'm just now realizing that Corning Glass, the name, has an actual city associated with it. It's a really good start to learning things today.

Jane: Yeah, the company was named after the city.

Ben: Really?

Jane: Yes.

Ben: It's not like, ah...

Bobak: Hershey, Pennsylvania.

Ben: Hershey, Pennsylvania.

Jane: Hershey, Pennsylvania. No, the company existed over in Brooklyn back in the 1850s to 1860s and then they packed up the whole company on a barge in about 1868, almost a 150 years ago and sent it up the rivers and canals and ended up over in Corning New York, over in western New York State in 1868. Corning was a better place to manufacture glass back in the 1860s because of cheap non-union labor and a confluence of coal from the coal fields and sand and other ingredients coming in from the St. Lawrence Seaway up and down the Erie Canal.

Ben: And the deal is that two of these tetrahedrons can share a corner. So, two silicone atoms, it's like we're building legs out of these little triangles where their corners can stick together. These little pyramids.

Jane: Oh, absolutely. When I give lectures to artists who often know absolutely nothing about chemistry. I actually bring, I went and bought tinker toys, old school 1960's tinker toys, ah, so that I can show them how electrons around a nucleus determine the bonding arrangements. But you can bond things together, ah, locally that are determined by, say the number of holes drilled in your hub. But that doesn't restrict you from having those individual combinations of a central hub and some hubs around it from actually having some twisty degrees of freedom so that they can actually make something that's disordered even though the central units themselves have a very restricted order based on inorganic chemistry rules. It's actually very eye opening for people to see when you can make something that looks totally random and crazy but it's made out of things that are absolutely highly structured.

79:39 End