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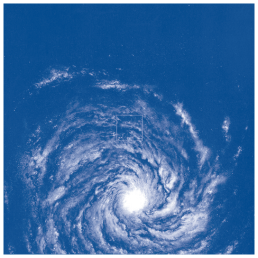

We picnicked inside a fiberglass radome (a portmanteau of radar and dome), atop the tallest building in Cambridge. The Green Building, otherwise known as Building 54, houses the fields of Geology and Earth Sciences on the lower floors and Astronomy and Atmospheric Sciences on the upper floors. It was only late October, but the temperature was already below freezing, so we bundled up in fur caps and heavy jackets to endure the cold inside the dome. We sat next to a defunct radar satellite that had recently been hacked by students to bounce beams off the moon.

Sara requested high-protein brain food, so we made hard-boiled eggs and prepared them so that each egg was boiled for a different increment of time, which was annotated on each of the dozen eggshells:

5 min, 6 min, 7 min, 8 min, 9 min, 10 min, 11 min, 12 min, 13 min, 14 min, 15 min, 16 min

Sara ate a twelve-minute egg to test her theory that there is a threshold beyond which there is no effect on the egg, so boiling longer only serves to waste energy.

(FIG. 1)

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MICHAEL: Do you know what your kids are going to dress up as for Halloween?

SARA: Yes, one son is going to be Buzz Aldrin, an astronaut, and the other son will be a pirate.

AMY: Similar.

SARA: Actually they are quite opposite in personality.

AMY: They are both going on journeys.

SARA: Yes, agreed. Astronauts are adventurous, most especially the early astronauts like Buzz Aldrin. Buzz Aldrin can be alternately outspoken, rude, obnoxious, and fun, while the current astronauts typically appear to be more conforming and obedient. A pirate is kind of like the early astronauts: a radical who challenges authority.

AMY: Is Buzz still alive?

SARA: Yes. For MIT's 150th anniversary in 2011, there were a number of celebratory symposia. One of the symposia was "Earth, Air, Ocean and Space: The Future of Exploration"

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and included a panel of ten to twelve astronauts all together. Buzz certainly stole the show.

Amy: Now that you're warmed up, can you tell us about your research?

Sara: My research is on exoplanets – planets that orbit stars other than our sun. We know of hundreds of exoplanets right now and there are likely far more than trillions of planets out there in the universe. We are trying to understand what exoplanets are made of, how to detect them, and how to find signs of life by way of unusual amounts of "biosignature" gases in exoplanet atmospheres.

(FIG. 2) Sara showing us our place in the universe, a rendering of what we believe our galaxy, the Milky Way, looks like. "This is showing us approximately where our sun is, and trying to illustrate how far away we can find other planets, around other stars. At the end of this little column, that's how far away the Kepler stars are, but even those stars we consider too far to see. So despite the fact that we have a hundred billion stars in our galaxy, and there are upwards of hundreds of billions of galaxies, we can only really find planets close to our home, right near our sun."

Amy: So we've been using the differing scales in *Powers of Ten* to frame our conversations with people; where would you place your research on that continuum?

Sara: Most of my research is placed in the planetary scale, which is 10^7. Our earth has a radius of about 6,400 kilometers, so its diameter is about 10^7 meters. What I love about exoplanets is that the research operates on other scales. For instance, 10^{12} encompasses the orbits of the Solar System's four inner planets. Or 10^{13}, which encompasses the solar system with Pluto partially off of the picture. In fact I could even argue that when we want to think about the probability of life in the Universe we first think of the scale of 10^{21}, the scale of our galaxy and even 10^{26}, the scale of the visible universe. One more thing I want to add is that because we are looking for signs of life by way of exoplanet atmospheric gases, we are trying to understand the gas outputs of microbial life on earth, trying to understand processes at a much smaller scale than planetary or planet orbit size, on the scale of 10^{-5}.

Amy: This movie was made in 1968, and it claimed that we were looking at the edges of our understanding at that time. How have the edges of understanding in your field changed from that period to now?

Sara: Well the movie went to 10^{24}, and in astronomy, we'd like to go a lot further. We have the capability for observing very, very far away. The size of the observable universe is roughly 47 billion light years or 4.4 times 10^{26} meters. We can't see further away than this because light more than 4.4 x 10^{26} meters away has not had time to reach us over the age of the universe. So the next power of ten, 10^{27}, is not observable. So, sorry you won't be able to do 10^{27}.

Michael: What is beautiful is that we will be able to observe it if we as a society keep aging. Eventually the light would reach us.

Sara: If we lived for billions and billions of years we could see a little further out.

Amy: So is that the goal of astronomy, to see out that far, but knowing you can't?

Sara: Astronomers have many different goals and most of our goals center around the concept of understanding where we came from. One of our goals is to know how the universe was born and evolved. And, we don't necessarily need to see the whole universe to move our understanding forward. For example, right now, outside of my window we can see the city of Boston on a macroscopic scale *(FIG. 3)*. And we know that there are other cities out there. We just can't see them from here but we could extrapolate or try to use other information about cities. With astronomy, it's a similar concept. We still have information about most of the components of the universe, even if we cannot see all of the very distant components.

Returning to the changes since the film was made, in the 1960s exoplanets were simply speculation; people hadn't even found them yet. There were a few leads which turned out not to be real planets, so people imagined that all planetary systems were just like our own. At the scale of 10^{13}, we see an image of our solar system where the planets are well sorted with the four small inner planets and the four outer giant planets. Theories were built, then, about planet formation based on the single example of our own solar system. But today with hundreds of known exoplanets – many, many known planetary systems – we have a completely different picture. And so now we believe that for exoplanets anything is possible within the laws of physics and chemistry. Any kind of planet you could imagine is out there somewhere.

Michael: What is an example that a layperson might not imagine?

Sara: A recent example is a planetary system called Kepler 11. Kepler 11 has six known planets, with five of those planets orbiting interior to what would be akin to the distance of Mercury's orbit. So five planets are squeezed into a location where our Solar System has one planet. Now imagine what kind of planets might the Kepler 11 planets be? Do you think they are like Mercury, very rocky and small? In fact they are not. Most of the Kepler 11 planets are twice the size of Earth and must have large quantities of gas in their atmospheres, making them more equivalent to a mini-Neptune than to an Earth. I can give you dozens of examples of anomalous exoplanets. So the sheer number of surprises is changing our philosophy about what other planets could be like. This changed paradigm of the range of exoplanet types is the biggest factor that has changed since the 1960s.

Amy: And how does that knowledge that there's more out there affect culture on a larger level?

Sara: What's fascinating about exoplanets is that in some ways popular culture is ahead of us scientists because of science fiction, things like *Star Trek*. Popular culture is already primed for our discoveries. I would say the public loves the discoveries that bring humanity one step closer to finding habitable worlds.

Amy: How do science fiction movies relate to scientific planetary knowledge?

Sara: Well you can pick any one. Let's pick *Avatar*. In terms of exoplanet knowledge, Avatar was ten years out of date. They depicted the Alpha Centauri star system in the film, and they imagined a Jupiter-sized planet in the so-called habitable zone of its host star, with a habitable moon in orbit about the planet. Right now, we know there are no big planets in the Alpha Centauri sun-like star systems; such planets have been ruled out by observations.

Michael: I'm imagining that *Avatar* must have had some team of scientists that helped them. Have you ever been consulted by Hollywood?

Sara: Absolutely. I really like Hollywood. At the end of the day Hollywood doesn't usually take my advice, but I have been a vessel for brainstorming in a unique way. The public has a huge appetite for black hole physics, time travel, outer space, relativity, exoplanets, and aliens. Even though the Hollywood fiction doesn't really match with our reality here in physics, it is wonderful to try and bridge that gap.

Michael: This fascination with life on other planets in popular culture, I wonder how that gets talked about in certain academic circles. I found it interesting that on the seventeenth floor of this building (The Green Building at MIT) the word "alien" is used.

Sara: It's not Hollywood, but in a strange way one great thing about MIT is that you can have a crazy idea, and it will be accepted. But there is a line drawn, and aliens definitely fall on the wrong side of that line. Instead we are doing the real search for planets that could have life; it's our goal to find so-called "habitable worlds," and when we find potentially habitable planets, we're going to look for signs of life on them. There is no question that others will follow and try to send or listen for radio signals. And, there's also no question in my mind that in the distant future people will try to go there, either with a robotic probe, which might take tens to hundreds of years, or alternatively to find a way for humans to travel there alone. The public loves the concept of aliens, and the public are our taxpayers who ultimately fund our space missions. So we want to connect with those people, but there's a difference between people who like to think emotionally and people who like to use logic. We were joking around that when I get my satellite communications ground station in the radar dome on the roof of my building, we will inaugurate the ground station by sending a radio signal message to a planetary system with a known planet that has some chance of being habitable *(FIG. 4)*.

Michael: What would that signal be?

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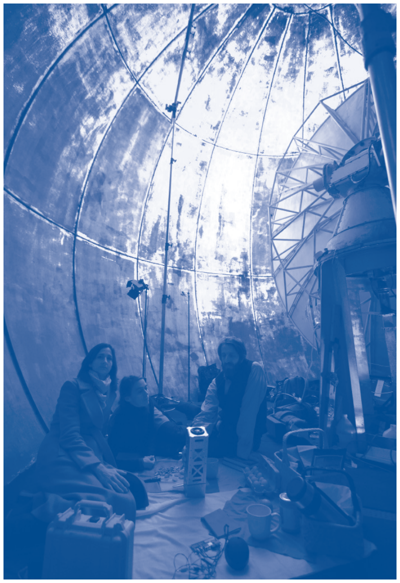

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SARA: Well, that's the question, what would the message be? I don't know. I think you two should think of something! Think of it this way: if the aliens are listening at the same frequency we are transmitting on, we would have to send something clever enough to get their attention. Because what if they're listening? We would have to send something really cool, but it must be something universally recognized as very clever, right? A message that is too specific to our own terrestrial-based culture might be a challenge for any alien society to interpret.

AMY: Can you talk about some of the tools you use in this search?

SARA: This nano-satellite demonstration model is called "ExoplanetSat".

This actual model illustrates a prototype nano-satellite we are building here at MIT and at our partner institution Draper Lab. The ExoplanetSat nano-satellite has three parts to it (in fact ExoplanetSat is a three-unit "CubeSat"). One part is this box here, inside of which would be a pointing system *(FIG. 5)*. The device has no fuel or propulsion, so the satellite will get disturbed by gravity and other forces while it is orbiting Earth. The pointing system inside the box would have reaction wheels to keep the satellite stably pointed towards a target star. Now, in addition to the reaction wheel control unit, ExoplanetSat requires an additional level of pointing control. The reason we want ExoplanetSat to point very precisely is to take the best images possible of the target stars, over and over and over again. Just like when you're taking a picture, if you shake your camera a little, the picture becomes blurry. The second pointing control is effectively an image stabilizer and is this little piece of hardware here: it's only little in size, not in dollar value! The second part of the ExoplanetSat nano-satellite is the camera. Here's the lens, and the camera also has a special detector here, similar to what the camera detector on your iPhone camera might be. Now moving to describe the third part of the nano-satellite, in the middle section is basically everything else: the flight computer, batteries, the board that controls power, and many other things. And on the outside, there would be deployable solar panels to gather energy to store in batteries. We might also have a baffle on the outside front of the nano-satellite, just like you have one on your camera, to protect the camera from stray light.

AMY: So you would launch this into space, and how do you get it back?

SARA: We don't get the satellite back. ExoplanetSat will communicate to us through radio signals that would reach our ground stations. And in later versions of ExoplanetSat, we plan to also communicate with the equivalent of the satellite cellphone.

AMY: So it lives out there forever?

SARA: Well, not exactly forever, but yes for about twenty years. After that, due to atmospheric drag, the satellite will spiral down and burn up in Earth's atmosphere. In fact, there is a rule for CubeSats that the lifetime must be twenty-five years or less. NASA and others want to have a bunch of CubeSats launch out of their standardized deployers (called P-Pods) on many of the rockets being launched. It's supposed to be a cheap way to get a lot of things to space.

AMY: There will probably be a secondary commercial service someday, a big magnet that goes up and collects all this orbiting junk once it's done being useful.

SARA: Well, it wouldn't be a magnet, but you could imagine a future where there is a requirement to include propulsions that will push small satellites into lower and lower Earth orbit so they can deorbit and eventually burn up in the atmosphere. Do you remember in the news, about a month ago, there was a big satellite that was looking down at earth that hadn't worked since the 1980s? It made mainstream news, because people were worried that a big chunk was going to hit a person, because they have no control over these old satellites. But I think it all burned up and no debris at all was found.

AMY: And the magazines on the blanket?

SARA: I chose a magazine from Iran, which covers exoplanets, just to show how the whole world loves exoplanets. And the thought of finding planets like Earth elsewhere, that has a chance to unify us as a human species, in that we all have a common interest that goes beyond any divisions that we have with each other.

MICHAEL: I found it interesting to see this IBM advertisement on the inside cover of this *National Geographic* (pointing to the inside cover of the December 2009 *National Geographic* with the text, "Are We Alone? Searching the Heavens for another Earth" over rendering of a newly discovered planet, Gliese 581e, that is theoretically twice the mass of Earth.)

It reads, "… a mandate for change is a mandate for smart" followed by a short text full of propaganda about economic opportunity connected to computation etc., but I'm interested in the sponsorship of your research: corporate, federal, or taxpayer dollars?

SARA: That's partly why I recommended this magazine (pointing to an October 2011 volume of *The Economist* with the text "Until politicians actually do something about the world economy … BE AFRAID" over a photo of a black hole), because it had a picture of the galaxy, with a black hole, but it wasn't about astronomy, it was about the economy. And we as scientists are tied to the economy for sure. We primarily have used taxpayer's dollars, and NASA supports a lot of exoplanet research. We are searching for and studying exoplanets in the interest of innovation, the intellectual strength of the nation, and education. That's why CubeSat projects like ExoplanetSat have really taken off, because CubeSat nanosatellites can be developed and built at the university level, where students can actually design, build, and integrate hardware and software for small space satellites that actually get launched. So, federal dollars support our research, and they support training students and we try to combine funding and training. A place like MIT has a big endowment, with continued private donations. But as the economy drops, these private donations go away. Right now, my research makes no profit, and so we rely on funds from the university, the government, or private donations, to keep the search for exoplanets moving forward.

AMY: Can you talk about where we are right now?

SARA: We are on the roof of the Green Building at MIT – the tallest building in Cambridge. We're inside one of two domes on the roof, the larger one.

In its heyday, the World War II-era radio dish inside this dome was used for Doppler radar. The dish measured raindrops and rain, sending out radio waves that bounced back to help study weather.

Right now the dish is used by a student group for moon bounce communications with people on other parts of Earth, done by bouncing radio waves off the moon. It's not used for research anymore, the students just do this because it's here and they can.

(FIG. 6) Extension cables pirated up to the roof of the Green Building to power a computer that reads signals received from the moon.

AMY: In terms of the life that you're searching for, do you ever imagine what that first sign of it might be?

SARA: I do imagine what it would be. It's extremely appealing to me, although it might not be that exciting for everybody else in the world. We're looking for a planet that is small and rocky, and one whose atmosphere shows unusual chemistry that indicates a high level of probability for life. We always blame people for being terra-centric, thinking of our own planet self-centeredly. But did you know the oxygen that fills our atmosphere to 20 percent by volume should only be present in the tiniest of quantities? Oxygen is actually created by life, by plant life, and photosynthetic bacteria. So we like to believe that there are aliens out there looking back at Earth, and that the aliens looking at our atmosphere see all this oxygen, and that the aliens realize so much oxygen shouldn't be here;

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and that the aliens will imagine there's life on our planet Earth generating all of that oxygen.

MICHAEL: Are there other things that would be abnormal to see in an atmosphere, besides oxygen, to that extreme?

SARA: There are many other gases that we can imagine. We just don't know, under conditions that are different from Earth, which gases would really be the ones to look for. We're working hard on this problem.

MICHAEL: We talked about the ExoplanetSat, and this new dome, which represent the technology currently in use. Can you talk about the tools that your field used in the 1960s and 1970s, around the time the film was made?

SARA: Many of the tools used in the research of exoplanets were simply not in existence in 1968. The best example is a space telescope, such as the Hubble Space Telescope, which was put into orbit in 1990. With Hubble (and other space telescopes) we can get above Earth's atmosphere, so our observations of other objects beyond Earth become much more clear. It's a great question because precursor technology existed, just not the modern technology that is needed. For example, space satellites were put up at that time, but not space telescopes. Similarly, computers existed, but not the kind with today's computing power. My field is driven by crunching large amounts of data that we get from space telescopes and modern ground-based telescopes, and also by computer programs that run at high speeds.

MICHAEL: One change in science hopefully has to do with women, being a woman in science. I'm thinking of stories about Vera Rubin at the Carnegie Institution for Science.

AMY: There is a story about Vera at an Astrophysics conference that took place at an observatory in the hills above San Jose, California in the 1940s. All the other physicists were men and were to stay the night upon the hill. At the end of the first day, Vera was asked to leave. She asked why she could not stay the night and the men told her that there was not a women's bathroom; therefore, they secured housing for her off-site. With that she stormed to the bathrooms and posted a handmade sign, 'WOMEN" and said, "Now there is!" and stayed the night.

SARA: Vera Rubin is one of the most famous astronomers alive. She is one of the discoverers of dark matter. I want you to know that before I came to MIT, I worked at Carnegie Institution for Science, where I got Vera Rubin's old job when she retired. It's not just that there are no women in science, but there are very few successful women. If you look around to say, who are the very best scientists, top of the field, regardless of gender or race or any other criteria, you still come up primarily with the names of white men. Things haven't changed enough. Vera and others were the pioneers who put up with a lot of stuff, and they made it easier for the next generation of women like me. But I've still had to face overt discrimination. The one thing that still upsets me is the internalization of gender issues and stereotypes. I've actually thought a lot about the problem of why there are so few women, and sometimes I think some of the simple solutions are helpful (like the timing of academic talks to accommodate for family schedules; and pausing the tenure clock for maternity leave) but there is a much deeper problem that is not being addressed. Vera used to complain and say that three academic generations have gone by, and there are not enough women in the physical sciences in academia to prove equality. So much more needs to be done.