Professor Sara Seager Dies Lecture
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Part I: Background

Over three billion years ago, an amazing event occurred. A humble life form, a simple single-celled bacteria, figured out something very clever: how to harness energy from the sun: photosynthesis. In the process the bacteria generated a waste gas, oxygen. Oxygen eventually filed the atmosphere to 20% by volume. We all need oxygen to breathe.

But oxygen is a highly reactive gas, it should not be in the atmosphere at all. Without plants and photosynthetic bacteria to continually replenish oxygen, our atmosphere would have virtually no oxygen.

This is how we aim to find signs of life, use telescopes to look at planet atmospheres far away for gases that might be attributed to life.

We assume that some life elsewhere uses chemistry to extract energy from the environment, to store energy, and to metabolize, just as Earth life does, and in the process generate waste gases. (We won't know if the gases are made by intelligent humanoids, or simple bacteria.)

Astronomers have found thousands of "exoplanets" and are on the verge of capability to search for exoplanet atmosphere biosignature gases

So, if there is an intelligent alien civilization out there, on a planet orbiting a nearby star, with the kind of telescopes we are hoping to build, looking back at Earth, the aliens will suspect life forms are here. Not by city lights, nor pollution, nor large structures such as the Great Wall of China, but by oxygen, a gas that doesn't belong that is not made in large amounts by volcanoes or lightning but only by life.

Every society in history has had astronomy as part of its culture. Today we are the first generation with the technological capability to find out whether or not we are alone.

Let me take you on a journey of scientific exploration.

Part II: Present

In the last year of the last century (millennium actually) we astronomers made a milestone discovery that enables our current search for atmospheric biosignature gases.

That is discovery of a transiting exoplanet—one that goes in front of its star as seen from our view point. Planets have all orbital orientations so it is just a fraction of planetary systems that are suitably aligned. The top shows an artist's conception—we do not spatially resolve any stars at that level other than the sun.

The bottom plot shows what we do see, the star's brightness is constant in time and drops by a tiny amount when the planet goes in front of the star. This amount is in the ratio of the planet-to-star area. And the animator has added noise to this curve which is why the line is "wiggly".

We know of thousands of transiting planets thanks to many ground- and space-based telescopes and also the method to find such planets is the dominant planet-finding method today.

Let us now look at some real and exquisite data from the James Webb Space Telescope. The drop in brightness is due to the planet-star-area ratio and is about one and a half percent for this particular exoplanet.

Here is how we observe exoplanet atmospheres. The exaggerated planet illustration at the top of the diagram shows a huge atmosphere. Let us think of observing the atmosphere at different wavelengths (or colors). At some wavelengths where the atmosphere is completely transparent, the planet is a fixed size as shown by the dark inner disk. At other wavelengths where the atmosphere is strongly absorbing and thus opaque, the atmosphere is an add-on, and so the planet appears slightly larger.

We are looking for a planet size that varies with wavelength to indicate the presence of an atmosphere.

Let's try it!

We are looking at real data from the James Webb Space Telescope. We see the transit depth on the y axis and time on the x axis. The colors are different wavelengths, as also indicated by the number in the top right. The black curve is a best-fit to the transit data.

Our job is to see if the transit looks deeper—that is the planet looks bigger—at any wavelength. Which wavelength?

Let us let this land. By eye we can see signs of an exoplanet atmosphere. An incredible time for astronomy.

Here is a different view of the same planet and some more details of current findings in exoplanet atmospheres.

Back in 1999 I was a newly minted PhD starting my postdoc at the Institute for Advanced Study in Princeton, USA. There were only about 30 known exoplanets at that time and no transiting exoplanets. So, hen I arrived at my new job, no one worked on exoplanets and people were confused about what exoplanet research was about. Everyone asked me, “What’s the next big thing?” I said, “A transit”. (At the time we knew of about seven so-called hot Jupiters, each a 10% chance to show transits, and had more such candidates in the pipeline). I had already begun my work on transiting planet atmospheres, so as soon as the first transit was announced I dropped everything and worked as hard as I could to finish my paper introducing the transit transmission spectra. Specifically, I predicted to look for sodium gas, a very strong absorber at visible wavelengths. Another team picked this up, proposed to use the Hubble Space Telescope to find sodium gas, and the field of exoplanet atmospheres was born.

Why am I telling you this? At the time, even with this invention and a successful prediction, I could not get a faculty job. People would say things like, “this is a one object one method success”. They didn’t think there would be enough bright host stars for this method to succeed. This was echoed by another comment. “Sigh, there will never be very many transiting exoplanets”. People thought the entire field of exoplanets would soon dead end.

Today there are thousands of transiting exoplanets and over a hundred exoplanet atmospheres observed.

By ignoring the naysayers, I was able to make inroads in many other areas of exoplanet characterization. Todays I have immense satisfaction in looking back on what was an amazing time of science exploration.

Now I say, “In exoplanets the line between what is mainstream research an what is crazy, is constantly shifting.”

Part III: Near Future

The planet we just talked about is a hot giant exoplanet with an easily observed puffy atmosphere, a planet too hot for life and with no solid surface. Our goal now is to push the methods down to small rocky planets of the kind that might host life.

To do this we focus on small stars, which are much more favorable for planet atmosphere detection with transmission spectra as compared to Sun-sized star hosts. This is because of the planet-to-star area ratios. Here you see an Earth-sized planet transiting a Sun-sized star. The same size planet transiting an M dwarf star takes out a much bigger area. Same for the atmosphere, because we can think of the planet atmosphere like the skin of an onion—that is tiny. So, the smaller the background star the better. And M dwarf stars are very common in our solar neighborhood.

We already have a handful of rocky exoplanets transiting small M dwarf stars that are the right temperature for life.

A couple of severe challenges need to be overcome. One is star spots which significantly contaminate exoplanet atmospheres even mimicking atmosphere signals. M dwarf stars tend to have a lot of spots.

The second problem is more insidious and has to do with the extreme lack of detail we have on exoplanets and the weak signals anticipated from trace gases in rocky explanet atmospheres. It will be a very tall task for us to robustly satisfy three key questions.

- Is the signal real?
- Is the signal correctly attributed (to the right gas)
- Is the signal a false positive—perhaps produced without life?

One major ongoing thrust is new sophisticated space telescopes that are specially designed to find an identify Earth twins. Perhaps by studying Earth twins—instead of the so-called Earth cousins around M dwarf stars—the more familiar context will enable a more secure detection and possible attribution of gases to life.

Part IV: Future

Or perhaps the evidence can never be 100% with our remote observations and we will need an entire new paradigm.

Like other research fields, exoplanets is a generations-long endeavor. And remember my saying, “In exoplanets the line between what is mainstream research an what is crazy, is constantly shifting.”

Here is one idea of what it might eventually take.

The “Solar Gravitational Lens Telescope” is a concept to use the Sun as a powerful gravitational lens. The Sun would be so highly magnifying it could enable images of exoplanet surfaces at a resolution of about 10 km. The telescope has to observe an exoplanet from the Sun's focal point, about 500 times the Earth-Sun distance, a distance to which no spacecraft has yet traveled. To reach 500 AU in a reasonable time (~25 years), the spacecraft would have to travel an order of magnitude faster than the one of our fastest ever space missions, the Voyager spacecraft.

My call to action is for all of us to continually to carve out some amount of time to spend on bold ideas. For us to use our personally honed judgement, to heed our “inner voice” and take action when the right mix of curiosity and opportunity align. The vast night sky reminds us of endless possibilities.

I wish you clear skies, clear thoughts, and your own incredible journey of exploration.