NASA Astrobiology Early Career Collaboration Award Report

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I'm lucky to be at one of the two universities in the country that offers a dual-title PhD in astrobiology and a related field (the other is Penn State). A major part of the philosophy of the astrobiology program at the University of Washington is teaching its students how to be interdisciplinary researchers because astrobiology is *hugely* interdisciplinary. Our field combines insights from astronomy, biology, Earth science, chemistry, and physics to synthesize a more complete picture of how life can arise and evolve on habitable planets. Being able to communicate effectively across disciplines is therefore a key part of being a good astrobiologist. In the UW astrobiology program, we're required to take survey courses that introduce us to major concepts and ideas in the patchwork of scientific disciplines that make up astrobiology, and we attend workshops on varied topics such as volcanism in Hawaii, marine life in the San Juan Islands north of Seattle, and instrumentation design at the Jet Propulsion Laboratory. After all of this, we're required to complete an astrobiology "research rotation" where we spend an academic quarter working on a project outside of our primary field of study.

I'm an astronomy PhD candidate working with Dr. Victoria Meadows, and for the past few years, I've already been working on a project that crosses over into the Earth sciences with my co-advisor Dr. Shawn Domagal-Goldman at NASA Goddard Space Flight Center. We've been studying how the climate, photochemistry, and spectrum of Archean Earth would have been affected by the global organic haze inferred from geochemical data. Shawn is also a member of the Advanced Technology Large Aperture Space Telescope (ATLAST, a name that reflects the community's impatience for such a telescope!) at Goddard, and Vikki suggested that I go out to Maryland for my research rotation to work on ATLAST and learn about the early stages of mission development. This sounded like a great idea to me!

I arrived at Goddard on April 13, 2015. In mid-April, the spring air was still brisk and chilly, but this changed rapidly as we moved into May as the azaleas burst into flower (I was living in the Takoma Park area, and one of its nicknames is "Azalea City." I *totally* understand why after spending springtime there!). At Goddard, I was introduced to Drs. Aki Roberge and Avi Mandell, other members of the Goddard ATLAST team who I'd met briefly before at conferences. I started working with them and attending ATLAST team meetings, so I was immersed in the discussions and concerns of early stage mission planning almost immediately.

1. Haystacks

One of the biggest challenges to directly imaging exoplanets is detecting the planet's signal above the noise background. A major component of that background is exozodiacal light (often abbreviated as "exozodi"), which is caused by starlight scattering off dust particles in the plane of the exo-solar system. Aki Roberge and her collaborators have developed the Haystacks model, which simulates how a solar system analog with realistic exozodi might appear to ATLAST. Picking out Earth against the background of shining dust can be like find the proverbial needle in the haystack.

Haystacks had simulated observations of the modern solar system, but a major theme of my own research is understanding how planets can change through time. So, one of my first projects was adding the early solar system (~3 billion years ago, corresponding to the Archean geological era) to Haystacks. I had previously generated spectra of Archean Earth with an organic haze, which I provided for Haystacks, and I generated new spectra of plausible early versions of Venus (based on Earth covered by water clouds and without biogenic gases) and Mars (based on an Amazonian Mars atmosphere generated by fellow UW grad student Meg Smith; *Smith et al.*, 2014). The giant planets remained the same. The spectra are shown in Figure 1.

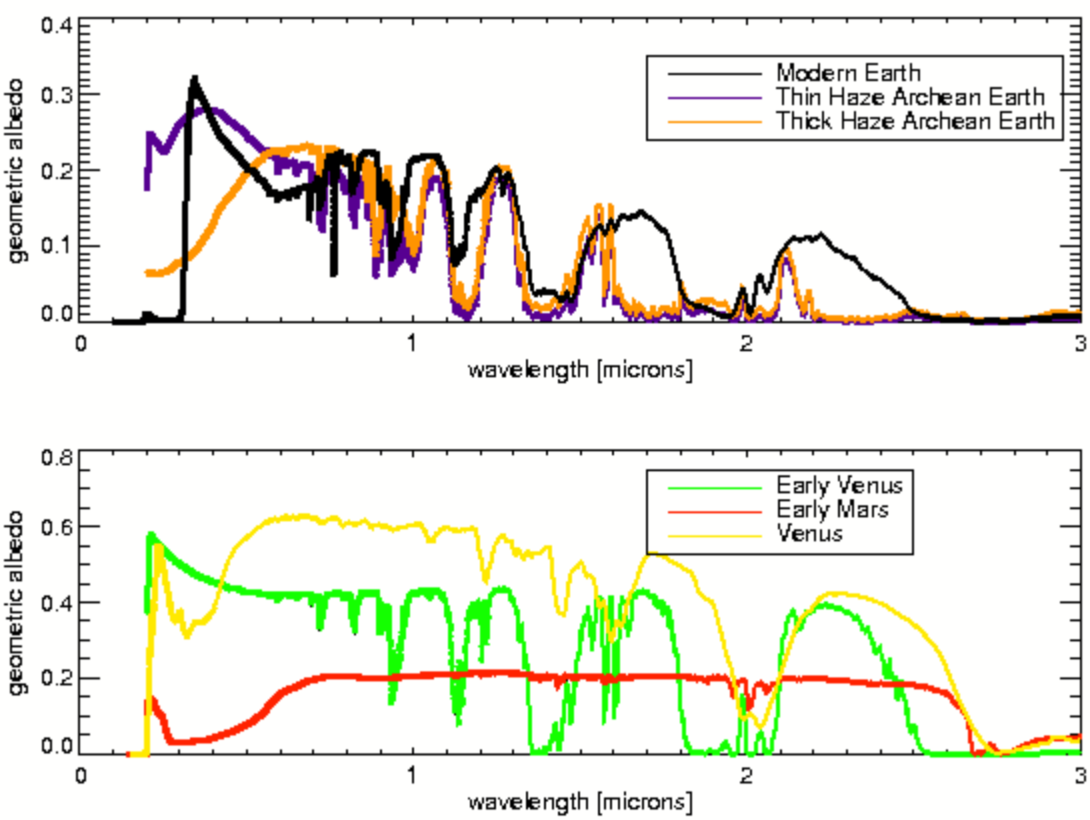

Figure 1. Spectra of planets used in the "early solar system" Haystacks model with modern Earth and modern Venus added for comparison.

The spectra in Figure 1 provide a good example of a type of challenge future exoplanet observations may face. Note how the strong short wavelength absorption ($\lambda < 0.6$ μm) of the "thick haze Archean Earth" spectrum superficially mimics the short wavelength absorption from iron oxide on Mars ($\lambda < 0.7$ µm) and the feature from Venus' unknown UV absorber and SO_2 ($\lambda < 0.5$ µm). Very different processes on these very different worlds generated these similar spectral features. Archean Earth's organic haze formed from methane photolysis, and the bulk of that methane was biogenically produced, so for Earth, this haze can be regarded as a type of biosignature. The nature of Venus' unknown UV absorber is still a mystery (hence the 'unknown' in its name!), but it may be caused by ferric chlorine cores or elemental sulfur coatings of sulfuric acid cloud particles [*Markiewicz et al.*, 2014]. Mars' iron oxide feature is the result of past oxidation of its surface, possibly through processes involving ancient liquid water. If a spectrograph characterized these worlds and provided no spectral information longward of 0.7 µm, it might appear that Archean Earth, modern Venus, and Mars are similar. Clues to the true nature of these worlds can be found at longer near infrared wavelengths where methane, water, and carbon dioxide produce strong absorption features. The wavelength range of ATLAST (or any similar space telescope attempting to characterize exoplanets) will have to be chosen carefully and be sufficiently broad to enable characterization of a diverse suite of worlds. The near-infrared hosts strong absorption features from a number of interesting gases, but as discussed below, there are significant challenges to going redward of approximately 2 µm.

There would have been more exozodi in the Archean because there was more dust in the plane of the solar system billions of years ago. We used a scaling relationship for Archean dust density from Su et al. (2006) (dust ~ $t0/t$ with $t0 = 150$ million years) to scale the dust level and approximated the Archean dust density as 3 times the modern level. The Archean sun was dimmer than the modern sun but more active at UV wavelengths, so its spectrum was scaled according to the relationship from Claire et al. (2012). A frame from the Archean haystacks datacube is shown in Figure 2.

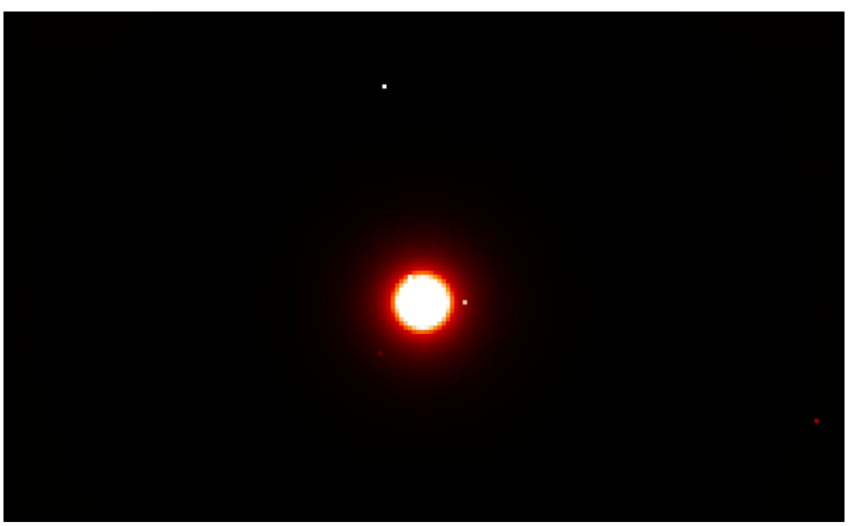

Figure 2: A frame from the Archean Haystacks datacube. The bright circular region in the center of the simulation is exozodiacal dust in the inner solar system. The inner planets are: Venus (11 o' clock position), Earth (3 o'clock), and Mars (6 o' clock). The outer planets visible here are Jupiter (11'o clock near the top of the frame) and Saturn (4 o' clock near the right edge of the frame).

Although Haystacks has a realistic exozodi model, it was missing a few other noise sources that might confuse observations of exo-Earth: background galaxies and Milky Way stars. My next project was to add these to the model. I went to the Space Telescope Science Institute in Baltimore with Shawn and Aki to meet with Dr. Gregory Snyder, a researcher whose focus is galaxy simulations. Our requirements for the "ideal" background galaxy field was to have a pixel scale (0.1 milliarcseconds per pixel) and spectral resolution that matched the Haystacks model. Gregory was kind enough to provide us with galaxy fields that matched our pixel scale requirements in the Hubble Space Telescope V, I, Z, J, and H filter bands. I was able to interpolate between these filter bands to recover spectral resolution that matched the Haystacks model.

The density of the Milky Way stars in a given field of view depends on the galactic latitude (i.e. the height above the plane of the galaxy, where most of the stars are concentrated) we observe at. The TRILEGAL Milky Way simulator [*Girardi et al.*, 2005] worked well for our purposes. TRILEGAL generates starfield densities at user-input latitudes and provides the stellar magnitudes in the Sloan u, g, r, i, z, J, H, and K filter bands. Similar to the galaxy fields, I was able to interpolate between the filter bands to recover the stars' wavelength dependence at the Haystacks spectral resolution. Figure 3 shows the Haystacks model's full exozodi against a field of background galaxies and Milky Way stars at galactic latitudes of 3 degrees (left) and 15 degrees (right). The Haystacks model is currently being written up in Roberge et al., *in prep*. As future work, I would like to investigate the best methods for distinguishing planets from background stars, which are also point sources. Some methods we might use are the proper motion of the planets against the background star fields, the motion of the planets around their stars, and spectral or color information of planets versus stars

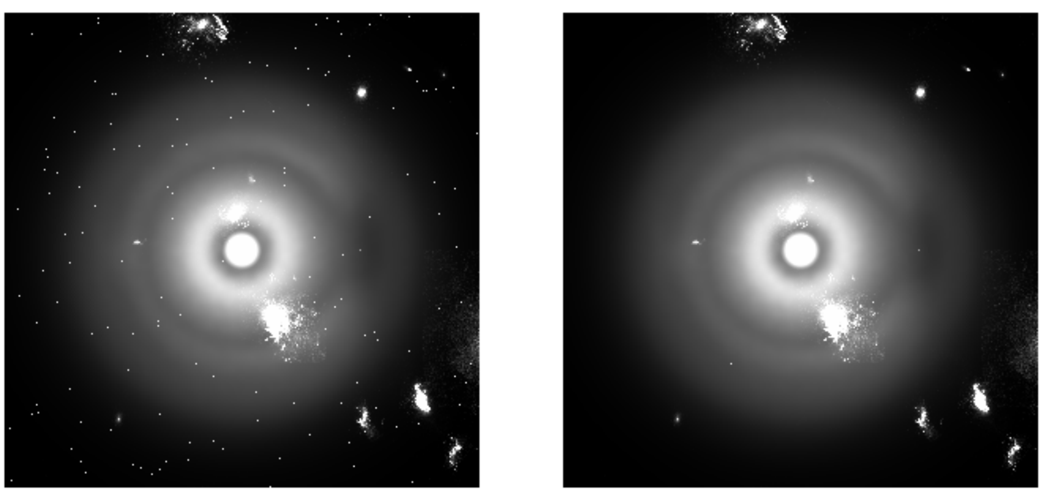

Figure 3: The haystacks model at 3 (left) versus 15 (right) degrees above the galactic plane. The higher density of stars closer to the galactic plane is clearly seen by comparing the number of point sources in the left and right frames.