NASA Astrobiology Early Career Collaboration Award Report

Giada Arney, University of Washington

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.

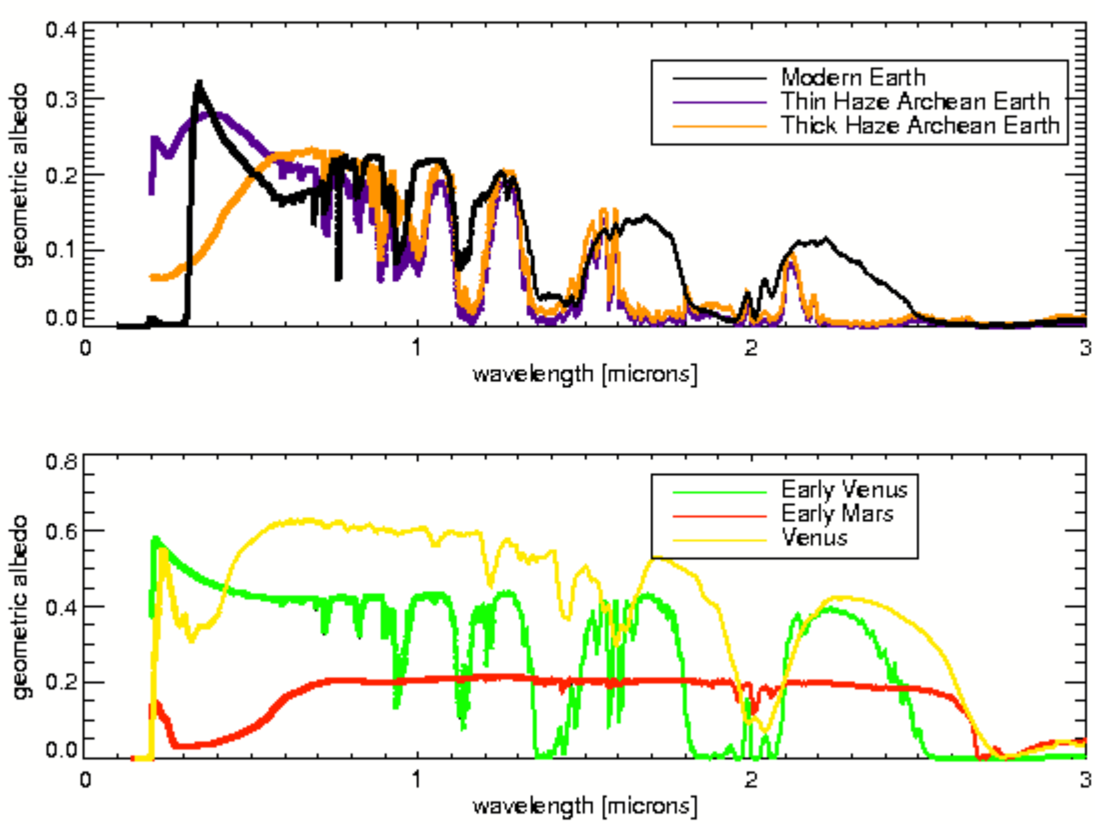

Figure 1. Spectra of planets used in the "early solar system" Haystacks model with modern Earth and modern Venus added for comparison.

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 (λ < 0.7 μm) and the feature from Venus' unknown UV absorber and SO_2 (λ < 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.

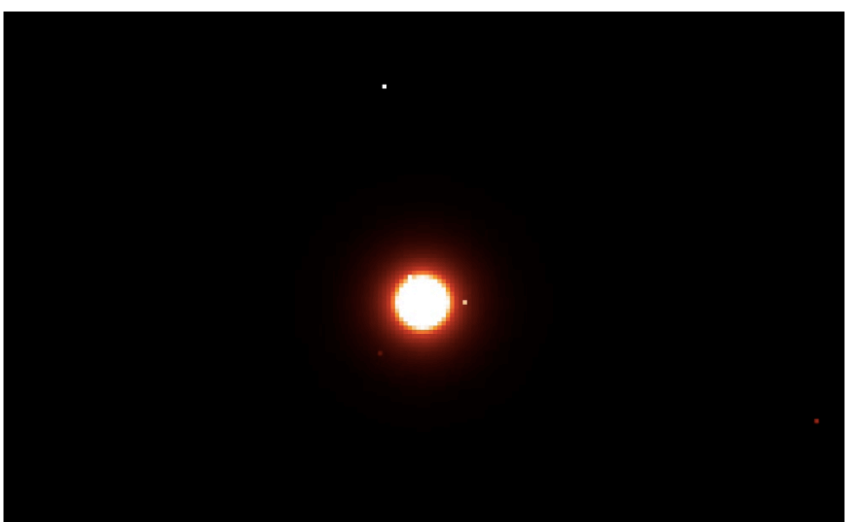

Figure 2: A frame from the Archean Haystacks datacube. The bright circular region in the center of the simulation is exozodiacal dust in the inner solar system. The inner planets are: Venus (11 o' clock position), Earth (3 o'clock), and Mars (6 o' clock). The outer planets visible here are Jupiter (11'o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

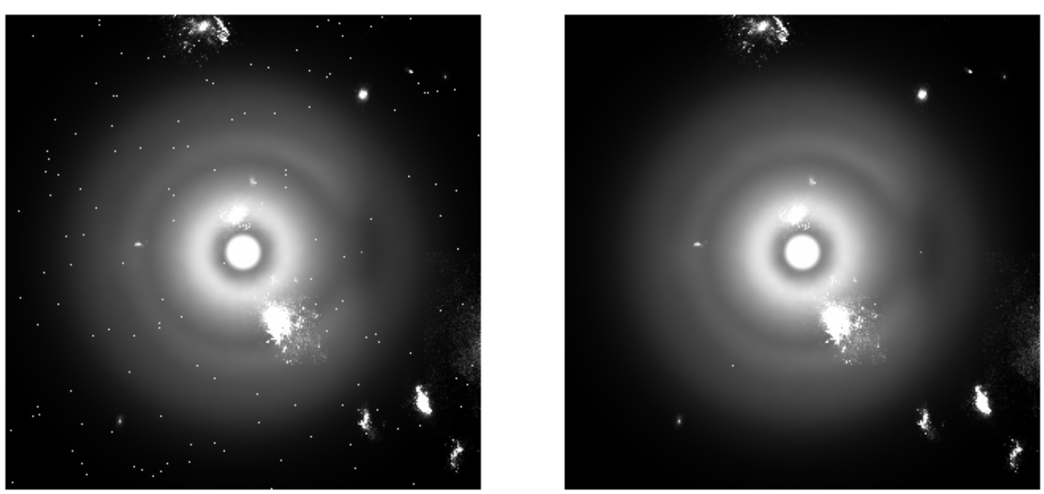

Figure 3: The haystacks model at 3 (left) versus 15 (right) degrees above the galactic plane. The higher density of stars closer to the galactic plane is clearly seen by comparing the number of point sources in the left and right frames.

2. The ATLAST Noise Simulator

Besides Haystacks, the other major project I worked on at Goddard involved using the noise simulator developed by Dr. Tyler Robinson to simulate observations of planets with ATLAST. I ran a variety of planet types through this simulator, including the spectra shown in Figure 1.

The integration time required to spectrally characterize a planetary target depends on a number of factors including the size of the telescope, the system throughput, and the telescope's operating temperature. The ATLAST nominal operating temperature is 274 K: this is the temperature the telescope would be tested at on the ground and is just warm enough to prevent ice crystallization on the optics. To maintain consistency, the telescope in space would be *heated* to 274 K so that it operates in the same conditions it was tested in. To go significantly colder, expensive cryogenic cooling is necessary for the ground tests, and this has been a major cost driver of the James Webb Space Telescope. There is a trade off we need to be concerned with here: observations at wavelengths longer than approximately 1.8 μm require a cryogenically cooled telescope because the telescope's thermal background starts to overwhelm the signal, but this is costly. Is it worth it? This is a question the ATLAST team is still grappling with, and simulators help us to understand what observations will be feasible with different telescope architectures.

Figure 4 shows the wavelength-dependent integration times necessary to achieve a signal-to-noise of 10 for Earth at a distance of 10 parsecs for three different telescope architectures: a 4 m telescope with 50% throughput and T = 274 K, a 4 m telescope with 50% throughput and T = 180 K, and an 8 m telescope with 20% throughput and T = 274 K. These are roughly equivalent to a small telescope with a starshade and no cryogenic cooling, a small telescope with a starshade and cryogenic cooling, and a larger telescope with a coronagraph and no cryogenic cooling. The impact of the thermal background becomes apparent near 1.6 μm: note how the integration times for the cryogenically cooled 4 m starshade-telescope system are actually shorter than the larger 8 m, warm coronagraph-telescope system longward of roughly 1.7 μm. However, these integration times are still unfeasibly long on the order of 10^2-10^3 days! Continuous observations of a planet over this amount of time may not be possible: unless the system is observed face-on, the planet will go through phases that may drop it below the brightness detectability threshold, and it may cross within the inner working angle of the telescope where it cannot be seen at all. These are issues that should be addressed by future work. (As an aside, phase-dependent information from planets can be very useful and may allow us to detect glint from oceans [*Robinson et al.*, 2010]).

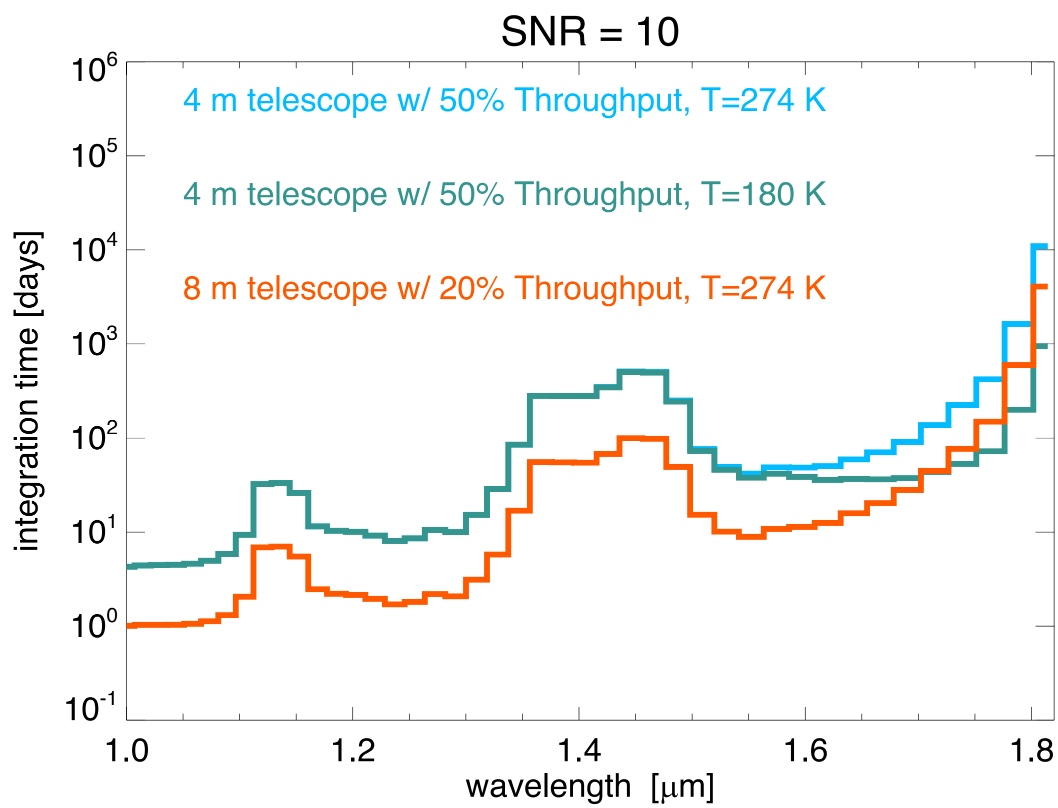

Figure 4: The integration times necessary to observe Earth at a distance of 10 parsecs for a signal-to-noise of 10 for three different telescope architectures at a spectral resolution of 70.

In the visible part of the spectrum, the thermal background does not affect observations, and the size of the telescope and its throughput dominates the observation time as shown in Figure 5. This figure shows two 4 m telescopes with 20% and 50% throughputs (to simulate coronagraph and starshade architectures, respectively), and an 8 m telescope with 20% throughput (coronagraph architecture). An 8 m telescope has integration times about an order of magnitude shorter than then 4 m telescopes. Shawn presented these results from the ATLAST noise simulator at the AbSciCon meeting in Chicago in June 2015.

Earth is, of course, not the only type of planet we will observe with ATLAST. For an 8 m telescope with spectral resolution R = 100, obtaining a signal-to-noise of 10 at 0.5 μm will take on the order of a few days. Figures 6 and 7 show the spectra of Earth, Venus, Mars, Jupiter, and Saturn that can be obtained in the same time it takes to observe and characterize Earth. Mars is the only one of these worlds that cannot be characterized in this amount of time due to its small size as evidenced from the large amount of noise in its spectrum. However, spectra for Venus, Jupiter, and Saturn, if they are visible to the detector, would come "for free" if we characterized Earth. Uranus and Neptune are not shown because they are too dim to be characterized, with characterization times on the order of 10^3 days.

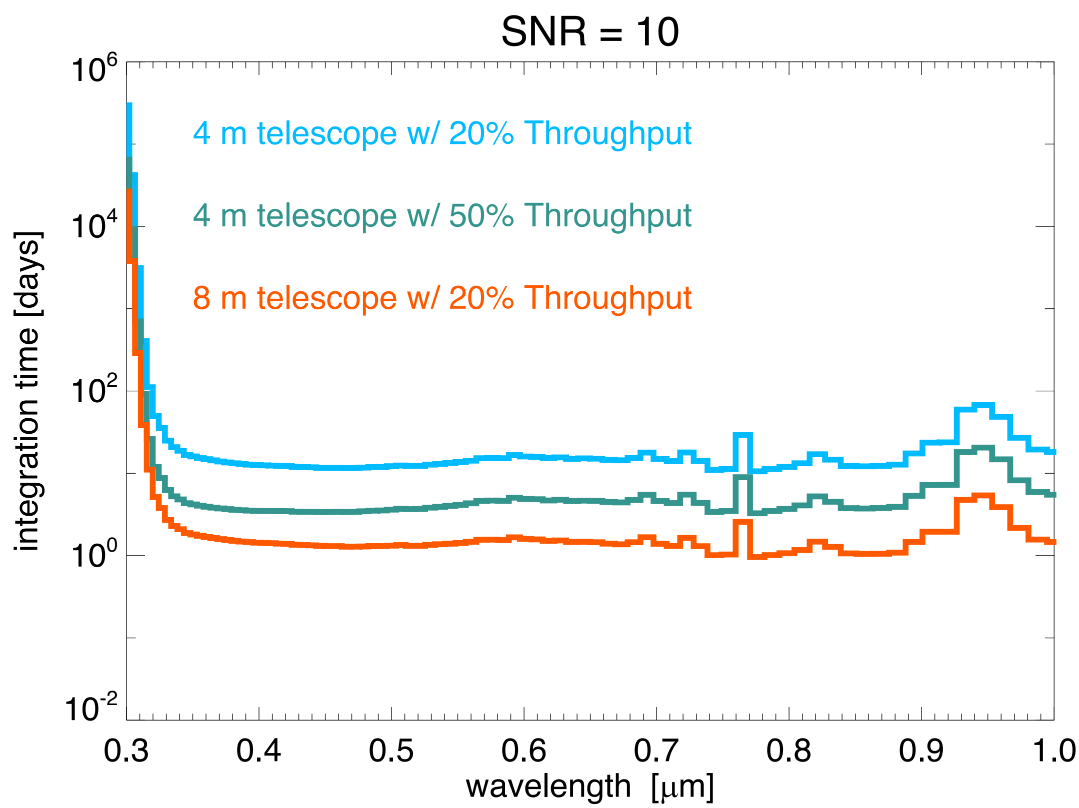

Figure 5: Integration times necessary to achieve signal-to-noise of 10 for three telescope architectures at a spectral resolution of 70. The 8 m telescope offers integration times roughly an order of magnitude smaller than even the 4 m telescope with 50% throughput.

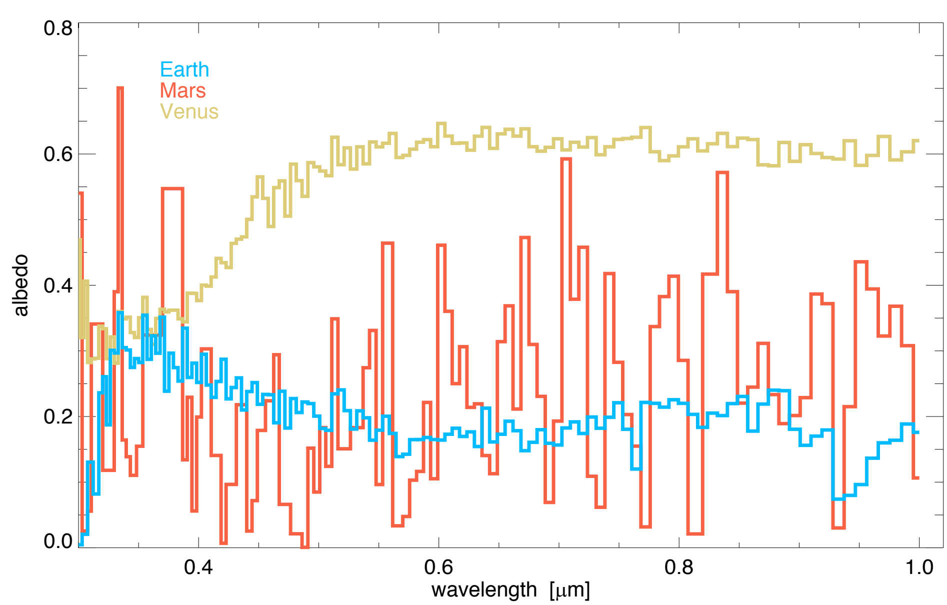

Figure 6: Spectra of Earth, Mars, and Venus obtainable in the integration time necessary to get a signal-to-noise of 10 for Earth at 0.5 μm.

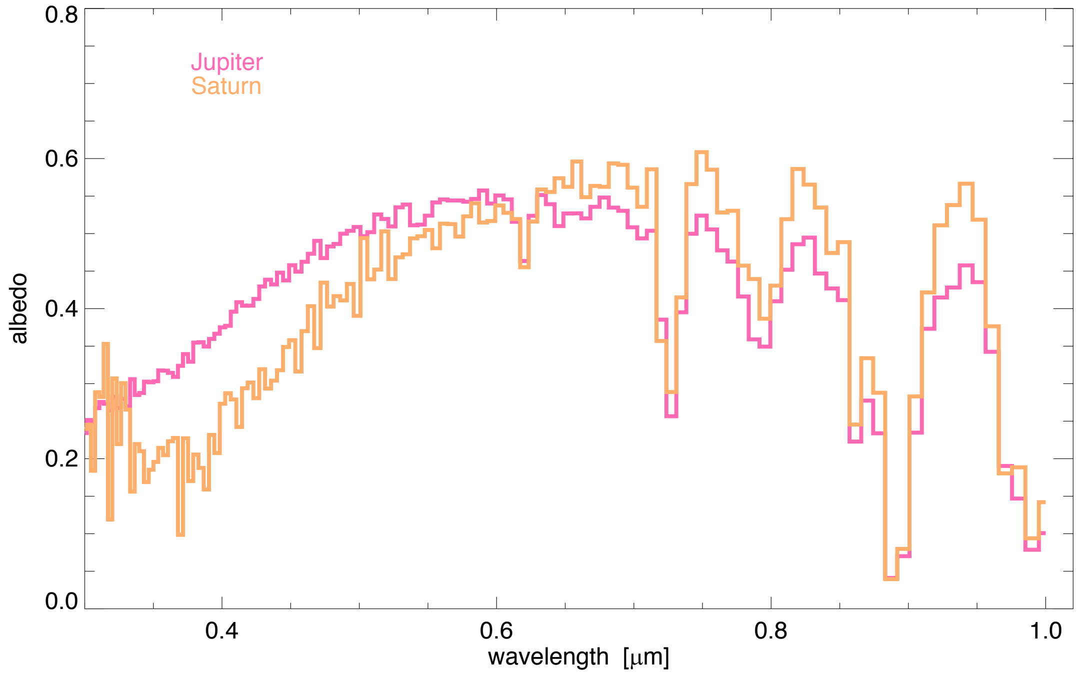

Figure 7: Spectra of Jupiter and Saturn obtainable in the integration time necessary to get a signal-to-noise of 10 for Earth at 0.5 μm.

The time I spent at Goddard was great for my professional development, and I am very glad to have had this opportunity! Although my time at Goddard was short, I now know a lot more about the early stages of mission design and planning, and I'm excited for the future of exoplanet direct imaging.

References

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