Once in a Pale Blue Dot

Simulated Observations of an Extrasolar Earth-Moon System

Tyler D. Robinson[1,2], V. S. Meadows[1,2], E. Agol[1]

[1] University of Washington Astronomy Department and Astrobiology Program
[2] NASA Astrobiology Institute's Virtual Planetary Laboratory (VPL)

Abstract

Surface temperatures on the Moon respond strongly to absorbed sunlight, leading to extremely low nightside temperatures and very large dayside temperatures. As a result, the Moon can contribute a significant amount of flux to infrared (IR) observations of the Earth-Moon system, especially at wavelengths where Earth's atmosphere is absorbing (see Fig. 1). We have paired a 3-D spectral Earth model with a model of the phase dependent spectrum of the Moon to investigate the effects of an unresolved companion on observations of Earth-like exoplanets.

The results demonstrate that:

- **the presence of an undetected satellite can have a significant impact on the spectroscopic characterization of terrestrial exoplanets.**
- **satellites may be detectable by future exoplanet characterization missions for a wide range of system inclinations.**

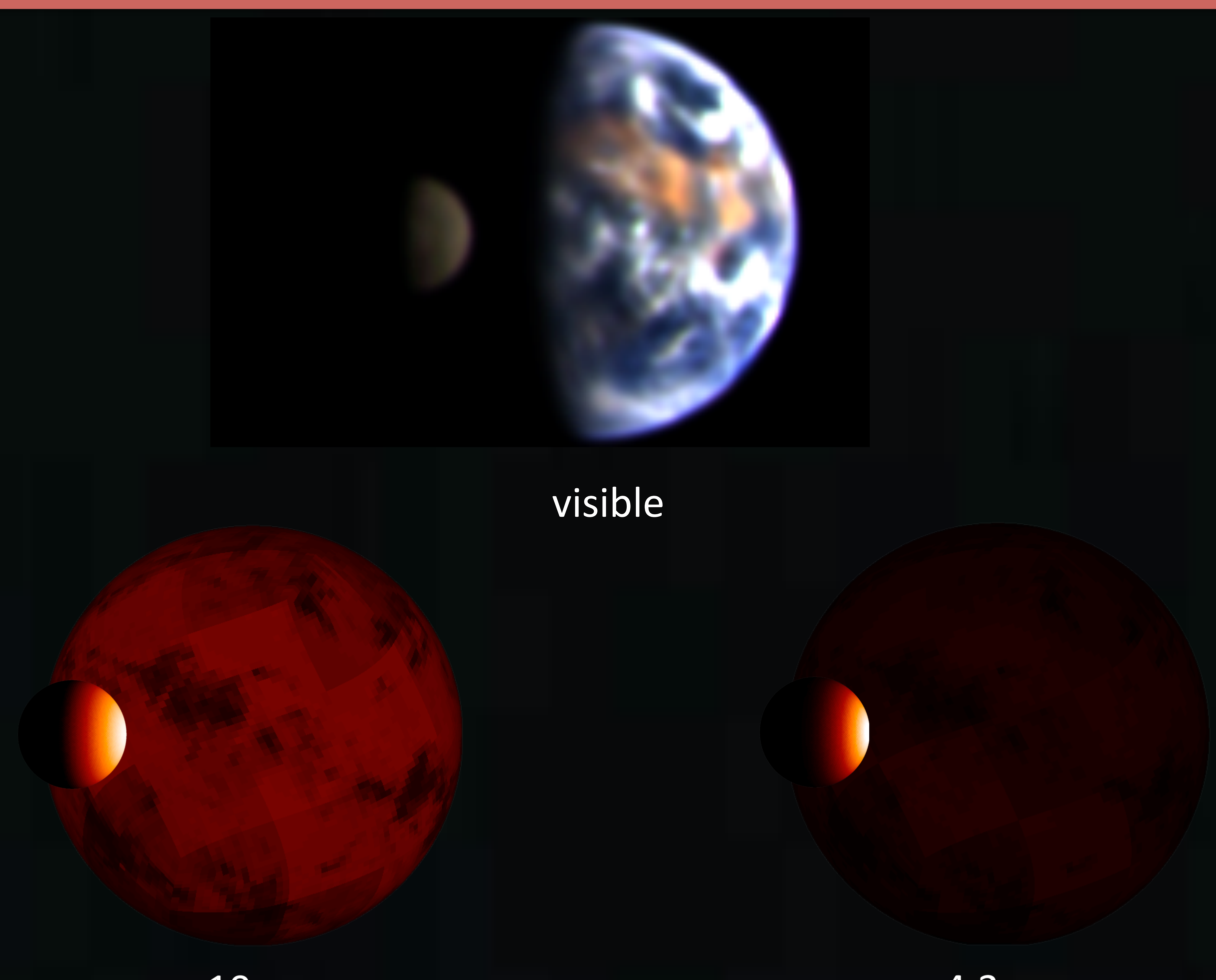

Figure 1: The Earth-Moon system at a variety of wavelengths. The visible-light image is from NASA's EPOXI mission, while IR images are from our models.

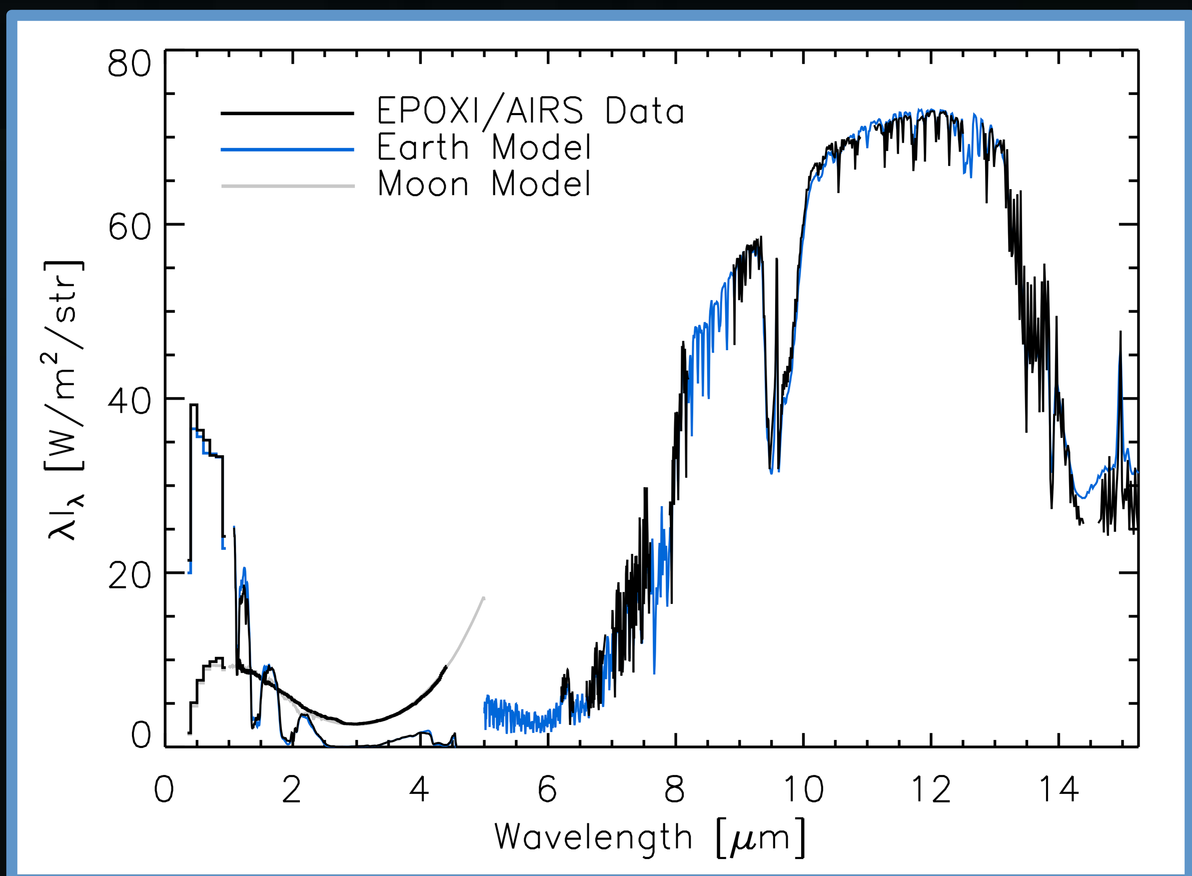

Figure 2: Model Validation. The VPL 3-D Spectral Earth model (blue) as compared to EPOXI (black, visible and near-IR) and AIRS (black, mid-IR). Our lunar spectral model (gray) is also compared to EPOXI observations.

Models

The NASA Astrobiology Institute's Virtual Planetary Laboratory 3-D spectral Earth model simulates Earth's appearance to a distant observer. Spatially-resolved, date-specific observations of key surface and atmospheric properties are taken from Earth-observing satellites and used as input. The model has been extensively validated over a wide range of wavelengths and timescales in Robinson *et al.* (2011a).

Reflected light spectra of the Moon are simulated using empirical models, and IR lunar spectra are generated using a model described in Robinson (2011b).

Detecting Exomoons

The thermal IR spectrum of an airless exomoon depends strongly on phase, so phase-dependent variability in an exoplanet's spectrum can be an indicator of the presence of a companion. The difference between a gibbous phase observation and a crescent phase observation can reveal an exomoon's spectrum, especially at wavelengths that are insensitive to seasonal variations in the host's spectrum (see Fig. 5).

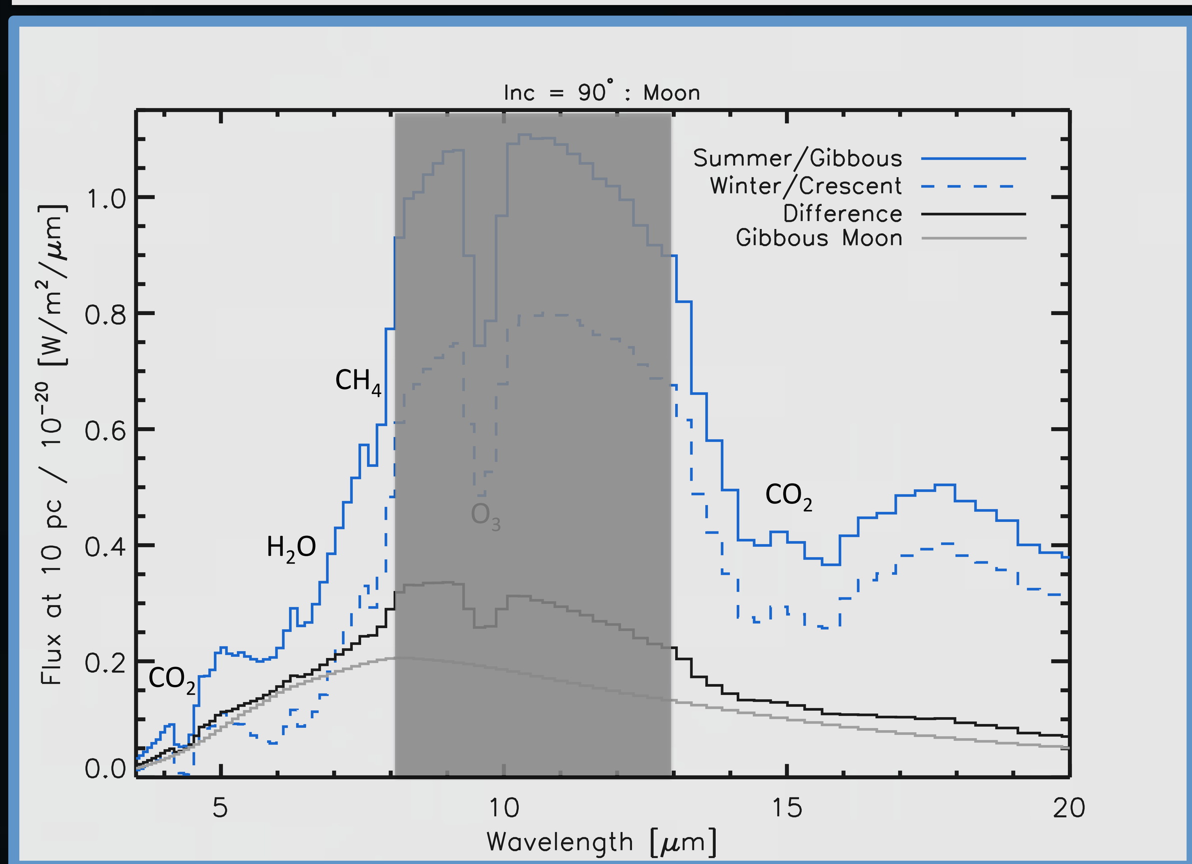

Figure 5: IR Spectra of the Earth-Moon System. Gibbous (blue, solid) and crescent (blue, dashed) phases are shown. Outside 8-13 µm (gray box) Earth's spectrum is nearly constant with phase/season, while the Moon only contributes at gibbous phase. Thus, the difference (black) reveals the gibbous phase lunar spectrum (gray).

Conclusions

- Companions can contribute a significant amount of thermal radiation to IR observations of terrestrial exoplanets, and can even outshine their host at some wavelengths and phases.
- In the case of the Earth-Moon system, the added light from the Moon translates to inferred brightness temperatures for Earth that are too large by about 20-40 K.
- Exomoons may be detectable by searching for variability in their host's spectrum at wavelengths that are insensitive to seasonal temperature variations.

Simulated Observations

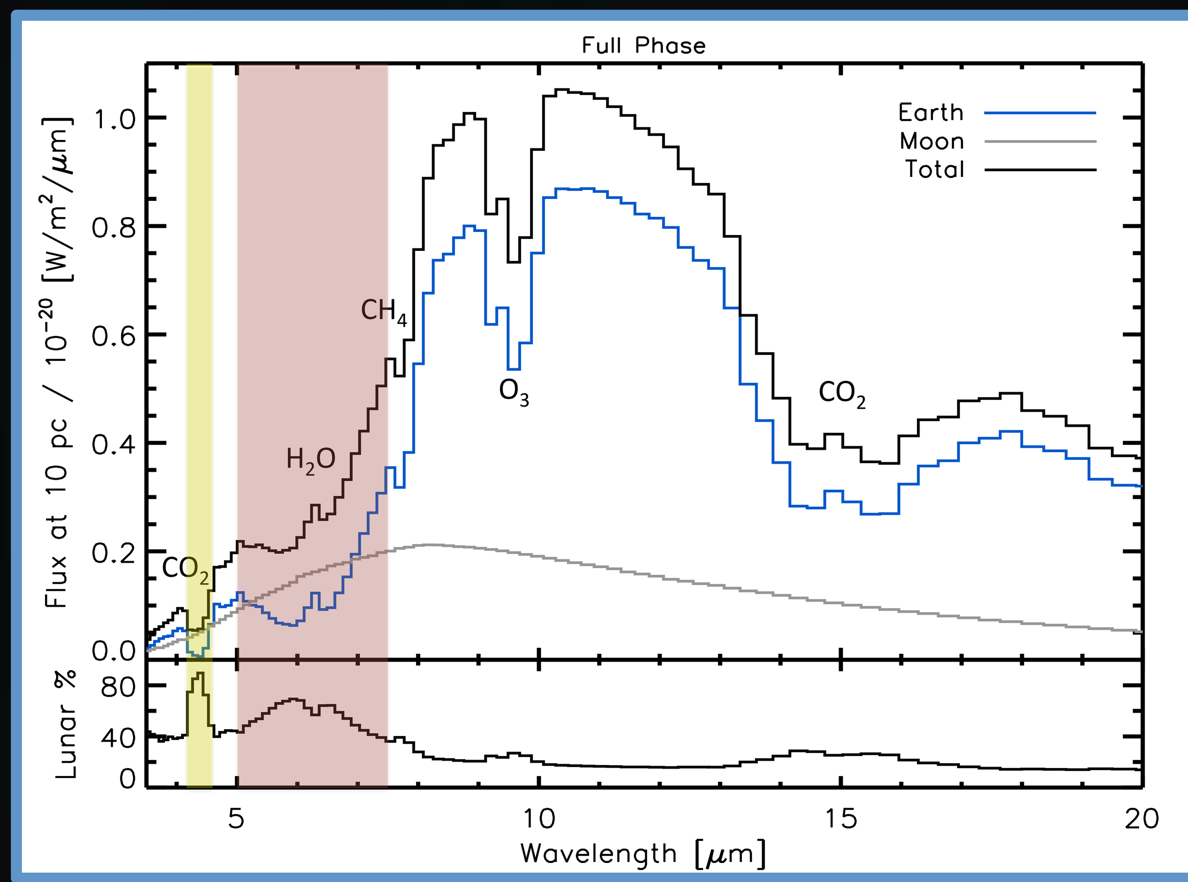

Figure 3: Simulated IR full-disk spectra. Earth (blue), the full phase Moon (gray), and their combined spectrum (black) are all shown. The bottom sub-plot shows the lunar fraction of the combined-light signal, which exceeds 90% at some wavelengths (yellow box).

Simulated spatially unresolved observations of an extrasolar twin Earth-Moon system were used to investigate how a companion affects the observed spectrum of its host (see Fig. 3, above). The Moon adds a significant amount of flux at IR wavelengths, comprising about 20% of the combined signal at most wavelengths, but approaching as much as 90% of the signal in the 4.3 µm CO_2 band (yellow box). The added flux from the Moon in the 6.3 µm H_2O band fills in the absorption feature (red box), creating the appearance of a more desiccated planet.

The added thermal flux from the Moon increases IR brightness temperatures for Earth by as much as 40 K (see Fig. 4, below). Radiation from the Moon more strongly affects temperatures measured in the 4.3 µm CO_2 feature than in the 15 µm CO_2 feature, which ordinarily sense similar temperatures in their bases. Thus, an asymmetry in these two features could indicate the presence of a Moon-like companion.

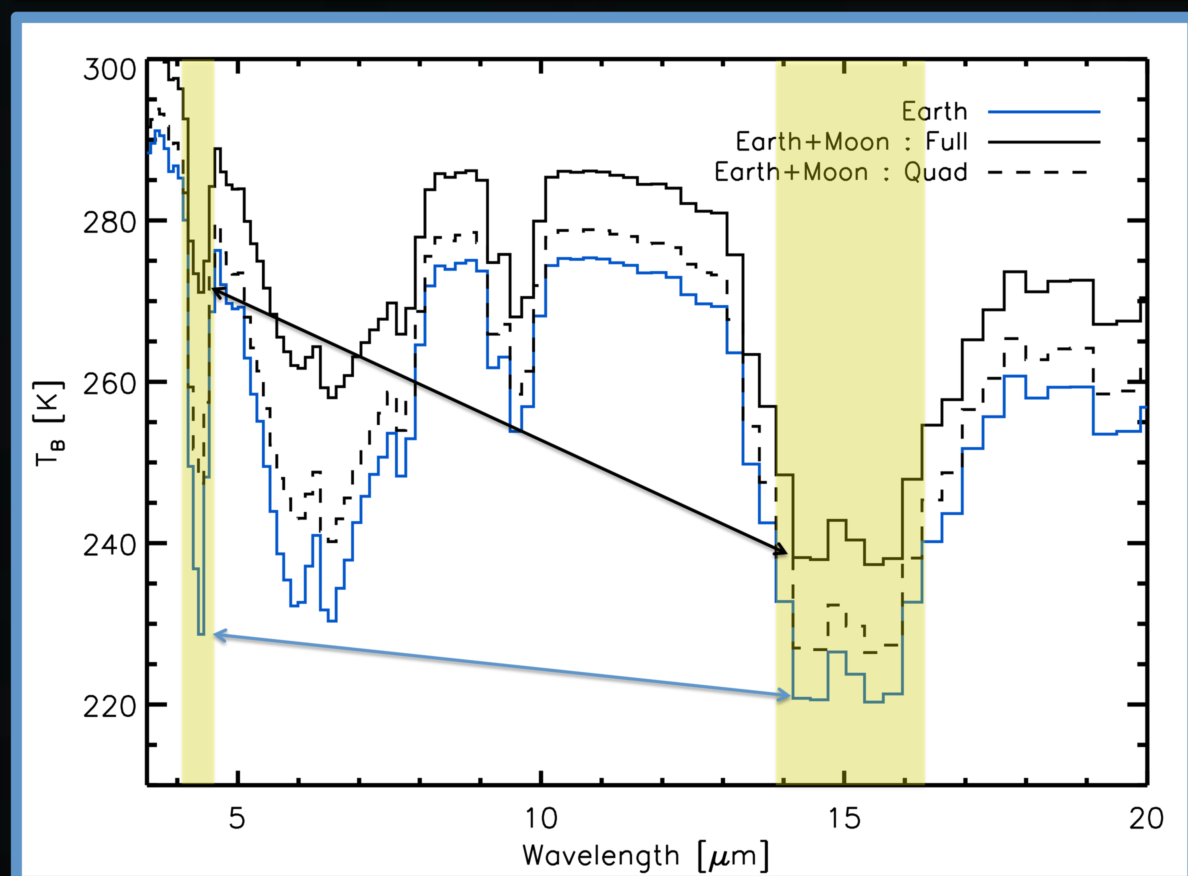

Figure 4: Simulated brightness temperature spectra. Earth (blue), a quadrature (50% illuminated) Earth-Moon system (black, dashed), and a full phase Earth-Moon system (black, solid) are all shown. Note the asymmetry between the bases of the 4.3 µm and 15 µm CO_2 features (yellow boxes) when the Moon is included.

References

Robinson, T. D., Meadows, V. S., Crisp, D., Deming, D., A'Hearn, M. F., Charbonneau, D., Livengood, T. A., Seager, S., Barry, R. K., Hearty, T., Hewagama, T., Lisse, C. M., McFadden, L. A., and Wellnitz, D. D. (2011a) Earth as an Extrasolar Planet: Earth Model Validation Using EPOXI Earth Observations. *Astrobiology*, DOI: 10.1089/ast.2011.0642

Robinson, T. D. (2011b) Modeling the Infrared Spectrum of an Extrasolar Earth-Moon System. *ApJ*, DOI: 10.1088/0004-637X/741/1/51