Topic 1: What do we need to know to characterize an exoplanet?

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with help from

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Talk Summary

Here is what we need to *measure* for exoplanets, roughly in order of how difficult the information is to obtain:

1. Semi-major axis/orbital period/eccentricity
2. Mass
3. Size (transiting planets only)
4. Multi-wavelength photometry
   a) Initial color characterization
   b) Diurnal variability in brightness
   c) Phase-dependent brightness
5. Disk-averaged spectra
   a) UV/vis/near-IR
   b) Thermal-IR
6. Polarization

Talk Summary (cont.)

This can potentially tell us about the following *planetary characteristics*, which become more difficult to determine as one moves down the list:

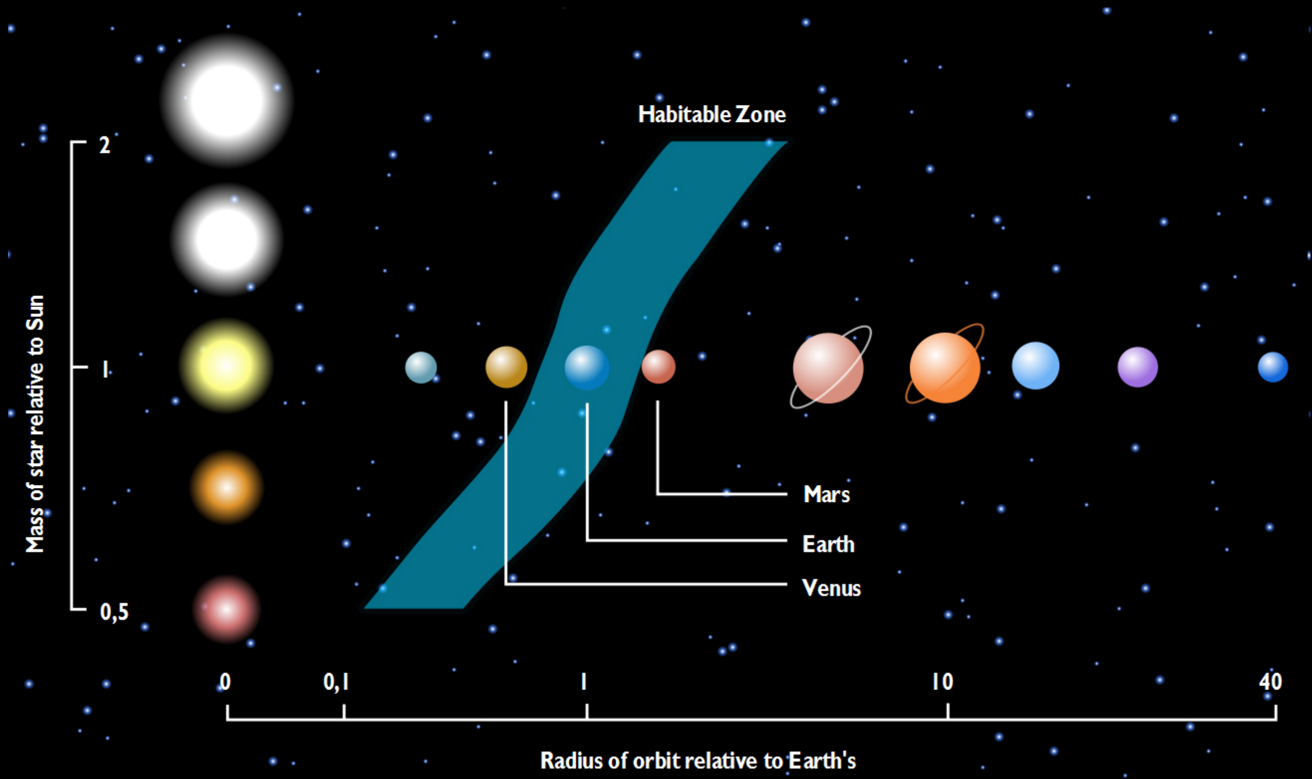
- Planetary density (from transits)
- Atmospheric composition (O_2, O_3, H_2O, CO_2, CH_4)
- Planetary surface heterogeneity (*e.g.*, land/sea distribution)
- Clouds
- Planetary rotation period
- Atmospheric density/N_2 concentration
- Ability of the planet to maintain plate tectonics (based on mass)
- Presence of liquid water
- Surface temperature
- Presence of life (?)

- *Why* do we need to measure these things and how might we do it?

What types of planets should we be looking for?

- Extrasolar planets are expected to be highly *diverse,* and so many of them may have no Solar System analogs
- *All* exoplanets are interesting, because they all have things to say about planetary formation and about planetary system environments
- Nonetheless, rocky, water-rich planets like the Earth are inherently the most interesting because they are the best place to begin the search for *life*

The (liquid water) habitable zone



- Hence, we want to search for (and characterize) rocky planets within the liquid water *habitable zone* around their stars
- The very first things we need to know about the planet are therefore its *orbital distance and eccentricity* and its *mass*

http://www.dlr.de/en/desktopdefault.aspx/tabid-5170/8702_read-15322/8702_page-2/

1-3: Orbital distance/mass/ size/eccentricity

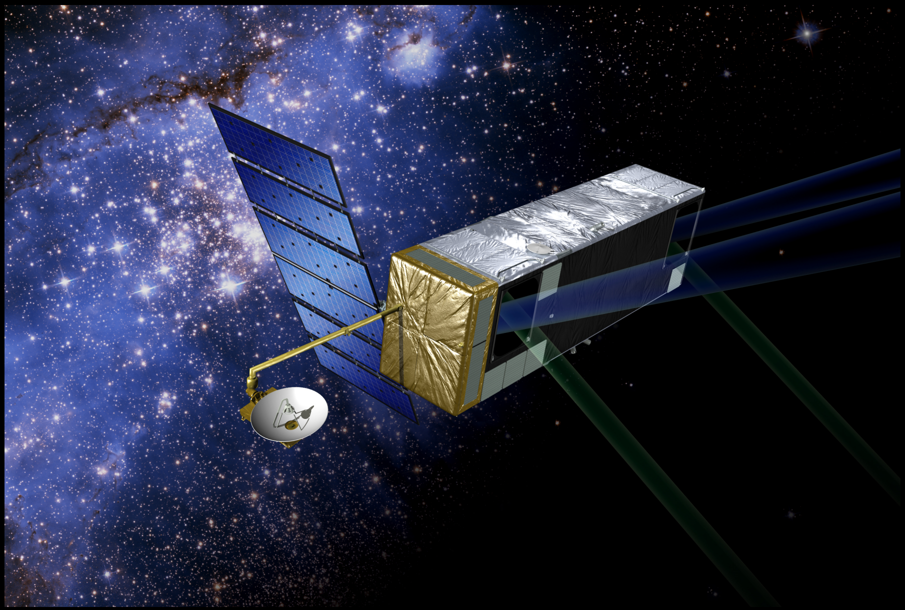
Two ways to get these:

1) RV + transits (eventually RV + direct imaging)
   - Ground-based RV *may* be able to get down to Earth-mass planets around solar-type stars, given sufficient time on large telescopes
     -- Only gives M sin I, of course, except for transiting planets
   - Follow-up direct imaging from space (or ground?) could in theory provide the orbital inclination, and thus the true mass in the more general case

2) Space-based astrometry
   - *e.g.*, SIM or SIM-Lite $\Rightarrow$

SIM – Space Interferometry Mission

- Narrow-angle astrometry: 1 μas precision on bright targets*
- Could be used to identify Earth-mass (or slightly larger) planets around a significant number of nearby stars
- Much of the required development work has already been done

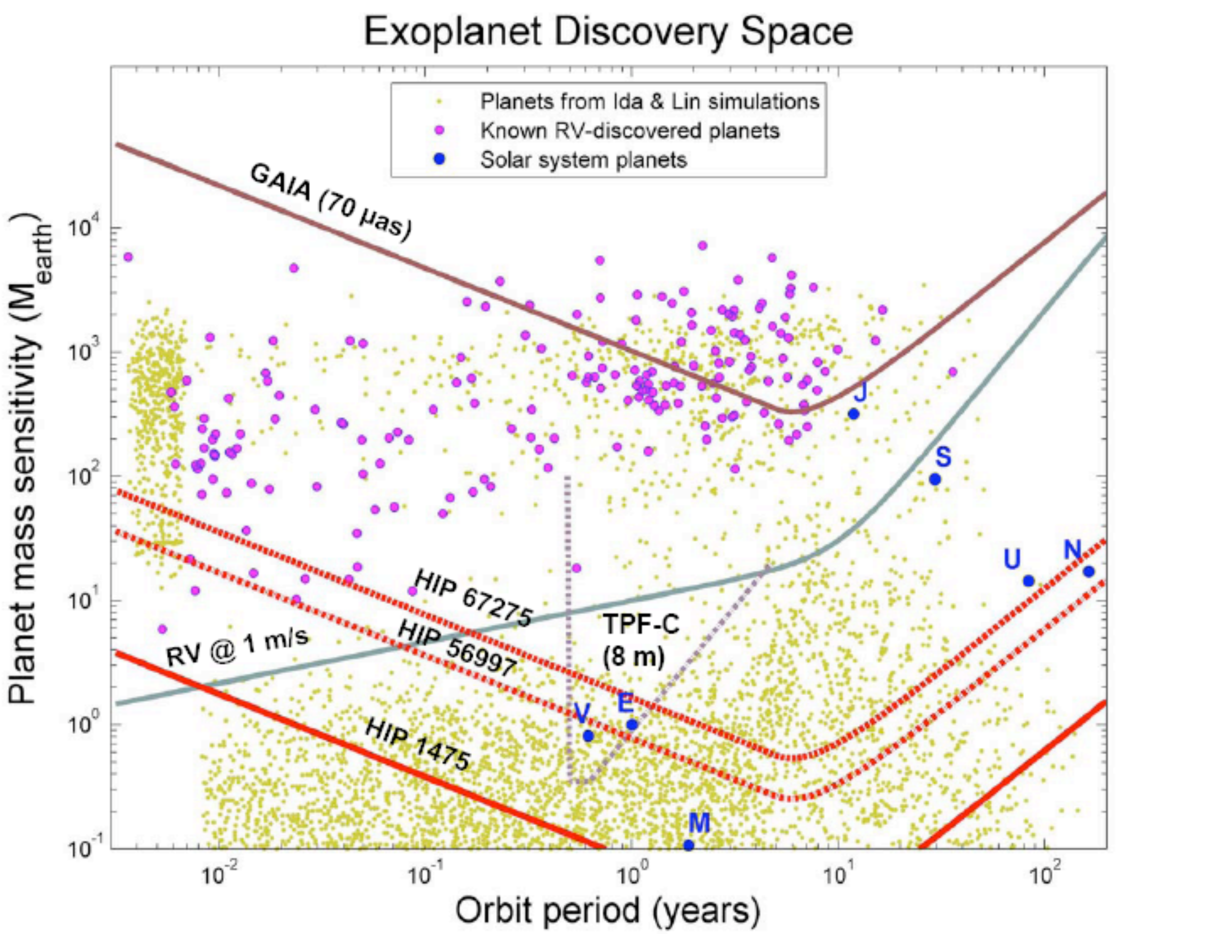


http://planetquest.jpl.nasa.gov/SIM/sim_index.cfm

*Ref: Unwin et al., *PASP* (Jan., 2008)

SIM target space

Earth analogue survey: 129 nearby stars



(Note the overlap with TPF-C…)

Poorest star

Median star

Best star

Ref: Unwin et al., *PASP* (Jan., 2008)

4a: Color as a planetary index

- Broad-band *photometry* can help to place planets within different categories
  - *But,* would we recognize a CH_4-rich early Earth-type planet with this technique?
  - ⇒ Be careful about the interpretation of such measurements!
- To make this type of measurement, we need *direct imaging* capability

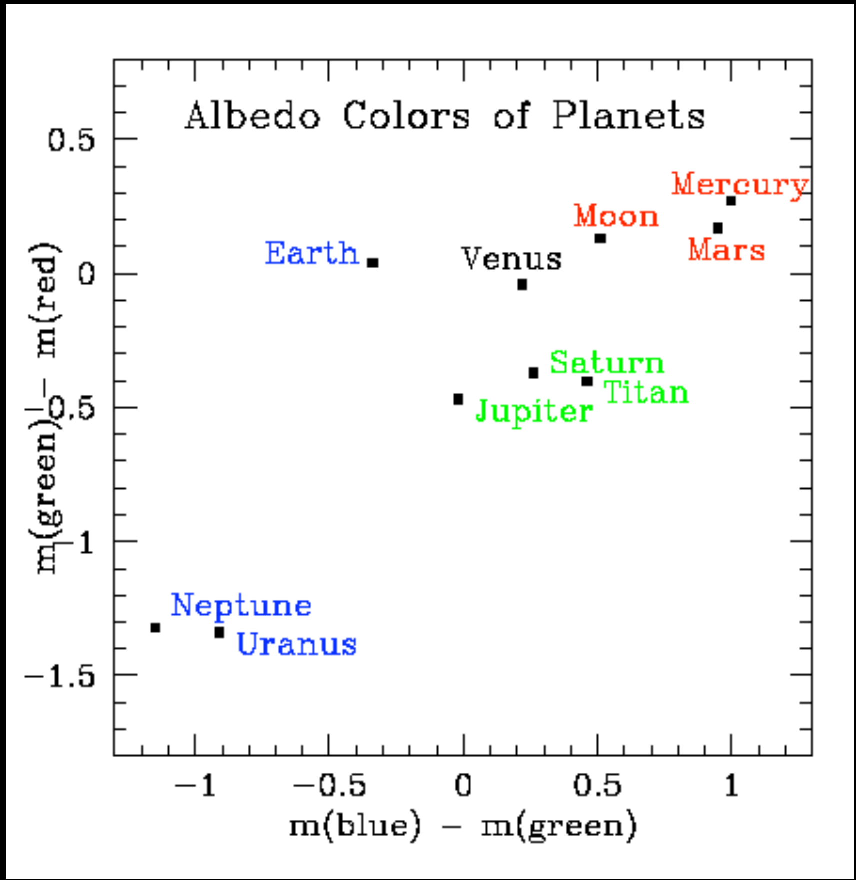
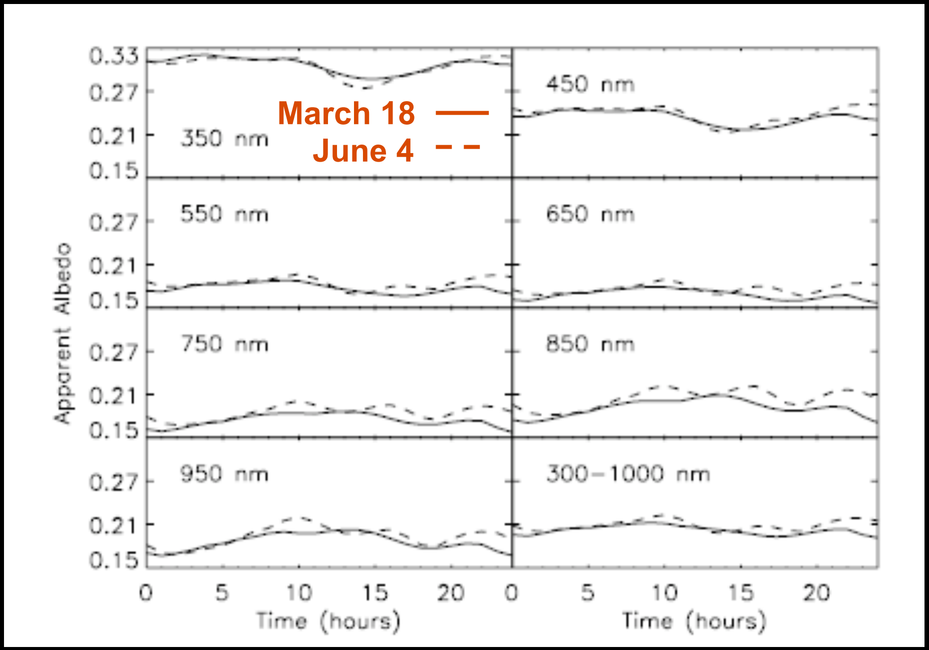
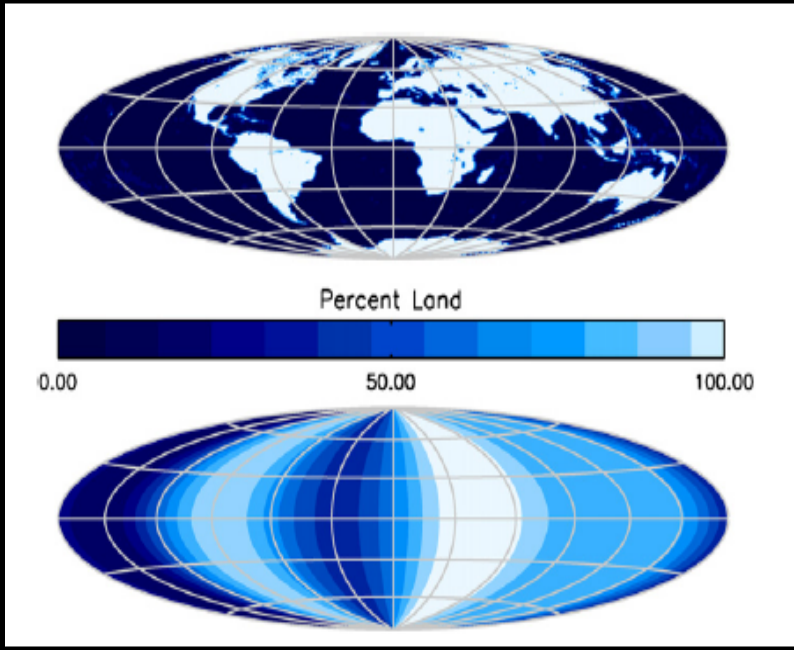


Diagram from the TPF-C STDT report, courtesy of Wes Traub

4b,c: Diurnal color variability



EPOXI light curves for Earth



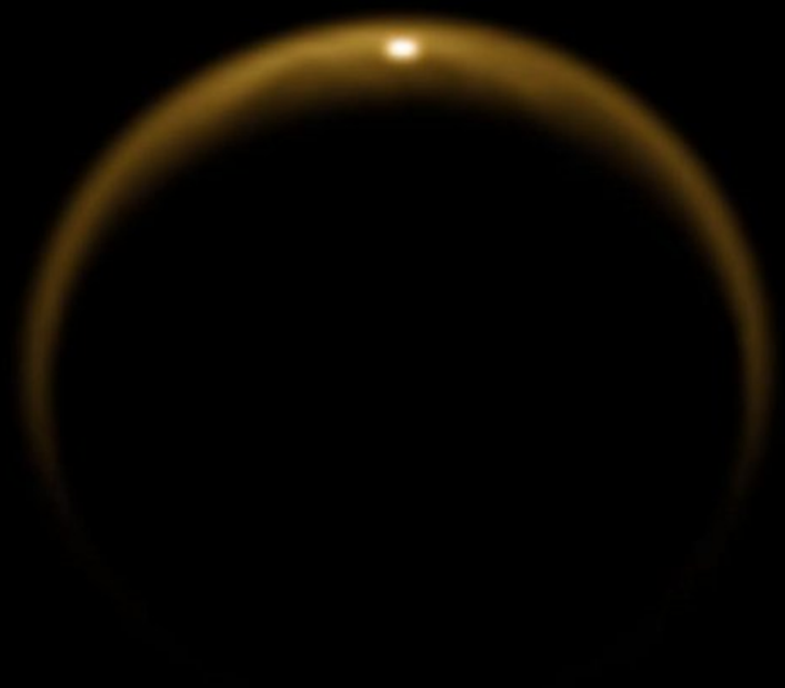
Inferred land/ocean distribution

- Time-resolved light curves can be used to infer land/ocean distribution, presence of clouds, and planetary rotation rate

N.B. Cowan et al., Ap.J. (2009)

4b,c: Specular reflection (glint)

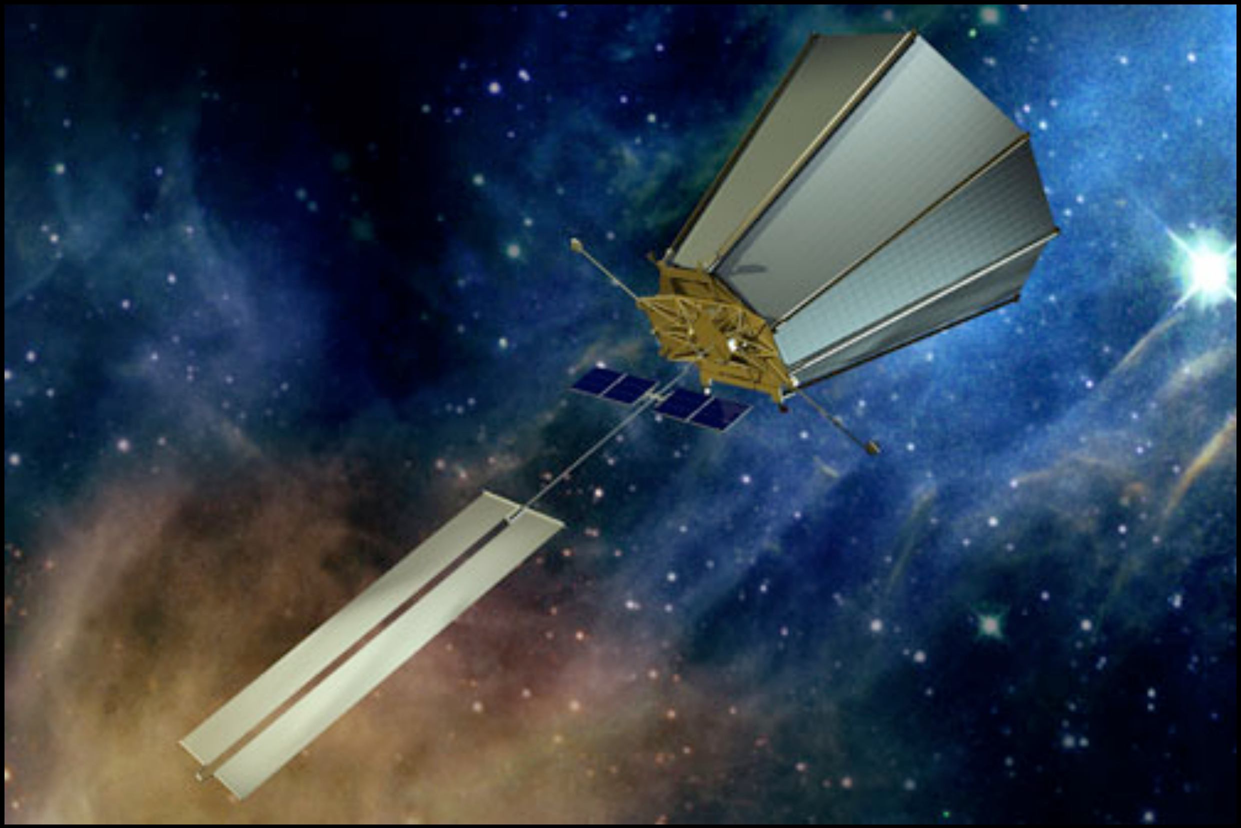
- Picture of *Titan* taken from the Cassini spacecraft, Dec. 23, 2009
- This is the first direct evidence for (filled) liquid lakes on Titan. These lakes, of course, are filled with *liquid methane,* not water
- The presence of a glint signal could cause modest (2-3%) variation in diurnal or phase-dependent brightness, and thus could be a relatively simple way to look for *liquid water*



http://ideafestival.typepad.com/my_weblog/2009/12/specular-reflection-titan-lakes-.html

5a: Disk-averaged spectra

TPF-C: Visible/near-IR coronagraph



- One way to do TPF is in the visible, using an internal coronagraph
- Advantages: single spacecraft and telescope
- Disadvantages: high contrast ratio between planet and star

5a: New Worlds Observer: a 2-spacecraft visible planet finder*

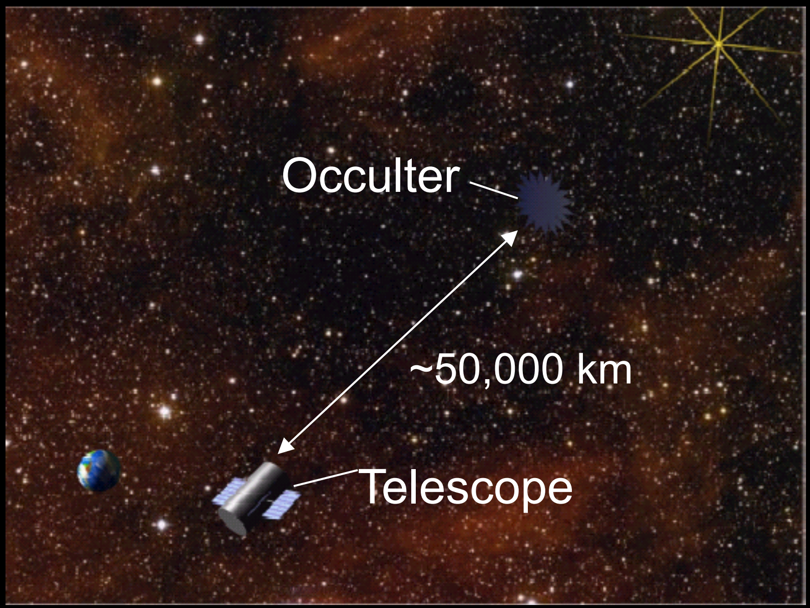
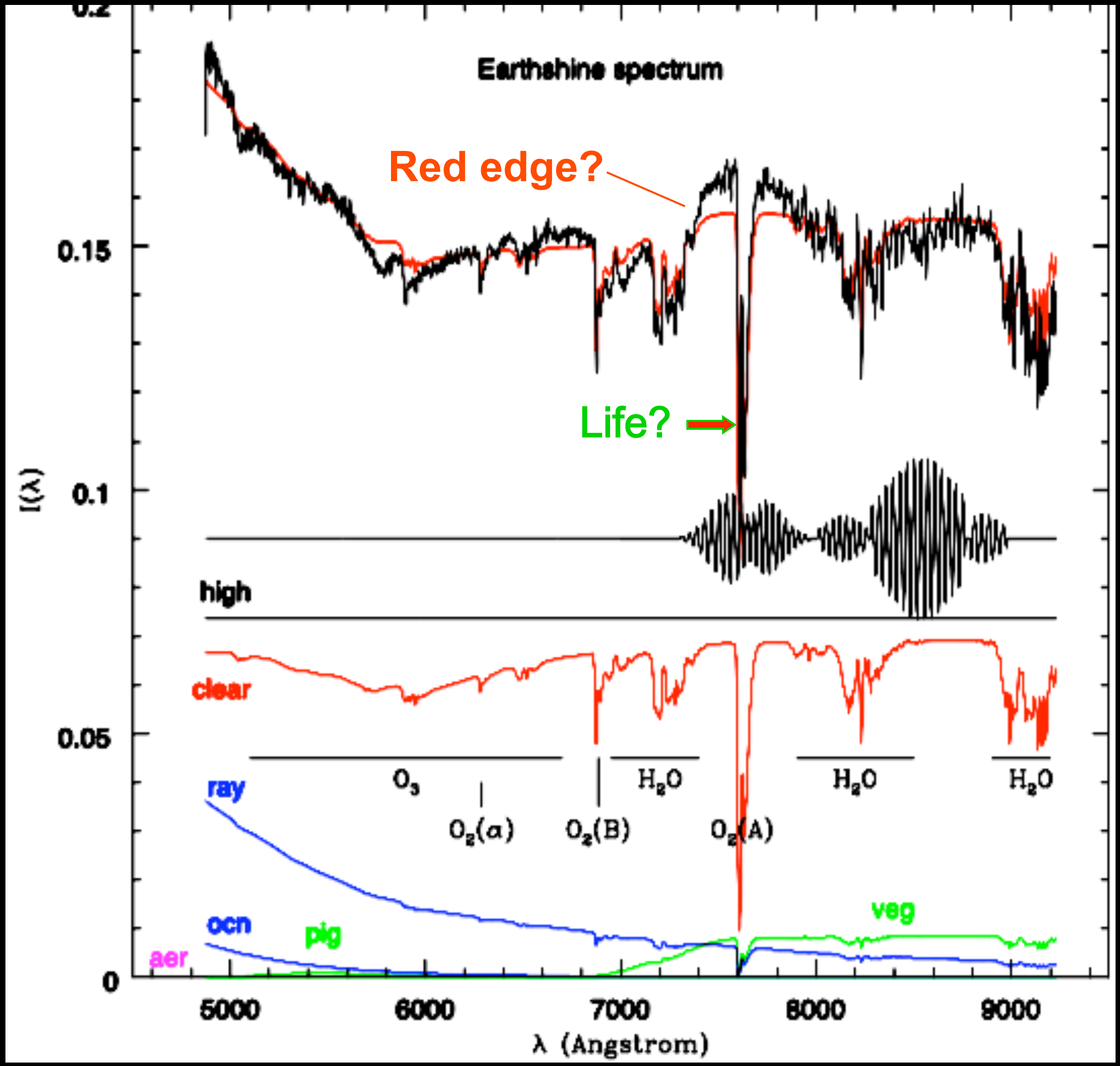


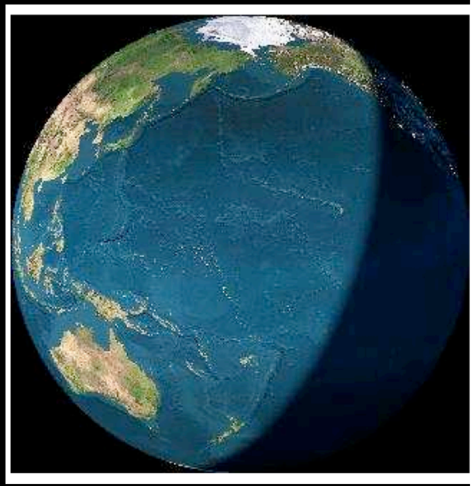
Diagram from homepage of Webster Cash, Univ. of Colorado

*Also now called "TPF-O"

- One can also detect terrestrial planets in the visible by placing an *occulting disk* (or flower) between the telescope and the target
- Advantages: Excellent starlight suppression capabilities
- Disadvantages: Pointing this array at multiple targets and maintaining precise inertial alignment over 50,000 km is time- and fuel-consuming. *But*, it may be easier to do if the target list is already known. Hence, there might be synergy with astrometry.

5a: Visible Spectrum of Earth



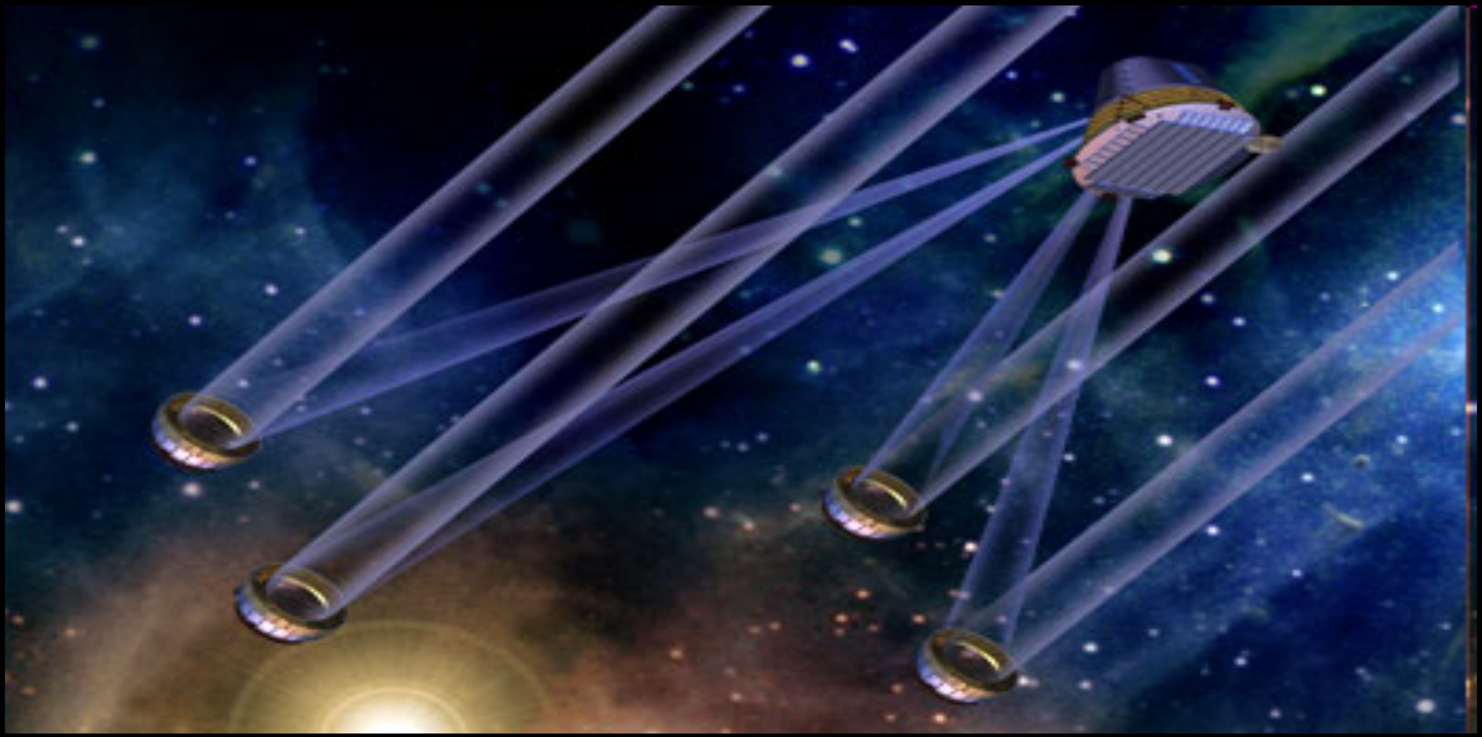


- If we can measure color, we can probably also obtain a *spectrum*, and this could tell us much more about the planet's atmosphere and surface

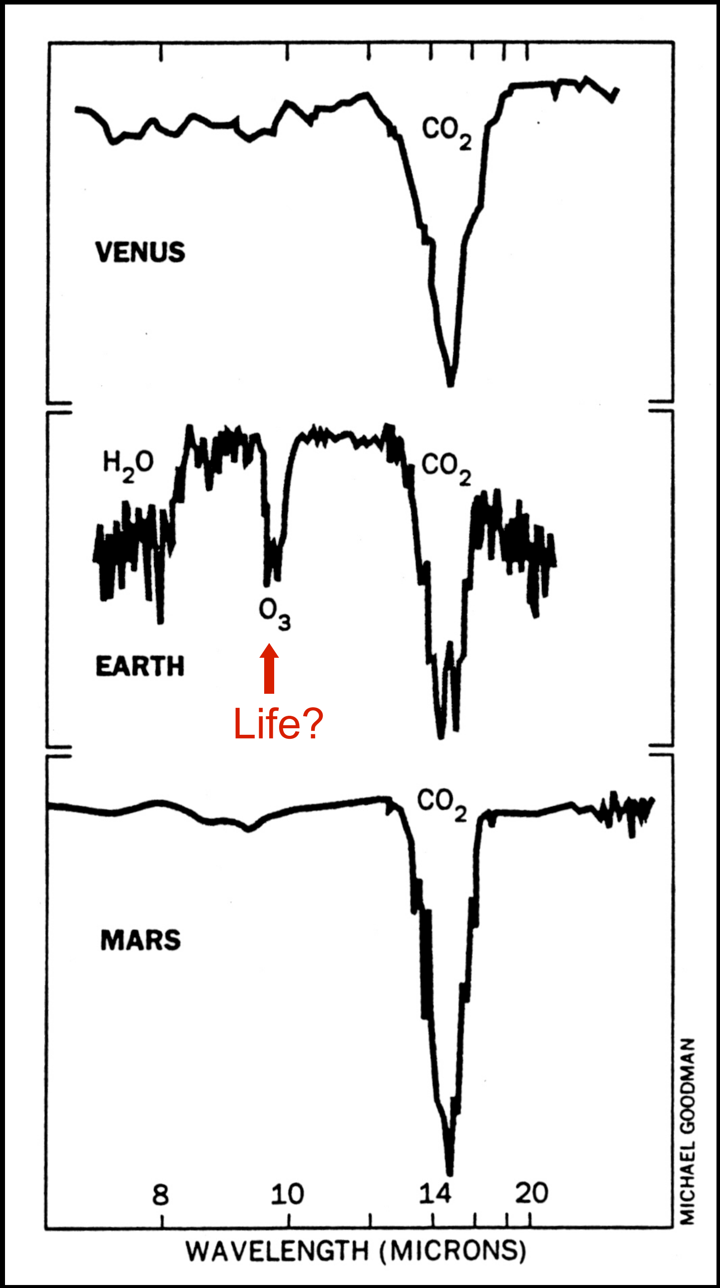
Ref.: Woolf, Smith, Traub, & Jucks, ApJ 2002; also Arnold et al. 2002

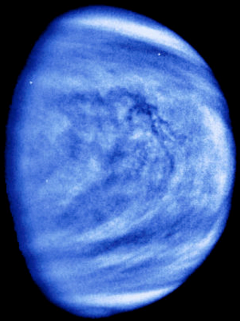
5b: Disk-averaged spectra (cont.)

TPF-I (or Darwin): Free-flying IR interferometer



- An alternative way to characterize exoplanets spectroscopically is to fly a free-flying interferometer, similar to ESA's (postponed) *Darwin* mission
- Advantages: good contrast ratio, excellent spectroscopic biomarkers
- Disadvantages: needs cooled, multiple spacecraft





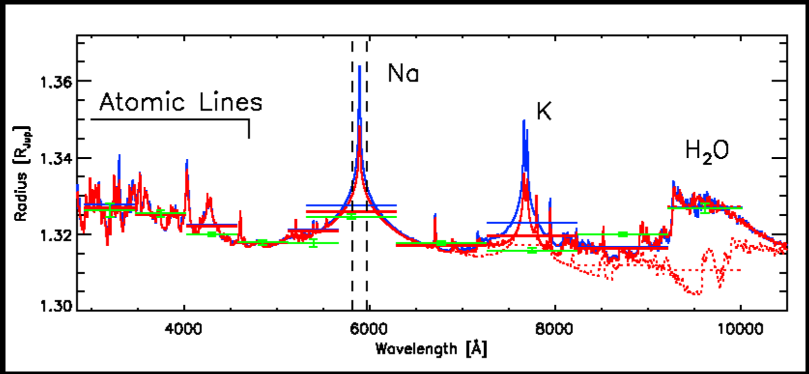
5b: Thermal -IR spectra

Source:
R. Hanel, Goddard Space Flight Center

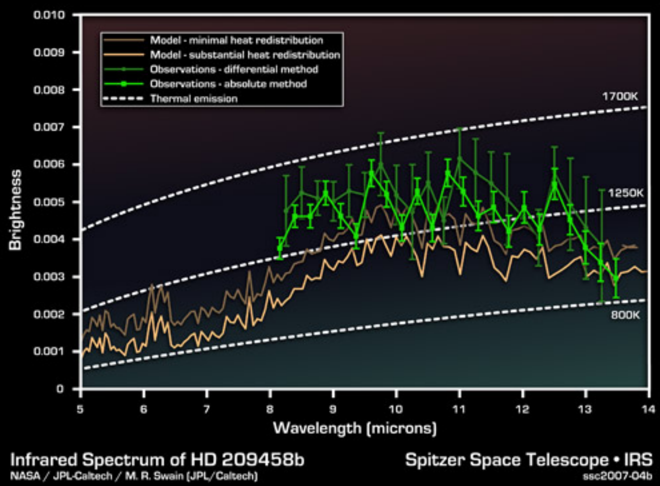
Let's back up for a moment…

Transit spectroscopy

- Some (limited) characterization of exoplanet atmospheres can be done for transiting exoplanets
- Top: A visible spectrum of HD 209458b obtained from HST during *primary transit*
- Bottom: A thermal-infrared spectrum of the same planet obtained from Spitzer during *secondary transit*



H_2O



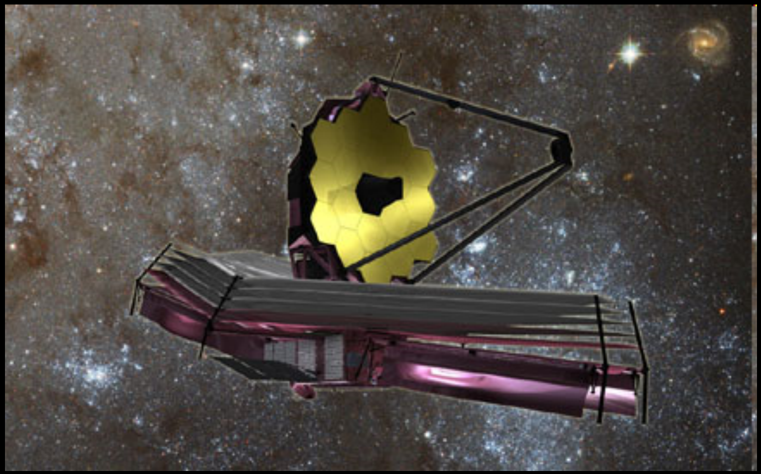
No H_2O?

Refs: HST--T. Barman, Ap.J. Lett. (2007), Spitzer—L.J. Richardson et al., Nature (2007)

Pluses and minuses of transit spectroscopy

Pluses

- We can do it now for Jovian planets!
- We should be able to do it even better in the near future with JWST



http://planetquest.jpl.nasa.gov/missions/jwstMission.cfm

Minuses

- Poor *signal-to-noise ratio* (because you are looking at both the planet and the star)
- Nearly all the planets that can be observed are far away (because the probability of transits is low)
- Earth-like planets may be difficult or impossible to characterize in this manner

6: Polarization (another possible way to detect liquid water)

- Polarization of light reflected from a water surface peaks at twice the *Brewster angle:* 2×53.1° = 106.2°
- Polarization from *Rayleigh scattering* peaks at 90°
- *Rainbows* also create polarization, so one might use this information to learn about atmospheric aerosols

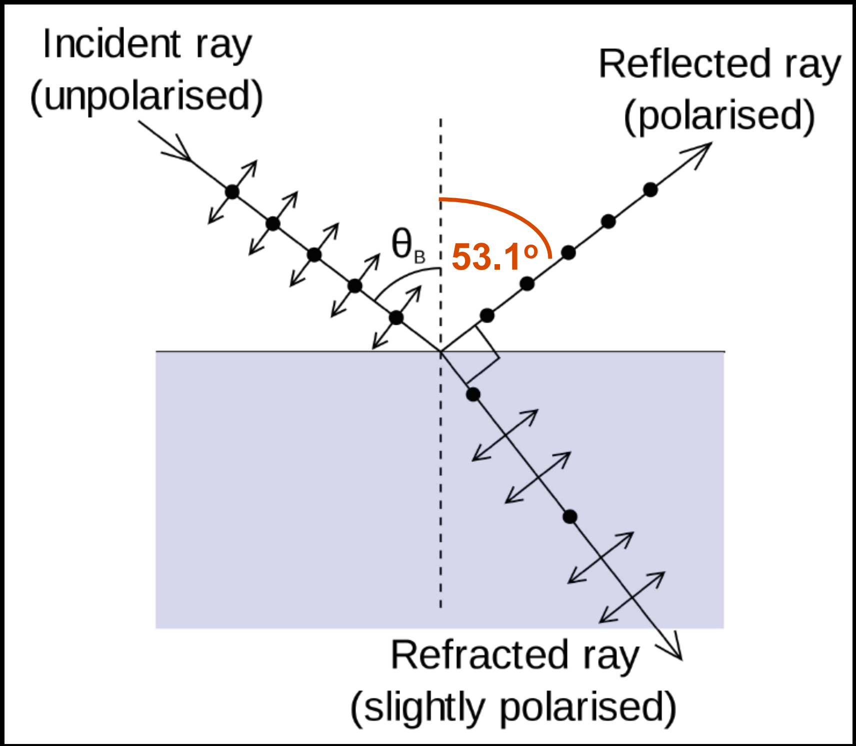


Image from Wikipedia

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What have I left out?