Prospects for Characterizing Potentially Habitable Planets with JWST

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There is a transiting Earth-sized planet (1-1.5 R_{Earth}) in the habitable zone of an M dwarf star within 10.6 pc (Dressing and Charbonneau, 2015).

Now we just have to find it!
Kepler’s Potentially Habitable Planets
TESS will most likely find JWST targets

- Predictions suggest 48 TESS planets lie within or near the HZ
- 2-7 of these planets will have host stars brighter than $K_S=9$ (Sullivan et al., 2015)
The most promising mechanism is from Yang et al., 2015 who show that for slowly-rotating planets, strong convection at the substellar point creates high albedo water clouds, stabilizing the climate against thermal runaway, pushing the HZ in to Venus’ orbit for Sun-like stars.

An update to this paper (Kopparapu et al., 2015 in prep) shows that this limit is strongly dependent on rotation rate and stellar metallicity/luminosity effects.
Assessing Potential Habitability
Assessing Potential Habitability

- Galactic Location
- Orbital Evolution
- Planetary System
- Sibling Planets
- Chemical & Structure
- Stellar Effects
- Spectral Energy Distribution
- Liquid Surface Water
- Planetary Properties
- Dynamics
- Surface
- Interior
- Atmosphere
Assessing Potential Habitability
The Habitability Index

The “Problem”

\[(P, d, D, R_*, M_*, T_{\text{eff}}) \rightarrow (L_*, a, e, A, S).\]

Use observables from a transit to constrain and assess the fraction of possible parameter combinations that would produce habitable climates.

Barnes, Meadows & Evans, 2015
Habitability Index for TESS Planets

From Barnes, Meadows & Evans, (2015), *in press*

Based on a the Sullivan et al. (2015) study to predict the exoplanet yield from TESS.
Limitations on Probing Exoplanet Environments with Transmission Spectra
Small planets in the HZ produce better transmission spectra around small (M dwarf) stars
- Increased transit depth for the same-sized planet (applies to atmospheric absorption too)
Refraction Also Limits Altitudes Probed

For every planet/star system there will be a maximum pressure (or minimum altitude) that can be probed. At deeper levels the refracted starlight is at too high an angle to be intercepted by the observer.
Refraction Reduces Spectral Features

For planets in the habitable zone of their parent stars refraction has less of an effect on detectability of spectral absorption for M dwarf planets, with a larger effect for G dwarf planets.

Misra, Meadows and Crisp, 2014
Haze can severely limit transmission spectra

GJ1214b: Not Solar composition

Not high mean molecular mass atmosphere

Conclusion: High-altitude cloud/haze

Kreidberg et al., 2014
JWST will get us beyond “the flat zone” for mini-Neptunes

Impact of cloud particle radii (100×sol)

GJ1214b

- no cloud
- with cloud (r=0.1 µm)
- with cloud (r=0.5 µm)
- with cloud (r=1 µm)

LMDZ 3D GCM can loft r=0.5µm cloud particles to recreate the flat HST spectra. Resultant haze should be optically thin at λ > 3µm. A single transit could detect molecules.

Thermal Phase Curves May Reveal Metallicity

Day-night T contrasts are strongly dependent on metallicity.

Could be observed in one full phase curve with JWST @ 6-8um

Venus in Transit

Visible-Near IR

Near IR - mid IR

Giada Arney
M Dwarf Planets May Make Their Own O\textsubscript{2}!

Depending on surface sinks, up to several hundreds of bars of photolytically-produced O\textsubscript{2} can potentially build up in the atmospheres of these planets.

Terrestrial planets can lose several Earth oceans of water via hydrodynamic escape during the PMS phase of M dwarfs.

Luger & Barnes (2015)
This extra pre-MS luminosity can last for up to a billion years and could dessicate planets formed in the habitable zone of low mass stars within the first 100 Myr.

**THE PUNCHLINE:** Planets orbiting stars above a stellar mass of \( \sim 0.4 \) are less likely to experience this phenomenon, especially towards the outer edge of the HZ.
Abundant \( \text{O}_2 \) may not indicate habitability

1. H Escape from Thin N-Depleted Atmospheres (Wordsworth & Pierrehumbert 2014)

2. Photochemical Production of \( \text{O}_2/\text{O}_3 \) (Domagal-Goldman, Segura, Claire, Robinson, Meadows 2014)

3. \( \text{O}_2 \)-Dominated Post-Runaway Atmospheres from XUV-driven H Loss (Luger & Barnes 2014)

4. \( \text{CO}_2 \) Photolysis in Dessicated Atmospheres (Gao, Hu, Robinson, Li, Yung, 2015)
Massive $O_2$ atmospheres may have $O_4$ features

Schwieterman et al., in prep
Measurements We Would Like to Make for Terrestrials
Detecting Surface Liquid
LCROSS Observations of Earth Glint

Images of the Earth taken with the LCROSS NIR2 camera (0.9-1.7µm) and MIR1 camera (6-10µm)

Robinson et al., 2014
LCROSS Data Confirm Glint Predictions

This phase (129°) would require 77mas separation for an Earth twin at 10pc.

Robinson et al., 11:30am Today in Salon A1!
For Exo-C
\( \alpha \text{ Cen A super-Earth (1.7 } R_E \) 

\[ R = \lambda / \Delta \lambda = 10 \]

SNR ~ 10

\[ \Delta t = 10 \text{ days} \]

IWA = < 460mas

low-res model

simulated data

hi-res model

0.6-0.9\( \mu m \) optimal for photometry to look for oceans (reduced Rayleigh) but does JWST have the sensitivity to do this? Nick doesn’t think so!

Ty Robinson

Meadows, Robinson, Misra et al., 2015
JWST may be able to detect (SNR > 3) the 1.06\(\mu\)m O\(_4\) and 1.27\(\mu\)m O\(_2\) features for an Earth-like planet orbiting an M5 dwarf 5pc away.

IF we can get every transit in the mission lifetime or IF the sensitivity is better than expected!

The oxygen A band would likely not be detectable (1.1-sigma), even in the cloud-free case.

Misra, Meadows, Crisp, Claire (2014)
Atmospheric Chemistry Around M Dwarfs

Earth-like planets around cooler stars show enhanced biosignature abundances (Segura et al., 2003, 2005)
- M stars less effective at O$_3$ photolysis.

Enhancements in biosignatures, (including O$_3$), are also seen when an Earth-like planet is moved towards the outer edge of its habitable zone (Grenfell et al., 2006, 2007).
Transmission Spectrum of Earth Orbiting an M Dwarf

Spectrum of self-consistent Earth around an M3.5V from Segura et al. (2005) Transmisson model (includes refraction) from Misra et al., (2014)

Model is cloud-free, however the deepest altitude reached is 10km, likely above any actual cloud deck. This also explains the lack of water vapor.
Self-consistent early Earth (anoxic atmosphere/sulfur biosphere) around M3.5V from Domagal-Goldman et al., (2011)

Model is cloud and haze-free, and the deepest altitude reached is 10km, likely above any actual cloud deck.

Distinctive sulfur gases in the troposphere are not seen in the spectrum.

Ethane is a biosignature in this context
Early Earth Orbiting an M Dwarf

Domagal-Goldman, Meadows et al., 2011
NIRISS Spectrum of M Dwarf Earth

10 transits/65 hrs
Rebinned 2048 -> 32 columns

Parts per million

CH₄  CH₄  CO₂  CH₄

Microns

Drake Deming
NIRSPEC Spectrum of M Dwarf Earth

10 transits/65 hrs

Stellar intensity dropping
Thermal rising

Drake Deming
Summary

• Warm mini-Neptunes (e.g. GJ1214b) should be straightforward targets for JWST, which has the potential to characterize their cloud and atmospheric composition using transmission spectra, secondary eclipse and phase curve measurements.

• JWST will be our first chance to characterize terrestrial planets, including those in the habitable zone of their parent star.

• For HZ planets observations will require ppm sensitivity
  – Refraction may limit observations to the stratospheres
  – Water and tropospheric biosignatures may be difficult to detect.

• Transit observations coadded over several years may be necessary.
  – Systematic noise sources will need to be characterized

• Target selection will be important, as features for these targets will take many transits to appear.
With Thanks To…

Eric Agol (UW)
Rika Anderson (NAI-NPP/WHOI)
John Armstrong (Weber State)
Jeremy Bailey (UNSW)
Giada Arney (UW)
Rory Barnes (UW)
John Baross (UW)
Cecelia Bitz (UW)
Bob Blankenship (WUStL)
Linda Brown (NASA-JPL/Caltech)
Roger Buick (UW)
David Catling (UW)
Benjamin Charnay (NAI-NPP/UW)
Mark Claire (U. St. Andrews)
David Crisp (NASA-JPL/Caltech)
Pan Conrad (NASA-GSFC)
Russell Deitrick (UW)
L. Drake Deming (U. Maryland)
Feng Ding (U. Chicago)
Shawn Domagal-Goldman (NASA-GSFC)
Peter Driscoll (CIW)
Peter Gao (Caltech)
Colin Goldblatt (U. Victoria)
Chester (Sonny) Harman (PSU)

Suzanne Hawley (UW)
Tori Hoehler (NASA-Ames)
Jim Kasting (PSU)
Nancy Kiang (NASA-GISS)
Ravi Kopparapu (PSU)
Monika Kress (SJSU)
Andrew Lincowski (UW)
Rodrigo Luger (UW)
Jacob Lustig-Yaeger (UW)
Amit Misra (UW)
Niki Parenteau (NASA-Ames)
Ray Pierrehumbert (U. Chicago)
Tom Quinn (UW)
Sean Raymond (Lab. Astrophysique de Bordeaux)
Tyler Robinson (Sagan Fellow – UC Santa Cruz)
Eddie Schwieterman (UW)
Antigona Segura (UNAM)
Janet Seifert (Rice U.)
Holly Sheets (U. Maryland)
Aomawa Shields (NSF/UCLA/Harvard)
Eva Stüeken (UW)
Lucianne Walkowicz (Adler Planetarium)
Robin Wordsworth (Harvard)
Yuk Yung (Caltech)
Kevin Zahnle (NASA-Ames)
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Other gases may show up false positives for life

Schwieterman et al., in prep
Dimers may indicate High-O$_2$ from atmospheric escape

Lack of methane or presence of CO may indicate O$_2$ from photolysis
Extreme Habitability

- Yang et al. (2014a) inner HZ limit
- Inner HZ limit for [Fe/H] = 0.3
- Inner HZ limit for [Fe/H] = -0.5

Graph showing the relationship between Stellar Effective Temperature (Kelvin) and Incident flux on the planet for three different stellar metallicities.
Glint Predictions From The VPL Earth Model

Robinson, Meadows, & Crisp (2010)