Water, Habitability, and Detectability

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Astrobiology Science Strategy NAS Committee,
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How to look for life on (Earth-like) exoplanets: find oxygen in their atmospheres

How Earth-like must an exoplanet be for this to work?

Seager et al. (2013)
How to look for life on (Earth-like) exoplanets: find oxygen in their atmospheres

Oxygen on Earth overwhelmingly produced by photosynthesizing life, which taps Sun’s energy and yields large disequilibrium signature.

Caveats:
Earth had life for billions of years without O₂ in its atmosphere.

First photosynthesis to evolve on Earth was anoxygenic.

Many ‘false positives’ recognized because O₂ has abiotic sources, esp. photolysis (Luger & Barnes 2014; Harman et al. 2015; Meadows 2017).

These caveats seem like exceptions to the ‘rule’ that ‘oxygen = life’.

How non-Earth-like can an exoplanet be (especially with respect to water content) before oxygen is no longer a biosignature?
Part 1: How much water can terrestrial planets form with?

Part 2: Are Aqua Planets or Water Worlds habitable? Can we detect life on them?

Part 3: How should we look for life on exoplanets?
Part 1: How much water can terrestrial planets form with?

Theory says: up to hundreds of oceans’ worth of water
Trappist-1 system suggests hundreds of oceans, especially around M stars

Many (most?) planets may be Aqua Planets or Water Worlds
How much water can terrestrial planets form with?

Standard models of accretion suggest abundant water.

Earth-like water content 0.025 wt%  
Raymond et al. (2004)
How much water can terrestrial planets form with?

“Aqua Planets” (6 - 35 oceans, enough to submerge continents) and “Water Worlds” (> 35 oceans, enough for high-pressure ice layer) might be most likely.

Raymond et al. (2004)
How much water can terrestrial planets form with?

Newer theories of ‘fossil snow lines’ (Morbidelli et al. 2016) suggest Jupiter’s formation deprived the inner solar system of H$_2$O ice.

Systems without Jupiters would still have water-rich inner planets.

Morbidelli et al. (2016)
How much water did the Trappist-1 planets form with?

Gillon et al. (2016, 2017)
### How much water did the Trappist-1 planets form with?

<table>
<thead>
<tr>
<th></th>
<th>Period</th>
<th>Semi-major axis</th>
<th>Mass (TTVs)</th>
<th>Radius (transit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>1.5109 d</td>
<td>0.01111 AU</td>
<td>0.79 +/- 0.27 M&lt;sub&gt;E&lt;/sub&gt;</td>
<td>1.086 +/- 0.035 R&lt;sub&gt;E&lt;/sub&gt;</td>
</tr>
<tr>
<td>c</td>
<td>2.4218 d</td>
<td>0.01522 AU</td>
<td>1.63 +/- 0.63 M&lt;sub&gt;E&lt;/sub&gt;</td>
<td>1.056 +/- 0.035 R&lt;sub&gt;E&lt;/sub&gt;</td>
</tr>
<tr>
<td>d</td>
<td>4.0498 d</td>
<td>0.02145 AU</td>
<td>0.33 +/- 0.15 M&lt;sub&gt;E&lt;/sub&gt;</td>
<td>0.772 +/- 0.030 R&lt;sub&gt;E&lt;/sub&gt;</td>
</tr>
<tr>
<td>e</td>
<td>6.0996 d</td>
<td>0.02818 AU</td>
<td>0.24 +/- 0.56 M&lt;sub&gt;E&lt;/sub&gt;</td>
<td>0.918 +/- 0.039 R&lt;sub&gt;E&lt;/sub&gt;</td>
</tr>
<tr>
<td>f</td>
<td>9.2065 d</td>
<td>0.0371 AU</td>
<td>0.36 +/- 0.12 M&lt;sub&gt;E&lt;/sub&gt;</td>
<td>1.045 +/- 0.038 R&lt;sub&gt;E&lt;/sub&gt;</td>
</tr>
<tr>
<td>g</td>
<td>12.3528 d</td>
<td>0.0451 AU</td>
<td>0.566 +/- 0.038 M&lt;sub&gt;E&lt;/sub&gt;</td>
<td>1.127 +/- 0.041 R&lt;sub&gt;E&lt;/sub&gt;</td>
</tr>
<tr>
<td>h</td>
<td>18.7663 d</td>
<td>0.0596 AU</td>
<td>0.086 +/- 0.084 M&lt;sub&gt;E&lt;/sub&gt;</td>
<td>0.715 +/- 0.047 R&lt;sub&gt;E&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

Wang et al. (2017)
How much water did the Trappist-1 planets form with?

Wang et al. (2017), using their data and Gillon et al. (2017) data and Zeng et al. (2016) mass-radius relationships

b, c = rocky, not a lot of ice?
d, e, = less well constrained
f, g, h = appear water-rich, > 50%

Can we better constrain the ice content?
Can we include a realistic Fe/Mg?
How much water did the Trappist-1 planets form with?

We assume no H\(_2\)/He atmospheres in mass-radius relationships.

Even a small (~ 10\(^{-6}\) M\(_E\)) H\(_2\)/He atmosphere would inflate planet, and is hard to rule out, but thick H\(_2\)/He atmospheres don’t seem to inflate planets with R < 1.6 R\(_E\) (Weiss & Marcy 2014; Rogers 2015).

Unlikely to accrete more than ~10\(^{-4}\) M\(_E\) of H\(_2\)/He gas (Stokl et al. 2015).

<table>
<thead>
<tr>
<th></th>
<th>(\Delta M / 5) Gyr</th>
</tr>
</thead>
<tbody>
<tr>
<td>b</td>
<td>0.031 M(_E)</td>
</tr>
<tr>
<td>c</td>
<td>0.008 M(_E)</td>
</tr>
<tr>
<td>d</td>
<td>0.014 M(_E)</td>
</tr>
<tr>
<td>e</td>
<td>0.013 M(_E)</td>
</tr>
<tr>
<td>f</td>
<td>0.006 M(_E)</td>
</tr>
<tr>
<td>g</td>
<td>0.003 M(_E)</td>
</tr>
<tr>
<td>h</td>
<td>0.007 M(_E)</td>
</tr>
</tbody>
</table>

Trappist-1 planets easily lose 0.003 – 0.03 M\(_E\) of H\(_2\)/He gas (following Wheatley et al. 2017: updated XMM X-ray fluxes, 10% efficient energy-limited mass loss).

Bolmont et al. (2017) also concluded b and c cannot retain atmospheres.
How much water did the Trappist-1 planets form with?

Fe/Mg ratio constrained using metallicity

$[\text{Fe/H}] = +0.04 \pm 0.08$

(Gillon et al. 2017)

From Hypatia catalog

(Hinkel et al. 2014):

stars with this $[\text{Fe/H}]$

have $\text{Fe/Mg} = 0.5 - 1.3$

$1\sigma = 0.55 - 0.95$

Unterborn et al. (in revision)
How much water did the Trappist-1 planets form with?

**ExoPlex** code written by my group (Lorenzo et al., in prep: Alejandro Lorenzo, Cayman Unterborn, Byeongkwan Ko, Steve Desch)

Computes internal structure and mass-radius relationships of rock/ice planets (no atmospheres)

Iteratively calculates both hydrostatic equilibrium and equilibrium mineralogy, using **PerpleX** Gibbs free energy minimization routine (Connolly 2009) that uses mineral thermodynamic data (Stixrude & Lithgow-Bertelloni 2011).

Similar to code of Dorn et al. (2015).
We can include impurities in core.
We added EOS for ice I, VI, VII.
How much water did the Trappist-1 planets form with?

ExoPlex algorithm:

- Stoichiometry, mass set in each zone.
- $\rho$, $r(M)$ initialized.

- $g(r) = -G \frac{M(r)}{r^2}$

- $\alpha, C_p$ found

- $\frac{dP}{dr} = -\rho(r) g(r)$
- $\frac{dT}{dr} = T(r) \alpha \frac{g(r)}{C_p}$

- $\rho(P,T)$ found in each zone using PerpleX

- Updated $\rho = \text{updated } r(M)$
How much water did the Trappist-1 planets form with?

Now possible to measure H$_2$O on terrestrial planets to $\sim$ 10 wt%

-1b > 7-15wt% H$_2$O,
-1c < 5-12wt% H$_2$O

Probably both 7-12wt%

-1f > 52wt% H$_2$O
-1g > 54wt% H$_2$O

Fe-Mg-Si-O only, no Ca,Al
Solar Mg/Si = 1.0
Fe/Mg = 0.55 – 0.95

Unterborn, Desch, Hinkel & Lorenzo, in revision at Nature Astronomy
How much water did the Trappist-1 planets form with?

Internal structure of Trappist-1b (Rp=6918 km), with:
Fe-Mg-Si-O only
Fe/Mg=0.8
Mg/Si=1.0
10 wt% water (400 oceans)
How much water did the Trappist-1 planets form with?

A LOT.

Internal structure of Trappist-1f (Rp=6658km), with:
Fe-Mg-Si-O only
Fe/Mg=0.8
Mg/Si=1.0
50 wt% water (2000 oceans)
How much water can terrestrial planets form with?

Our solar system (planets around a G star):
Kuiper Belt Objects, icy moons ~ 50 wt% H₂O
Earth ~ 0.025 wt% H₂O
Dryness of inner solar system planets attributed to Jupiter trapping icy grains in pressure maximum beyond it (Morbidelli et al. 2016).

Trappist-1 system (planets around an M star):
Trappist-1f, -1g ~ 50 wt% H₂O
Trappist-1b, -1c ~ 7-12 wt% H₂O

Trapping of ice in pressure maxima may not work in M dwarf disks (Desch, Kalyaan, White, in preparation)
Perhaps all planets around M stars have at least several wt% H₂O.
Part 2: Are Aqua Planets or Water Worlds habitable? Can we detect life on them?

Water-rich planets can be perfectly habitable.

Water-rich planets generally are not good places to look for life (at least using $O_2$)
Should *Habitability* be our Main Guiding Principle?

**habitable**

Are water-rich planets habitable?

Why is a “habitable world” one with liquid water on the surface?

Why do we try so hard to define “habitability”?

What we really want to do is measure something about an exoplanet that tells us there is life on it.
# Should Habitability be our Main Guiding Principle?

Habitability is not restrictive enough to prioritize observations. There are already more habitable planets than JWST can characterize.

Low mass (< 4 $M_E$) transiting exoplanets in their stars’ habitable zones

<table>
<thead>
<tr>
<th>Exoplanet</th>
<th>Host Sp Type</th>
<th>Host [Fe/H]</th>
<th>$M_p / M_E$</th>
<th>$R_p / R_E$</th>
<th>$T_{eq}$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kepler 62f</td>
<td>K2</td>
<td>-0.37</td>
<td>2.8 +1.6 +7.4</td>
<td>1.41 -0.07 +0.07</td>
<td>244</td>
</tr>
<tr>
<td>Kepler 442b</td>
<td>K5</td>
<td>-0.37</td>
<td>2.3 -1.3 +5.9</td>
<td>1.34 -0.18 +0.11</td>
<td>233</td>
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<tr>
<td>Kepler 186f</td>
<td>M1</td>
<td>-0.26</td>
<td>1.5 -0.9 +3.2</td>
<td>1.17</td>
<td>188</td>
</tr>
<tr>
<td>TRAPPIST-1e</td>
<td>M8</td>
<td>+0.04</td>
<td>~ 0.6</td>
<td>~ 0.6</td>
<td>230</td>
</tr>
<tr>
<td>TRAPPIST-1f</td>
<td>M8</td>
<td>+0.04</td>
<td>~ 0.7</td>
<td>~ 0.7</td>
<td>200</td>
</tr>
<tr>
<td>TRAPPIST-1g</td>
<td>M8</td>
<td>+0.04</td>
<td>~ 1.3</td>
<td>~ 1.3</td>
<td>182</td>
</tr>
<tr>
<td>Kepler 1229b</td>
<td>M?</td>
<td>-0.06</td>
<td>&gt; 3.8</td>
<td>&gt; 3.8</td>
<td>213</td>
</tr>
</tbody>
</table>

TESS (2018) and PLATO (2026) will soon greatly expand this list.
**POP QUIZ**: You have just enough JWST time for IR transmission spectroscopy to measure the abundance of oxygen \([O_3 \text{ or } O_2-O_2]\) in the atmosphere of **one** exoplanet.

On which exoplanet is the discovery of oxygen most *diagnostic* of life?

Your choices:

- **A.** 1 M<sub>E</sub> planet in the Habitable Zone of a G star, with ~1% H<sub>2</sub>O
- **B.** 1 M<sub>E</sub> planet in the Habitable Zone of a G star, with “no” (< 0.1%) H<sub>2</sub>O
- **C.** 1 M<sub>E</sub> planet in the Habitable Zone of an M star, with ~ 1% H<sub>2</sub>O
- **D.** 1 M<sub>E</sub> planet in the Habitable Zone of an M star, with “no” (< 0.1%) H<sub>2</sub>O

Should *Habitability* be our Main Guiding Principle?
Detectability of Life as a Guiding Principle

We must move beyond defining habitability, and start figuring out on which exoplanets is life detectable.

“Detectability” means if life exists, it can be identified, because it dominates the geochemical cycle over abiotic processes.

Excess water changes the geochemical cycles of a planet: 6 oceans will submerge the continents.... 35 oceans will create a high-pressure ice layer... 100 oceans suppress silicate melting....

Planets with more water than Earth can be habitable --- even have measureable biogenic oxygen in their atmospheres --- but are lousy places to be sure you’ve seen the signs of life.
“Earth-like”

1 Ocean = $1.5 \times 10^{21}$ kg = 0.025% $M_E$

Average depth = 3-4 km
(Earth radius = 6371 km)

Seafloor to top of Mauna Loa = 9 km.
Carbon Cycle on Earth

**outgassing**

+4 Tmol/yr

**continental weathering**

+22 Tmol/yr

**seawater**

pH = 8.2*

**pCO₂ = 0.27 mbar**

* = pre-industrial

**subduction & uplift**

-2 Tmol/yr

**seafloor alteration**

-24 Tmol/yr

**burial**

Ca²⁺, Mg²⁺, Fe²⁺

Ca²⁺ + CO₃²⁻ -> CaCO₃

Rain

pH = 5.7*

Sleep & Zahnle (2001), Fig. 1; Wallmann & Aloisi (2012)
Organic Burial

Organisms remove C from the ocean when they sink to seafloor and are buried.

Most organisms have C:N:P = 106:16:1 (Redfield ratio). P needed in DNA and ATP.

1 P atom buried for every 106 – 170 C atoms buried (Colman & Holland 2000)
Oxygen Cycle on Earth

Catling (2014)

- Outgassed: $H_2$, CO, $H_2S$, CH$_4$
- 5 Tmol/yr $O_2$ consumed

$H_2O + CO_2 + \text{light} \rightarrow CH_2O + O_2$

$CH_2O + O_2 \rightarrow CO_2 + H_2O$

$H_2O + CO_2 + \text{light} \rightarrow CH_2O + O_2$

photosynthesis & respiration $10^4$ Tmol/yr

$C$, Fe$S_2$, FeO

continental weathering -17 Tmol/yr

photolysis, H escape +0.02-0.2 Tmol/yr

burial of biological C 18 Tmol/yr

$O_2$

$H_2$

$H_2O$

$CO_2$

$C$
Phosphorus Cycle on Earth

The seafloor is a net sink for phosphorus.

- Rain: pH = 5.7* 
- Dissolution of continental phosphates: ~ +0.07 Tmol/yr
- Organic burial: ~ -0.1 Tmol/yr
- Subduction & uplift
- Rock-water reactions in hydrothermal vents: ~ -0.03 Tmol/yr
- pH = 8.2*
- Organic burial: ~ 18 Tmol/yr
"Aqua Planet"

6 Oceans = 0.15\% \text{M}_\text{E}

Average depth = 18 km

Higher pressure changes speciation of outgassed volatiles

Ocean rather than rain water changes weathering/dissolution rates
Carbon Cycle on an Aqua Planet

Outgassing

$+4 \text{Tmol/yr}$

CO$_2$

Subduction & uplift

$-2 \text{Tmol/yr}$

Seafloor alteration

Ca$^{2+}$, Mg$^{2+}$, Fe$^{2+}$

Continental weathering

$pH = 8.0$

Precipitation

Ca$^{2+} + \text{CO}_3^{2-} \rightarrow \text{CaCO}_3$

Seawater

$pH = 5.4$

Rain

$pCO_2 = 0.59 \text{ mbar}$

Sleep & Zahnle (2001), Fig. 4; Wallmann & Aloisi (2012)
Oxygen Cycle on an Aqua Planet

Outgassed
$H_2$, CO, $H_2S$, CH$_4$
- 3 Tmol/yr

Photosynthesis & respiration
$10^4$ Tmol/yr ??

Photosynthesis, H escape
+0.02-0.2 Tmol/yr

Continental weathering
-0 to -15 Tmol/yr

Burial of biological C
X Tmol/yr
Oxygen Cycle on an Aqua Planet

outgassed
H₂, CO, H₂S, CH₄
-3 Tmol/yr ?
-30 Tmol/yr ?

As ocean depths increase, outgassed species more reducing (H₂S / SO₂ increases). Reductant flux sensitive to pressure and redox of mantle.
Phosphorus Cycle on an Aqua Planet

Phosphate dissolution sensitive to ~8x slower weathering, and higher pH: ~80 times slower at pH = 8.0 than at pH = 5.7 (Adcock et al. 2013)

Dissolved phosphate is the limiting nutrient.

Lower P flux = lower C burial flux

Dissolution of continental phosphate

\[ \text{PO}_4^{3-} \sim 0.00011 \ Tmol/yr \]

pH = 8.0

-0.03 Tmol/yr

Organic burial

\[ \sim -0.00011 \ Tmol/yr \]

Subduction & uplift

Rock-water reactions in hydrothermal vents

0.015 Tmol/yr C

Organic burial
Oxygen Cycle on an Aqua Planet

Photosynthesis & respiration
$\text{CO}_2$ + $\text{H}_2\text{O}$ ≈ $\text{O}_2$ + $\text{CH}_4$ + $\text{CO}$ + $\text{H}_2$ + $\text{H}_2\text{S}$

Burial of biological C
$0.015 \text{Tmol/yr}$

Continental weathering
$-0 \text{ to } -15 \text{Tmol/yr}$

Outgassed
$\text{H}_2$, $\text{CO}$, $\text{H}_2\text{S}$, $\text{CH}_4$

- $3 \text{Tmol/yr}$

Photolysis, H escape
$+0.02 - 0.2 \text{Tmol/yr}$

Outgassed
$10^4 \text{Tmol/yr} ??$

Continental weathering
$-0 \text{ to } -15 \text{Tmol/yr}$

Burial of biological C
$0.015 \text{Tmol/yr}$
“Water World”

Kuchner (2003); Leger et al. (2004); Fu et al. (2010)

50 Oceans = 1.0% $M_E$

Average depth of water+ice $\sim 150$ km

$P > 1$ GPa, depth $> 100$ km

Ice VI

Noack et al. 2016
Carbon Cycle on a Water World

outgassing
+0 Tmol/yr?
+5 Tmol/yr?

CO₂

pH = 5.0

Ice VI

pCO₂ = 20 bars?
Sleep & Zahnle (2001)
Phosphorus Cycle on a Water World

inputs of $PO_4^{3-}$ into ocean severely limited or even totally shut off

Ice VI
Oxygen Cycle on a Water World

Photosynthesis & respiration

$\text{CO}_2 + \text{H}_2 \rightarrow \text{H}_2\text{O} + \text{C}$

Photolysis, $H$ escape

$+0.02\text{--}0.2 \text{Tmol/yr}$

Hotolysis, $H$ escape

$+0 \text{Tmol/yr}$

Outgassed

$H_2, \text{CO}, H_2\text{S}, \text{CH}_4$

0 Tmol/yr?

- 3 Tmol/yr?

No input of $\text{PO}_4^{-3}$ = no burial of $\text{C}$ = no production of $O_2$

Diagram:

- Water cycle
- Photosynthesis
- Respiration
- Photolysis
- Hotolysis
- Outgassing
More Water Just Makes Things Worse

100 Oceans = 2.0% $M_E$

Average depth of water+ice $\sim$ 300 km

Pressures in rock layer too high for rock to melt. Continents don’t form. No geochemical cycling between mantle and ocean.
Detectability of Life on Aqua Planets, Water Worlds

Earths, Aqua Planets, Water Worlds: All may be habitable. All may have life producing measureable oxygen.

**But Ocean + Land needed to be sure the oxygen signifies life.**

**On Earth,** $O_2$ is overwhelmingly biotic and is a biosignature.

$$DI = \log_{10}(\frac{20 \text{ Tmol/yr}}{0.02 \text{ Tmol/yr}}) = +3$$

**Aqua Planets:** Low P input = low C burial = low $O_2$ production. $O_2$ supplied by biology and photolysis at comparable rates. We can’t be sure $O_2$ is biotic.

$$DI = \log_{10}(\frac{0.015 \text{ Tmol/yr}}{0.02 \text{ Tmol/yr}}) \approx 0$$

**Water Worlds:** Oceans may have no P inputs: no ability to export C, so no $O_2$ buildup.

$$DI = \log_{10}(\frac{0.0 \text{ Tmol/yr}}{0.02 \text{ Tmol/yr}}) = -\infty$$
POP QUIZ: On which exoplanet is the detection of oxygen most diagnostic of life?

A. 1 $M_E$ planet in the Habitable Zone of a G star, with $\sim 1\%$ $H_2O$

$\text{DI} = -\infty$

B. 1 $M_E$ planet in the Habitable Zone of a G star, with “no” ($< 0.1\%$) $H_2O$

$\text{DI} = 0$ (Aqua Planet) to $\text{DI} = +3$ (Earth-like)

C. 1 $M_E$ planet in the Habitable Zone of an M star, with $\sim 1\%$ $H_2O$

$\text{DI} = -\infty$

D. 1 $M_E$ planet in the Habitable Zone of an M star, with “no” ($< 0.1\%$) $H_2O$

$\text{DI} = -1$ (Aqua Planet) to $\text{DI} = +2$ (Earth-like)
Part 3: How should we look for life on exoplanets?

Oxygen is a biosignature on exoplanets with water AND land.

We must prioritize those rocky exoplanets with less than measurable water content.
0. Find transiting planets with R < 1.5 RE in HZs of multi-planet systems.

1. Measure host star X-ray, UV fluxes, constrain stellar activity

2. Obtain high-precision (~10%) Mass & Radius from transits, TTVs, RVs

   Yes
   
   Is H₂/He atmosphere likely stripped?

   No
   
   Can't Resolve H₂/H₂O Degeneracy

3. Get precise (~10%) stellar abundance ratios, esp. Mg/Fe, Si/Fe

   Yes
   
   M, R, X still imply < 0.1wt% H₂O?

   No
   
   Probably a Water World

4. Measure transit depth vs. color.

   Yes
   
   Probably a Water World

   No
Covered in Hazes or no Atmosphere

No

Transit depth varies with color?

Yes

5. Measure atmospheric gases using transmission and emission spectroscopy

<1 bar CO₂?

Yes

Oxygen, H₂O present?

Yes

Continents & Oceans?

No

Likely an Aqua Planet

No

6. Measure Reflectance Lightcurve

No

Probably No Biosignatures
Part 1: How much water can terrestrial planets form with?

Theory says: up to hundreds of oceans’ worth of water
Trappist-1 suggests hundreds of oceans, especially around M stars
Many (most?) planets may be Aqua Planets or Water Worlds

Part 2: Are Aqua Planets or Water Worlds habitable?
Can we detect life on them?

Water-rich planets can be perfectly habitable.
Water-rich planets generally are not good places to look for life (at least using O₂)

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We must prioritize those rocky exoplanets with less than measureable water content.