What makes a planet habitable?
Why this course?
Why now?
NASA Planet Hunter Finds Earth-Size Habitable-Zone World

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Planets are numerous ... and many have atmospheres

For more information: Madhusudhan et al., “Exoplanetary atmospheres,” arXiv:1402.1169
Launching soon:
Today:

• Logistics (mutual introductions, course handout, introductions, designate presenters for Tue 14 paper presentation)

• Course outline, motivation, scope

• Earth history, post-Hadean
Course outline

Foundations (1-2 weeks)
• Earth history
• HZ concept, atmospheric science essentials
• Post-Hadean Earth system

Principles – how are habitable planets initiated and sustained? (4-5 weeks)
• Volatile supply, volatile escape
• Long-term climate evolution
• Runaway greenhouse, moist greenhouse

Specifics (~2 weeks)
• Early Mars
• Hyperthermals on Earth
• Oceans within ice-covered moons
• Exoplanetary systems e.g. TRAPPIST-1 system
PDFs of all required and suggested reading will be made available at http://geosci.uchicago.edu/~kite/geos32060_2020/

Particularly useful books:

Atmospheric evolution on inhabited and lifeless worlds, Catling & Kasting (Full text available through library!) e.g. http://geosci.uchicago.edu/~kite/doc/Catling_and_Kasting_ch_5.pdf

How to build a habitable planet, Langmuir & Broecker (on reserve at Crerar)

Ingersoll, Planetary Climates (Princeton Primers) (lovely, insightful, short)

Accessible and solid introductions:

Life on a young planet, Andy Knoll (climate/life on Earth) (slightly outdated but excellent intro to how Earth Scientists think)

Planet Mars, Francois Forget (climate history on Mars) (superficially picture-booky but actually top notch)

Five billion years of solitude, Lee Billings (exoplanets) (science journalism but good)

Good references/cookbooks:

Principles of planetary climate, Pierrehumbert (if you model rocky planet climate, you need this book)

Planetary Science, de Pater and Lissauer (very up-to-date, not great on geoscience, but great on many other things)
Fundamental Planetary Science, de Pater and Lissauer (good, sub-Carroll-and-Ostlie level)
Lecture 1 Key points

• A useful definition of a habitable world is one that maintains $T < 400$ K liquid water on its surface continuously for timescales that are relevant for biological macroevolution.

• Earth has stayed habitable for $>3$ Gyr
  – Continuously
  – Earth inhabited only by microbes pre-1 Gya.

• A ‘difficult step’ is a step in biological evolution whose characteristic wait time (given a habitable planet) is $>> 10$ Gyr. There are at least three candidate difficult steps on the evolutionary path leading to people.

• Earth’s continuous habitability implies that Earth’s climate has stayed within the habitable range at least for the last 3.5 Ga
  – However, Earth’s $pO_2$, $pCO_2$, and ocean chemistry have changed over time.
What makes a planet habitable?

For the purposes of this course: A planet is a sub-stellar mass object that has never undergone nuclear fusion and which has sufficient self-gravitation to assume a spheroidal shape adequately described by a triaxial ellipsoid regardless of its orbital parameters.

For the purposes of this course: A habitable exoplanet maintains $T<400K$ liquid water on its surface continuously for timescale that are relevant for biological macroevolution ($>>10^7$ yr). Sub-ice oceans in extrasolar planetary systems may be habitable, but this cannot be confirmed from Earth by remote sensing. (Sub-ice oceans will be covered in Week 9).
Habitable for what?

Carl Sagan’s “Cosmos”
Habitable for what?

Specular reflection from Punga Mare, Titan

How do we know habitability when we see it?

Recurring Slope Lineae on Mars

Ojha et al. Nature Geosci. 2015
Round-table exercise

- Definitions?
- Habitability assessment workflow = ?
- What do we look for?
- For each thing we look for:
  - is it intrinsically necessary, maybe necessary, not necessary?
  - is it thought to be needed \textit{for Earth}?
Habitable environments can be short-lived. How short-lived is too short-lived to be interesting?

Comet impacts on Titan

Armetieva & Lunine
Icarus
2003
If definition of habitability involves geologic timescales → geologic data needed
Earth history post-Hadean

dark purple: >2.5 Ga rocks (most have been subjected to high T/P which destroys fossils)
Plate tectonics has destroyed most of the evidence of Earth’s earliest (pre-3.8 Ga) history

Pilbara (NW Australia), Barberton (SE Africa), Isua (W Greenland)
Carbon Isotopes

$^{14}\text{C}$, $^{13}\text{C}$, and $^{12}\text{C}$.

Organisms prefer to use $^{12}\text{C}$ - most abundant, most reactive, preferred by enzymes in the cell.

Biomass enriched in $^{12}\text{C}$, carbonate enriched in $^{13}\text{C}$.

Ratio of $^{12}\text{C}:^{13}\text{C}$ provides carbon isotopic fractionation value.

Measured as a $\delta^{13}\text{C}$ value:

$$\delta^{13}\text{C} = \frac{^{13}\text{C} / ^{12}\text{C}}{^{13}\text{C} / ^{12}\text{C}}_{\text{standard}} - 1$$

‰, per mil.

Fig. 5-1 Ranges for $\delta^{13}\text{C}$ values in selected natural compounds. Especially noteworthy is the spread in $^{13}\text{C}$ seen in different plant groups and the resulting soil $\text{CO}_2$.

Clark & Fritz, 1997
Tiny but remarkably persistent excess of photosynthesis over respiration in Earth sediments

\[ \delta^{13}C_{in} = f_{org}\delta^{13}C_{org} + (1 - f_{org})\delta^{13}C_{carb} \]

from text ‘Fundamentals of geobiology’
Continuity of life: body fossils

1.9 Ga
Gunflint
Chert
Continuity of life: Proterozoic molecular fossils

Pawloska et al. Geology 2012
Body size has increased over geologic time.
<10⁸ yr increase in complexity of life in Ediacaran -> Cambrian

High levels of atmospheric oxygen are required for animal life

Spicules from sponges (modern sponge shown)

Rangeomorph

Yacatus
Why did the development of complex, multicellular life on Earth take so long?

- Long wait for origin of life? (very unlikely)
- Evolutionary innovations the rate-limiting step?
- Environmental changes the rate-limiting step?
- Focus for the rest of this course: microbial habitability
The remarkable coincidence between the timescale of past biological evolution on Earth and the future life expectancy of the Sun

The coincidence to which I am referring is based on the very well known fact (see, for example, Dickerson & Geiss 1976) that the time $t_e$, say, that has been taken so far by biological evolution on this planet since its formation is given to within a few tens of percent by

$$t_e \approx 0.4 \times 10^{10} \text{ years}$$

(3.1)

and the almost equally well known fact (see, for example, Hoyle 1955) that the ‘main sequence’ lifetime, $\tau_0$, say, of the Sun, during which the energy output from steady hydrogen burning can maintain favourable conditions for life on Earth, is estimated to be given with not quite comparable precision by

$$\tau_0 \approx 10^{10} \text{ years}.$$  

(3.2)

Now the biological processes that have governed the evolution of life up to the present stage of emergence of civilization and the astrophysical processes determining the lifetime of the Sun have nothing directly to do with each other (the slowness of the former arising from the numerical complexity of living systems, whereas the slowness of the latter arises from the weakness of gravitation). Therefore the coincidence of these numbers to within a factor close to two, representing the observation that the Sun is now just about half way through its expected life, does not deserve to be just taken for granted as it seems to have been until now. (Indeed, simply in terms of precision, this coincidence is much more striking than the order of magnitude cosmological coincidences which not unjustifiably caught the attention of Dirac.)

Possible responses to Carter’s argument include:

(A) It is a very powerful argument that uses only a few unobjectionable assumptions,

(B) One bit of data is worth more than a hundred pages of this kind of argument.
What can we infer about climate from the continuity of life?

Continuous surface (or near-surface) liquid water

Life is known to proliferate at least within this range:

\[ T = -25^\circ\text{C} \text{ to } 122^\circ\text{C} \]

\[ \text{pH} = 0 \text{ to } 13 \]

\[ P \text{ up to } 200 \text{ MPa} \]

Water activity as low as 0.6
Evidence for oceans on Earth >4.0 Ga

Jack Hills zircons
Glaciation uncommon in Earth history
History of Earth’s climate
Figure 2. Co-evolution of life and surface environments on Earth. The top panel shows the timing of major transitions in the history of the biosphere. The middle panel shows Earth’s oxygenation trajectory, while the bottom panel shows the abundance of CH₄ through time. In each, the vertical blue bars denote the timing of low-latitude glaciations, while colored lines show one possible trajectory through the parameter space implied by proxy reconstructions (shaded boxes; see Fig. 1 and Fig. 3b).
Figure 3. **Greenhouse constraints through Earth history.** For each geological eon, grey boxes represent inclusive ranges for model and proxy-based constraints on atmospheric $pCO_2$ (a) and $pCH_4$ (b). The minimum and maximum values for each grey box are specified in Table 3 for CO$_2$ and Table 4 for CH$_4$. The colored bars represent preferred ranges corresponding to constraints from specific proxies discussed in the text, including: paleosols (red), organic haze (orange), ice core records (for the last 800,000 years (Loulougue et al 2008; Luthi et al 2008); light blue), and Mauna Loa observations (since 1958 for CO$_2$ (e.g., Keeling 1976) and since 1983 for CH$_4$ (Dlugokencky et al 1994); yellow).
Figure 4. \( N_2 \) and pressure constraints through Earth history. For each geological eon, grey boxes represent inclusive ranges for model and proxy based constraints on \( pN_2 \) (a) and total atmospheric pressure (b). The colored bars represent preferred ranges corresponding to constraints from specific proxies discussed in the text, including: N isotopes (blue), basalt vesicles (green), and ice core records (light blue). As elsewhere, yellow line denotes modern \( pN_2 \) and total pressure. Total pressure generally tracks \( N_2 \) abundance, but the dark grey box in (b) represents elevated surface pressure due to very high O\(_2\) during the Carboniferous (see Fig. 1a). In the Archean, the apparent incompatibility of \( pN_2 \) and total pressure constraints may be reconciled by considering the temporal separation between the \( pN_2 \) constraints (3.5-3.0 Ga; Marty et al 2013) and the total pressure constraints (2.7 Ga; Som et al 2016); these complementary datasets may suggest a secular decline in atmospheric pressure during the Archean eon (e.g., Stüeken et al 2016).
Next lecture: why has Earth avoided the fates of Mars and Earth?

http://geosci.uchicago.edu/~kite/geos32060_2020/
Bonus slides
Complex life and complex biospheres are lacking for most of Earth history.

**TEXT-FIG. 1.** A conceptual view of the macroecological differences between the pre-Ediacaran and post-Ediacaran marine biospheres, and the transitional Ediacaran. The disparity curve is derived from acritarch data and estimated number of cell types (McShea 1996; Huntley et al. 2006), and ecosystem stability from estimated rates of evolutionary turnover (Sepkoski 1984; Knoll 1994). The spikes in ecosystem stability following Phanerozoic mass extinctions are inferred from observed and modelled recovery times (Solé et al. 2002). Biomass spectrum very broadly tracks disparity through this interval (see Bell and Mooers 1997) except during mass extinctions, which are characterized by the loss of large organisms but not cell types. Also shown are the age ranges of pre-Ediacaran eukaryotes discussed in the text, and the Cryogenian and Ediacaran glaciations (triangles). Note that the Ediacaran/Cambrian boundary as depicted here (at the base of the Tommotian; c. 530 Ma) differs from the IUGS-ratified position, which corresponds to the base of the preceding Nemakit-Daldyn Stage (c. 542 Ma). Vertical scale for all curves is qualitative only.

Nick Butterfield, Macroevolution and macroecology through deep time, Paleontology, 2007
Using genetic data to probe paleoclimates? *= new, little-tested method*

- Resurrect ancestral proteins
- Determine their temperature sensitivity

**NDK = nucleoside diphosphate kinases**

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**Fig. 4.** Environmental temperature ranges inferred from reconstructed ancestral NDK $T_m$s plotted against fossil-record-indicated first appearance of the various groups. Paleotemperatures inferred from δ$^{18}$O (5) and δ$^{30}$Si (7) in marine cherts are included for comparison. Blue boxes show the inferred NDK-based temperature ranges (Fig. 3) and fossil-based age uncertainties, the red diamonds denoting temperature and age midpoint values for which ViridiNDK and Viridi18S have been combined due to the similarity of their $T_m$s.

Garcia et al. PNAS 2017
Origin of oxygenic photosynthesis

Fischer et al., Annual Reviews, 2016
Table 1. Atmospheric $O_2$ constraints for each geologic eon

<table>
<thead>
<tr>
<th>Eon</th>
<th>Constraints (xPAL)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Archean</strong></td>
<td>$10^{-12}$  $10^{-5}$</td>
<td>The minimum estimate arises from abiotic photochemical production of $O_2$ (1); the maximum derives from the persistence of MIF-S (2), but transient excursions to higher $pO_2$ (3) are allowed (4).</td>
</tr>
<tr>
<td><strong>mid-Proterozoic</strong></td>
<td><em>Incl.</em> $10^{-5}$ $10^{-1}$</td>
<td>The minimum is constrained by absence of MIF-S (2); the maximum is likely constrained by the absence of Cr isotope fractionation (5), but is difficult to reconcile with photochemical models (6).</td>
</tr>
<tr>
<td><strong>Phanerozoic</strong></td>
<td>$10^{-1}$  2</td>
<td>The minimum and maximum values here reflect temporal variability rather than ambiguities in proxy interpretation as above (7).</td>
</tr>
</tbody>
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By convention, $pO_2$ is expressed with respect to the present atmospheric level (PAL) of $O_2$: 0.21 atm. Minimum and maximum values are provided for inclusive and preferred ranges where divergent constraints exist. Inclusive ranges correspond to the grey boxes in Fig. 1 whereas preferred ranges are highlighted with colored boxes. The numbered references within the table correspond to: (1) Kasting et al. 1979; (2) Pavlov and Kasting 2002; (3) Anbar et al. 2007; (4) Reinhard et al. 2013b; (5) Planavsky et al. 2014b; (6) Claire et al. 2006; (7) Berner 1999.
Table 3. Atmospheric CO₂ constraints for each geologic eon

<table>
<thead>
<tr>
<th>Eon</th>
<th>Constraints (μatm)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min.</td>
<td>Max.</td>
</tr>
<tr>
<td>Archean</td>
<td>Incl.</td>
<td>2500</td>
</tr>
<tr>
<td></td>
<td>Pref.</td>
<td>2500</td>
</tr>
<tr>
<td>mid-Proterozoic</td>
<td>Incl.</td>
<td>1400</td>
</tr>
<tr>
<td></td>
<td>Pref.</td>
<td>1400</td>
</tr>
<tr>
<td>Phanerozoic</td>
<td></td>
<td>200</td>
</tr>
</tbody>
</table>

Here pCO₂ is expressed in units of μatm as plotted in Fig 3, whereas paleo-pCO₂ constraints are often expressed as a multiple of the pre-industrial atmospheric level (PAL) in the Precambrian literature and/or ppmv in the more recent past. We have converted to μatm from PAL assuming pCO₂ = 280 μatm, unless otherwise specified by the original authors. Note that in the recent past for which total pressure has been 1 atm, 1 μatm is synonymous with 1 ppmv—but this equivalence is invalid for most of Earth history because total atmospheric pressure has changed substantially (see Fig. 4b) and we have thus avoided use of ppmv here. Minimum and maximum values are provided for inclusive and preferred ranges where divergent constraints exist. Inclusive ranges correspond to the grey boxes in Fig. 3a whereas preferred ranges are highlighted with colored boxes. The numbered references within the table refer to: (1) Hessler et al 2004 (2) Rye et al 1995; (3) Sheldon 2006; (4) Walker et al 1981; (5) Mitchell and Sheldon 2010; (6) Kaufman and Xiao 2003; (7) Sheldon 2013; (8) Royer et al 2004.
Fig. 6. Smoothed $f_{\text{org}}$ (solid line) with 95% confidence intervals (dashed lines) from the updated carbon cycle model and parameter distributions described in the main text. Smoothed $f_{\text{org}}$ from the simple carbon cycle model using LOWESS (section 4.1) is denoted by the dot-dash line for comparison, with 95% confidence intervals shaded gray.