The Nature and Evolution of Habitability

A discussion of Bennett and Shostak Chapter 10
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Chapter Overview

• Concept of a Habitable Zone
• Venus: An Example in Potential Habitability
• Surface Habitability Factors and the Habitable Zone
• Future of life on Earth
• Global Warming

Habitability: Introduction

• Define “habitability”
  – Anthropocentric perspective
  – Astrobiological perspective (capable of harboring liquid water)
• Key physical and chemical features of habitability
  – Surface habitability
  – Temperature
  – Source of energy
  – Liquid water (present and past)
  – Biological macromolecules (e.g., sugars, nucleotides)
  – Atmosphere and magnetosphere

Concept of a Habitability Zone

• Definition of habitability zone (HZ)
  “Region of our solar system in which temperature allows liquid water to exist (past, present and future)”
• Phase diagram for H₂O
• Retrospective analysis of HZ using the terrestrial planets as case study
  – Mars, Venus and Earth
• Prospective analysis of HZ

Luminosity of the Sun

• Definition of luminosity (watts/m²)
• Sun’s luminosity has been changing: earlier in its evolution, luminosity was only 70% of what it is today (how could temperature be maintained over geological time)
• Future for luminosity
  – Remember star sequence from lab and lecture
  – 2-3 BY, luminosity will place Earth outside habitability zone
Distance from the Sun

- Terrestrial planets – heat mostly from Sun
- Jovian planets – 2/3 of heat from interior (all planets originally had internal heat source due to bombardment)
- Heat from Sun is inversely proportional to distance\(^2\) or heat energy = \(k \cdot \frac{1}{(\text{distance})^2}\)
- Heat falls off rapidly with distance

Habitability Zone of Our Solar System

- Exploration of Mars, Venus and Earth provides a framework to establish a HZ in terms of water
  - Venus (0.7 AU): liquid H\(_2\)O in the past
  - Mars (1.5 AU): oceans primordially
  - Thus, range of habitability around stars like Sun is 0.7 to 1.5 AU
- Zone of “continuous habitability” versus zone of “habitability” (which is more narrow?)
  - needs to maintain habitability for billions of years

Continuous Habitability Zone of Our Solar System

- Outer edge of HZ must be less than Mars (1.5 AU) orbit (closer to Earth than to Mars)
  - Estimate of ~1.15 AU
- Inner edge of HZ closer to Earth than Venus because Venus lost its greenhouse of H\(_2\)O early in its evolution
  - Estimate of ~0.95 AU
- Conclusion: for planet to maintain liquid H\(_2\)O continuously for 4 BY, HZ is as follows:
  - >0.95 AU < 1.15 AU
  - HZ of only 0.2 AU in breadth

Habitability Zone in Our Galaxy

- Use the range from our solar system as a basis for analysis
  - In our solar system, 4 rocky planets that orbit the Sun from 0.4 to 1.4 AU and spaced 0.4 AU apart
- If typical, likelihood of other solar systems having continuous habitability zone is just width of the zone divided by the typical spacing
  - 0.2/0.4 = 0.5
  - Probability of 50%
  - Discuss this probability

Habitability Zones Elsewhere in the Galaxy

- Other factors also relevant
  - Several stars in our galaxy with planets the size of Jupiter within terrestrial zone from their sun
  - Mass of star
    - Larger mass, greater luminosity, shorter life
    - Most abundant stars in galaxy are least luminous and longest-lived (M-dwarfs)
Signatures of Habitability and Life

- Distance from sun
- Luminosity of sun
- Planet size
- Atmospheric loss processes
- Greenhouse effect and gases in the atmosphere
- Source of energy (internal/external)
- Presence of water
- Presence of carbon biomolecules
- Biota

Earth-like planets: Rare or Common

Comparative Habitability of Terrestrial Planets

- Venus (0.7 AU; radius 0.95E; same density as Earth)
  - Very hot; evidence of liquid water in the past
- Mars (1.5 AU; radius 0.53E)
  - Very cold; evidence of water today and in the past
- Earth (1.0 AU; radius 1.0E)
  - Temperature moderation; liquid water today and in the past
- Keys
  - greenhouse effect
  - size of planet
  - proximity to Sun

Greenhouse Effect

- Factors to consider
  - light energy (visible wavelengths) from Sun
  - transfer through a planet’s atmosphere
  - absorption on the planet’s surface (soil, H2O)
  - re-radiation of energy as longer wavelengths
    - i.e., infrared radiation
  - inability of infrared radiation to escape atmosphere
  - Conversion of energy from light to heat energy
- Analogy to a greenhouse
  - Glass versus atmosphere as “barrier”

Greenhouse Effect In the Terrestrial Planets

- Earth’s greenhouse effect
  - without greenhouse effect: -23°C
  - with greenhouse effect: 15°C (+Δ 38°C)
- Venus’ greenhouse effect
  - without greenhouse effect: 43°C
  - with greenhouse effect: 470°C (+Δ 427°C)
- Mars’ greenhouse effect
  - without greenhouse effect: -55°C
  - with greenhouse effect: -50°C (+Δ 5°C)

Principles of the Greenhouse Effect

- Primary principle of the Greenhouse Effect
  - A greenhouse gas is a gas that allows visible light to be transmitted but is opaque to IR (infrared) radiation
- Key is trace gases in atmosphere and cycling in the oceans and terrestrial landscapes
  - Water (H2O)
  - Carbon dioxide (CO2)

<table>
<thead>
<tr>
<th>Gas</th>
<th>Venus (%)</th>
<th>Earth (%)</th>
<th>Mars (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2O</td>
<td>0.0001</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>CO2</td>
<td>98</td>
<td>0.03</td>
<td>96</td>
</tr>
<tr>
<td>Pressure</td>
<td>90 (atm)</td>
<td>1</td>
<td>0.007</td>
</tr>
</tbody>
</table>

**% is relative abundance of that gas versus the other gases**
Greenhouse Effect: 
\[ \text{H}_2\text{O} \]
- Water: a “runaway” greenhouse gas
  - Prolonged periods of excessive heat or cold to change temperature at a global scale
- Two key chemical properties of \( \text{H}_2\text{O} \)
  - High heat capacity
  - Decrease in density with freezing (insulation and reflectance)
- Temperature scenario on planetary surface as \( f[\text{H}_2\text{O}] \)
  - Cooling of \( \text{H}_2\text{O} \), leading to ice formation, followed by more cooling (albedo)...runaway greenhouse effect
  - “Positive Feedback”

Greenhouse Effect: 
\[ \text{CO}_2 \]
- Carbon dioxide: “compensatory” greenhouse gas
  - Need a molecule to compensate for “positive feedback” of \( \text{H}_2\text{O} \), resulting in a “negative feedback”
- Key chemical properties of \( \text{CO}_2 \)
  - Importance of atmospheric state (absorbs visible light)
  - Concentration in atmosphere linked to oceans, geological reactions, and biota (plants)

Cycling of \( \text{CO}_2 \) on Earth

\[
\text{Atmosphere} \quad \rightarrow \quad \text{Rock} \quad \leftarrow \quad \text{Ocean} \quad \rightarrow \quad \text{Sedimentation/bicarbonate} \\
\quad \text{plate tectonics} \quad \text{dissolution}
\]

Keys:
(i) recycling of \( \text{CO}_2 \)
(ii) geological time scales (millions to billions of years)
(iii) Earth’s long-term thermostat
(iv) interplay of \( \text{CO}_2 \) and \( \text{H}_2\text{O} \) cycles

Greenhouse Effect: 
\[ \text{CO}_2 \] (cont)
- Temperature scenario on planetary surface \( f[\text{CO}_2] \)
  - As temperature increases, \( \text{CO}_2 \) goes from atmosphere to geological substrates so that cooling occurs (negative feedback)
  - As temperature decreases, \( \text{CO}_2 \) in atmosphere increases (off-gassing from geological substrates) so that temperature increases (positive feedback)
- Evidence that \( \text{CO}_2 \) and \( \text{H}_2\text{O} \) have achieved control of Earth’s temperature
  - Surface temperature delicately balanced for at least 3.8 billion years
  - Sedimentary rocks in geological record (3.8 BY)

Greenhouse Effect: 
\[ \text{CO}_2 \] (cont)
- Catastrophic effect of too much \( \text{CO}_2 \)
  - Venus
    - 100 times more \( \text{CO}_2 \) than on Earth
    - Venus lost most of its \( \text{H}_2\text{O} \) early in its evolution as a planet
      - therefore no greenhouse effect via \( \text{H}_2\text{O} \)

Temperature of Earth’s Surface
- Related to the energy received from the Sun
  - Luminosity of Sun
  - Distance from Sun
- Albedo/reflectivity of the surface
  - Total absorption (albedo of 0)
  - Total reflection (albedo of 1)
- Greenhouse gases
  - \( \text{H}_2\text{O} \)
  - \( \text{CO}_2 \)
Habitability of Venus

- Key factors
  - Nearer to Sun (1.9 x more sunlight than Earth)
  - Temperature high enough to melt a lot of stuff
  - Massive atmosphere of CO$_2$ and little H$_2$O
    - Due to mass of Venus and atomic mass
  - CO$_2$ in atmosphere approached theoretical maximum of CO$_2$ from carbonate in rock
    - analogy to earth if oceans were to boil
  - Divergent paths for Venus and Earth due to early loss of massive volumes of H$_2$O from Venus atmosphere
    - Data to support original presence of H$_2$O (stable isotope)

Habitability of Venus (cont)

- Reason for loss of H$_2$O
  - Heat from Sun transferred H$_2$O from oceans to atmosphere
  - In atmosphere, H$_2$O further accelerated heating ("positive feedback")
    - Increase in temperature “boiled” oceans (100 MY)
    - H$_2$O as a “runaway greenhouse gas”
  - UV light in upper atmosphere breaks up H$_2$O bonds
- With H$_2$O gone, die was cast
  - all CO$_2$ could not be locked up in oceans and could not escape
- Absence of plate tectonics, so no re-cycling of CO$_2$

Habitability of Mars

- Mars atmosphere similar to Venus
  - High CO$_2$
  - Very small pressures and no greenhouse warming
  - Small pressure + distance from Sun = cold and dry
  - H$_2$O present today in polar ice caps and ground ice
- Geological hints of warmer, early Mars
  - Volcanic activity but no re-cycling of CO$_2$ (small size preclude plate tectonics)
  - Higher/thicker atmosphere = Earth early in evolution
  - Evidence of liquid H$_2$O is great (lab last week)
    - Dry channels and valley etched by liquid H$_2$O; sedimentary deposits

Habitability of Mars (cont)

- Unlike Earth, Mars climate changed as CO$_2$ disappeared and temperature dropped
  - Mars’ small size facilitated more rapid cooling after bombardment and no tectonics to re-cycle CO$_2$
- History
  - Formation of Mars (as with Earth via accretion)
  - Heavy cratering during bombardment
  - High CO$_2$ and high H$_2$O (0.5 BY)
    - Probability of life most likely
  - Progressive loss of CO$_2$ to carbonates
  - Drop in atmosphere and temperature

Recall Comparative Habitability of Terrestrial Planets

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- Keys
  - greenhouse effect (CO$_2$, H$_2$O, oceans)
  - size of planet (tectonics, gravity, atmosphere)
  - proximity to Sun (luminosity)

Parable of the Daisyworld

- Introduction
  - What is a parable?
  - Daisyworld as a parable
- Methodologies in the sciences
  - Scientific method and testing of hypotheses
  - Use of modeling as a method/tool
- GAIA Hypothesis
  “Climate (temperature) on the surface of the Earth is regulated like a thermostat by biota (plants, animals and microbes)”
Parable of the Daiseyworld (cont)

- Gaia and systems theory (cybernetics)
- Key features
  - Feedback processes
    - Positive feedbacks
    - Negative feedbacks
  - Homeostasis ( liken to that of living organisms and thermostat)
  - Role of biota
  - Albedo of surface features

Parable of the Daiseyworld (cont)

- Simple mathematical model of the earth’s surface and temperature
- Biota is simplified to be solely two species of daisies
  - White daisy
  - Dark/black daisy
- Temperature response of daisies is species specific
  - Albedo of the surface
    - Reflect light (1)
    - Absorb light (0; greenhouse effect)

Parable of the Daiseyworld (cont)

- Hypothesis: if theory is correct, presence of biota imparts more stability of climate (temperature) over time than a planet without daisies
- Run simulation and look at results
- Examples

Parable of the Daiseyworld

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<th>Water/Ice/Land</th>
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<tbody>
<tr>
<td>0°C</td>
<td>+</td>
<td></td>
</tr>
<tr>
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Increasing Luminosity of Sun

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Increasing Luminosity of Sun
Parable of the Daiseyworld: Summary

- Basic principles of Daiseyworld model
  - Cybernetic system
- Role of biota in governing temperature when luminosity changes (i.e., increases as in Earth’s evolution; catastrophic change)
- Appreciate role of models in scientific method
- Hypothesis: atmosphere as a signature of life on a planet
- Add biota to your list of factors affecting habitability

Planet Habitability Questions

- Tectonics
  - why important?
- Effects of Magnetosphere
  - Especially with respect to solar wind
- Gravity and relationship to plate tectonics

Atmospheric Loss Processes to Consider

- Solar winds of charged particles
  - Sweeps away atmosphere in episodic wind events
- Planet’s magnetic field (magnetosphere)
  - Deflect solar winds
  - Earth and Mercury have magnetospheres
  - Mars and Venus do not have magnetospheres
- Atmospheric loss processes
  - Escape velocity of gases

Greenhouse Gases

- Why is this relevant to habitability?

Sources of Energy

- Why is this relevant to habitability?
- What are the sources of energy?

Presence of Water

- Is this relevant to the topic of habitability and if so what are the factors that are important?

Presence of Carbon Biomolecules

- Is this relevant to the topic of habitability and if so what are the factors that are important?

When does it end on Earth?

- Change in our atmosphere
  - human causes and others
- Change in magnetosphere
- Change in Earth interior
  - cooling of the Earth
- Change in Sun
  - life cycle of any star like our Sun