Unit Overview

- Searching for Planets
- 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

Are Habitable Planets Common?

- Really two questions
  - Are planets common?
  - How many exoplanets are habitable?
- Review formation of stars and planets
  - evidence from HST

Habitability Zone Around Other Stars 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 Zone in Our 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 (red dwarfs)
Different Stars – Different Habitable Zones

Another View of Habitability

iClicker Question

• Compared to a star of spectral type K, a star of spectral type A is generally
  - A hotter, more luminous, and more massive.
  - B hotter, more luminous, and less massive.
  - C cooler, dimmer and less massive.

iClicker Question

• Stars of types O and B are unlikely to have planets with life because
  - A they have short stellar live.
  - B their intense ultraviolet light would sterilize any planets.
  - C they don’t have enough heavy elements.

iClicker Question

• How does the habitable zone around a star of spectral type M compare to that around a star of spectral type G?
  - A It’s larger and farther from its star.
  - B It’s hotter and brighter.
  - C It’s smaller and closer to its star.

How to Find an Extrasolar Planet

• Think about how a planet effects the star around which it orbits
  - light seen from star
  - gravitational effects
    • translate into visual effects
  - spectroscopic effects
    • translate into observed spectroscopic observations
    • remember Doppler Effect
Four Ways to Find an Extrasolar Planet

- **Photometrically**
  - light from star blocked by planet decreasing light seen from star in concert with orbit
- **Astrometrically**
  - change in position caused by "dance with planet"
- **Spectroscopically**
  - Doppler Effect on spectral lines due to "dance with planet"
- **Gravitational Microlensing**
  - large gravitational force effecting light path

Change in position of Sun due to Jupiter as seen from 10 parsecs distant

Remember Doppler

Applying Doppler

Applying Einstein's General Theory of Relativity
Extraosolar Planets Capability

Considerations for Habitability
- 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

Phases of Water and CO₂

Planetary Spectra
Planet Size Questions

- Tectonics: why important
- Magnetosphere and solar winds
- Gravity and tectonics

Atmospheric Loss Processes to Consider

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

iClicker Question

- About how many extrasolar planets have been detected to date?
  - A between 10 and 100
  - B between 100 and 1000
  - C more than 1000

iClicker Question

- How have we detected most extrasolar planets discovered to date?
  - A Transits
  - B Hubble Space Telescope images
  - C the Doppler related technique

iClicker Question

- Which technique will the Kepler mission use to search for Earth size planets around other stars?
  - A Transits
  - B The astrometric technique
  - C The Doppler related technique
  - D Gravitational lensing

iClicker Question

- Nearly all the extrasolar planets discovered to date are
  - A terrestrial-like planets
  - B jovian-like planets
  - C large, icy worlds
Is Earth Rare?

- What are the odds?
  - Location, location, location
  - Special events
- What are the odds of any special event?
  - Example of coin toss

Habitability: Introduction

- Define "habitability"
  - Anthropocentric perspective
    - capable of supporting humans
  - 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

Planet Surface Temperatures

Recall Solar System Formation

Summary of the Techniques for Searching for Habitable Worlds

- Planet Formation
- Extrasolar Planets
  - Detection
- Earth-like Planets?
  - Transit Detection of Exoplanets

Planet Gravity, Density and Rotation
iClicker Question

• The habitable zone refers to
  – A the regions of a planet where good weather allows life to exist.
  – B the range of distances from a star where a planet’s surface temperature is always above the freezing point of water.
  – C the range of distances from a star within which water could exist in liquid form on a suitably sized planet.

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

Phase Diagrams – Water and CO₂

iClicker Question

• A planet that is not within a habitable zone cannot have
  – A life.
  – B subsurface oceans.
  – C abundant liquid water on its surface.

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 life cycle of stars
  – In another 2-3 BY, luminosity will place Earth outside habitability zone
  – More about at end of chapter
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 distance² or heat energy = k*1/(distance)²
- Heat falls off rapidly with distance

Habitability Zone of Solar System

- Exploration of Mars, Venus and Earth provides a framework to establish a HZ in terms of water
  - Venus (0.7 AU): liquid H₂O 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 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 H₂O early in its evolution
  - Estimate of ~0.95 AU
- Conclusion: for planet to maintain liquid H₂O 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)
  - Don’t forget, 2/3 of stars in galaxy are binary stars
Signatures of Habitability

• 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

Comparative Habitability of Terrestrial Planets

• Venus (0.7 AU; radius 0.95E)
  - Very hot; evidence of liquid water in the past
• Mars (1.5 AU; radius 0.53E)
  - Very cold; evidence of subsurface water today and surface water in the past
• Earth (1.0 AU; radius 1.0E)
  - Temperature moderation; liquid water on surface 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

• Venus’ greenhouse effect
  - without atmosphere/greenhouse: 43°C
  - with atmosphere/greenhouse effect: 470°C (+427°C)
• Earth’s greenhouse effect
  - without atmosphere/greenhouse effect: -23°C
  - with atmosphere/greenhouse effect: 15°C (+38°C)
• Mars’ greenhouse effect
  - without atmosphere/greenhouse effect: -55°C
  - with atmosphere/greenhouse effect: -50°C (+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 has two effects, one greenhouse, one cooling (think clouds)
• 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>3</td>
<td>0.1</td>
</tr>
<tr>
<td>CO₂</td>
<td>98</td>
<td>0.03</td>
<td>96</td>
</tr>
<tr>
<td>Pressure (atm)</td>
<td>90</td>
<td>1</td>
<td>0.007</td>
</tr>
</tbody>
</table>

*% is relative abundance of that gas versus the other gases

iClicker Question

• Venus’ atmosphere has much more carbon dioxide than Earth’s because
  - A Venus was born in a region of the solar system where more carbon dioxide gas was present.
  - B Venus lacks oceans in which carbon dioxide can be dissolved.
  - C Venus has volcanoes that outgas much more carbon dioxide than those on Earth.
Greenhouse Effect: $\text{H}_2\text{O}$

- Water can act as a 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 a function of $\text{H}_2\text{O}$
  - Cooling of $\text{H}_2\text{O}$, leading to ice formation, followed by more cooling (albedo) - "Positive Feedback"

Greenhouse Effect: $\text{CO}_2$

- Carbon dioxide sometimes called a "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
  - Concentration in atmosphere linked to oceans, geological reactions, and biota (plants)

Cycling of $\text{CO}_2$ on Earth

\begin{itemize}
  \item Atmosphere
  \item Oceans
  \item Plate tectonics
  \item Sedimentation/bicarbonate
  \item Dissolution
\end{itemize}

- Recycling of $\text{CO}_2$
- Geological time scales (millions to billions of years)
- Earth's long-term thermostat
- Interplay of $\text{CO}_2$ and $\text{H}_2\text{O}$ cycles

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
  - $\text{H}_2\text{O}$
  - $\text{CO}_2$

Greenhouse Effect: $\text{CO}_2$

- Temperature scenario on planetary surface as a function of $\text{CO}_2$
  - 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: $\text{CO}_2$

- 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 $\text{H}_2\text{O}$
Consider This

- If the Sun were twice as bright as it actually is, life on Earth would not be possible.
  - A True
  - B False

Now Consider This

- Consider the following
  - If the Sun were twice as bright the temperatures on Earth would be much greater, but how do you calculate this?
    - $E \propto T^4$ therefore $T \propto E^{1/4}$
    - So if $E$ doubles, then temperature increases by about 1.2 times, so the temperature on Earth would be about 360 Kelvin (boiling point is 373 Kelvin at 1000 millibars).

Consider This

- If the Sun were several times brighter than it actually is, the habitable zone would include Jupiter's orbit.
  - A True
  - B False

Now Consider This

- Consider the following
  - Jupiter's temperatures now are about 150 Kelvin. In order to double that to get within the liquid water range, the Sun's brightness would have to increase by 2 to the 4th power (in accordance with Stefan-Boltzmann Law), or 16 times the brightness that it is now.
  - What does "several times brighter" mean?

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

- Reason for loss of H$_2$O
  - Heat from Sun transferred H$_2$O from oceans to atmosphere
  - 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
    - no re-cycling of CO$_2$
Venus and Earth Comparisons

![Venus/Earth Comparisons](image)

iClicker Question

- What is the likely reason for Venus' lack of water in any form?
  - A The planet accreted little water during its birth.
  - B The water is locked away in the crust.
  - C The water was in the atmosphere, where molecules were broken apart by ultraviolet light from the Sun.

Habitability of Mars

- Mars atmosphere similar to Venus
  - High CO₂
  - Very small pressures and no greenhouse warming
  - Small pressure + distance from Sun = cold and dry
  - H₂O present today in polar ice caps and ground ice
- Geological hints of warmer, early Mars
  - Volcanic activity but no re-cycling of CO₂ (small size preclude plate tectonics)
  - Higher/thicker atmosphere = Earth early in evolution
  - Evidence of liquid H₂O is great
    - Dry channels and valley etched by liquid H₂O; sedimentary deposits

Habitability of Mars (cont)

- Unlike Earth, Mars climate changed as CO₂ disappeared and temperature dropped
  - Mars' small size facilitated more rapid cooling after bombardment and no tectonics to recycle CO₂
- History
  - Formation of Mars (as with Earth via accretion)
  - Heavy cratering during bombardment
  - High CO₂ and high H₂O (0.5 BY)
  - Probability of life most likely
  - Progressive loss of CO₂ to carbonates
  - Drop in atmosphere and temperature

Summary of Terrestrial Planets wrt Habitability

- Mercury (forget about it)
- Venus (0.7 AU; radius 0.95 E)
  - Very hot; evidence of liquid water in the past
- Mars (1.5 AU; radius 0.53 E)
  - Very cold; evidence of water beneath surface today and in the past on surface too
- Earth (1.0 AU; radius 1.0 E)
  - Temperature moderation; liquid water today and in the past too
- Keys
  - greenhouse effect (CO₂, H₂O, oceans)
  - size of planet (tectonics, gravity, atmosphere)
  - proximity to Sun (luminosity)

Test Your Understanding Questions

- If Venus were just a little bit smaller, its climate would be Earth-like.
- Venus is not in the habitable zone now, but it may have been in the past.
- Venus is not in the habitable zone now, but in a few billion years from now it will be.
- If we could somehow start plate tectonics on Venus, its surface would cool and it would regain the oceans it had in the past.
- Mars will someday undergo a runaway greenhouse effect and become extremely hot.
Consider This

- If Venus were just a little bit smaller, its climate would be Earth-like.
  - Consider the following
    - If Venus were smaller, what physical characteristics would change?
      - Gravity \(\rightarrow\) Escape Velocity \(\rightarrow\) Atmosphere Gases
        - May change atmospheric pressure, but then if it were much smaller it would not be able to hold onto any atmosphere, like Mercury
        - Less gravity would also mean the interior cooling off faster
    - What does "a little bit smaller" really mean?

Parable of the Daisyworld

- Introduction
  - What is a parable?
  - Daiseworld 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 Daisyworld (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 Daisyworld (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 Daisyworld (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 Daisyworld

- Increasing Luminosity of Sun

<table>
<thead>
<tr>
<th>Luminosity of Sun</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>No water/land</td>
<td>No biota</td>
</tr>
<tr>
<td>Albedo = 1</td>
<td></td>
</tr>
</tbody>
</table>
Parable of the Daisyworld

Increasing Luminosity of Sun

0°C

Parable of the Daisyworld

Increasing Luminosity of Sun

0°C

Parable of the Daisyworld: Summary

- Basic principles of Daisyworld 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

iClicker Question

- Are the presence of greenhouse gases relevant to habitability?
  - A Yes
  - B No
iClicker Question
• Are energy sources relevant to habitability?
  - A Yes
  - B No

iClicker Question
• Which are sources of energy for a planet?
  - A The Sun
  - B Remnant heat from formation in the core of the planet.
  - C Radioactive decay of elements in the interior of the planet.
  - D All of the above.

iClicker Question
• Is the presence of water relevant to the topic of habitability?
  - A Yes
  - B No

iClicker Question
• Is the presence of carbon biomolecules relevant to the topic of habitability?
  - A Yes
  - B No

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

Post Main Sequence on the HR Diagram
Test Your Understanding

Questions

• We are not yet certain, but it is quite likely that Earth has suffered through a runaway greenhouse effect at least once in the past 4 billion years.
• While the habitable zone of the Sun migrates outward over time, the habitable zones of other Sun-like stars might instead migrate inward over time.
• If earth someday becomes a moist greenhouse, it will have a climate that is humid but still quite comfortable.
• The fact that additional atmospheric CO2 must cause a greenhouse effect is all we need to know to link global warming to human activity.
• Earth has been warmer in the past than it is today, so there is nothing to worry about with global warming.

Consider This

• While the habitable zone of the Sun migrates outward over time, the habitable zones of other Sun-like stars might instead migrate inward over time.
  - Consider the following
    • What constitutes Sun-like stars?
      - Our Sun is a G2 V (main sequence)
    • Assuming all F, G and K main sequence stars
      - All main sequence stars increase luminosity over time