In-Class Question

1) Do you think that there are planets outside the solar system which would be habitable for human life?

   a) 1 (yes, definitely)
   b) 2
   c) 3 (maybe)
   d) 4
   e) 5 (no, definitely)
Lecture Topics

- The question of life.
- The balance of powers.
  - Why is the Earth the temperature it is?
- Ecospheres and Habitable Zones.
  - The Greenhouse Effect
  - Influence of the stellar spectrum.
- The lifetimes of stars
- The solar system from afar

Does life exist elsewhere?

- How can we find out about
  - Other planetary systems
  - Planets like earth
  - Other intelligent species
- If other civilizations exist can we
  - communicate with them?
  - travel there?
Lec. 31: The Habitability of Worlds

What kind of life?

- We are relegated to discussing life as we know it.
  - Carbon-based life?
  - For every 200 atoms in your body – H: 126, O: 51, C: 19, N: 4, all other elements: 1
- That is, physical conditions somewhat similar to earth.
- There could be life on Jupiter and we would never know it!

What kind of star?

- Do we need a star like our sun?
- Issues
  - Temperature of the planet
  - Spectrum of the radiation from the star
  - Lifetime of the star
Temperature

- Temperature is the main quantity which can influence the feasibility of life.
  - Too hot $\Rightarrow$ water is not liquid
  - Too cold $\Rightarrow$ water is frozen (chemical reactions slow)
  - We’d like it “just right”
- Temperature is governed by
  - distance from the planet to the star
  - thickness of the planet’s atmosphere

What keeps the earth warm?

- The power received from the Sun is balanced by emission by the Earth.
Power Received

- The power absorbed by the Earth is
  \[ P_a = \frac{L}{4\pi d^2} \pi R_{\text{earth}}^2 (1 - A) \propto \frac{L}{d^2} \]
  
  where
  - \( L \) = luminosity of the Sun
  - \( d \) = Sun-Earth distance
  - \( R_{\text{earth}} \) = radius of Earth
  - \( A \) = albedo (fraction of light reflected)

- This is an application of the inverse square law!

Power Emitted

- The power emitted by the Earth is
  \[ P_e = \varepsilon 4\pi R_{\text{earth}}^2 \sigma T_e^4 \propto \sigma T_e^4 \]
  
  where
  - \( R_{\text{earth}} \) = radius of Earth
  - \( T_e \) = temperature of Earth
  - \( \varepsilon \) = infrared emissivity ~ 1.0

- This is the Stefan-Boltzmann Law!
  - with a correction factor because Earth does not quite emit like a black body
A Balance of “Powers”

- In equilibrium, the absorbed and emitted power are equal

\[ P_a = P_e \implies \frac{L}{4\pi d^2} \pi R_{\text{earth}}^2 (1 - A) = \varepsilon 4\pi R_e^2 \sigma T_e^4 \]

simplifying

\[ \implies \frac{L}{4\pi d^2} (1 - A) = \varepsilon 4\sigma T_e^4 \]

\[ \implies T_e^4 = \frac{L}{16\pi d^2} \left(1 - A\right) \implies T_e^4 \propto \frac{L}{d^2} \]

Moving Earth

- Thus we have

\[ T_e^4 \propto \frac{L}{d^2} \implies T_e \propto \frac{L^{1/4}}{d^{1/2}} \]

The temperature of the Earth is ~ 300 K. If we quadrupled our distance from the Sun,

- then \( T = 150 \) K (-120 C)
- This is almost the distance of Jupiter
- The oceans would be frozen!
Changing the Sun

- The star Vega is 3 times as massive as the Sun and 58 times more luminous,
  \[ M = 3 \, M_{\text{Sun}}, \quad L = 58 \, L_{\text{Sun}} \]
- If we place a planet 1 AU from Vega, then
  \[ T = (58)^{1/4} T_e = 2.7 \times T_e = 810 \, \text{K} \]
- No oceans, no people! Too hot!!

Moving further away

- We get back to the temperature of the earth if the planet is moved 8 times further away!!

Since
\[ T_e \propto \frac{L_{\text{sun}}^{1/4}}{d_{\text{earth}}^{1/2}} = \frac{L_{\text{Vega}}^{1/4}}{d_{\text{planet}}^{1/2}} \]

\[ \Rightarrow \quad d_{\text{planet}} = (L_{\text{Vega}} / L_{\text{sun}})^{1/2} d_{\text{earth}} \]
Habitable zones and Ecospheres

- The **habitable zone** is the range of distances around a star over which “comfortable” temperatures are possible.
- The is also called the **Ecosphere**.
- Let us choose this range to be where water is liquid.
  - Inside this zone, water boils.
  - Outside this zone, water freezes.
The Ecosphere

- The distance of the habitable zone from the star will vary depending on the type of star.
- More luminous stars ⇒ the habitable zone is further away than the Sun’s
- Less luminous stars ⇒ the habitable zone is closer than the Sun’s

Sample Ecospheres

- More luminous stars have a large habitable zone.
- F-type star
- G-type star
- M-type Star
Lec. 31: The Habitability of Worlds

Ecospheres for Stars

- Water boils
- Water freezes

Distance from Star (AU) vs. Stellar Mass ($M_{\text{sun}}$)

- Venus at 0.72 AU is within the Sun’s ecosphere!
- But its surface temperature is 745 K!
- A runaway greenhouse effect.
- The Earth is helped by a mild greenhouse effect!

Ecosphere (cont’d)
The Greenhouse Effect

- Photons (blue) from the sun penetrate the glass.
- Infrared photons (red) are trapped inside by the glass.
- So the greenhouse heats up.

Greenhouse Effect on Earth

- Photons from the sun reach the surface of the earth.
- Carbon dioxide prevents infrared photons from radiating energy to space.
- The Earth can’t cool.
- Too much CO₂ will cause the earth to get too hot.
Temperature is not everything.

- More luminous stars have a larger habitable zone, however they will emit a lot of UV radiation!
- The peak of the spectrum is given by Wien’s Law

$$\lambda_{peak} = \frac{2900 \mu m}{T}$$

Comparing some stars

<table>
<thead>
<tr>
<th>Star</th>
<th>Type</th>
<th>T (K)</th>
<th>$\lambda_{peak}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun</td>
<td>G2</td>
<td>5,800</td>
<td>0.5 $\mu$m</td>
</tr>
<tr>
<td>Vega</td>
<td>A0</td>
<td>10,000</td>
<td>0.29 $\mu$m</td>
</tr>
<tr>
<td>Barnard’s</td>
<td>M5</td>
<td>2,800</td>
<td>1.0 $\mu$m</td>
</tr>
</tbody>
</table>

- Vega would give you a bad sunburn!
- Barnard’s star could not support photosynthesis.
The Spectrum of the Star

- If the star is too hot it will emit lots of UV photons (high energy!)
  - Life will be damaged
- If the star is too cool, it will emit mostly infrared photons (low energy!)
  - Photosynthesis not possible
  - Chemical reactions not helped by the star

In-Class Question

1) The range of distances from a star over which water could be liquid is called:
   a) The buffer zone
   b) The habitable zone
   c) The ecosphere
   ⇒ d) b and c
   e) a and b
In-Class Question
1) The range of distances from a star over which water could be liquid is called:
   a) The buffer zone
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   c) The ecosphere
   d) b and c
   e) a and b

2) What is the significance of the “balance of powers”?
   a) It assures countries won’t destroy one another
   b) It determines where planets are formed
   c) It determines the temperature of a planet
   d) It keeps planets from falling into the Sun
   e) No significance, you made it up

The Lifetime of Stars
- Stars must live long enough for life to evolve.

<table>
<thead>
<tr>
<th>Star</th>
<th>Mass ($M_{\text{sun}}$)</th>
<th>Lifetime ($10^9$ yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>3.5</td>
<td>0.44</td>
</tr>
<tr>
<td>F0</td>
<td>1.7</td>
<td>3.0</td>
</tr>
<tr>
<td>G0</td>
<td>1.1</td>
<td>8.0</td>
</tr>
<tr>
<td>K0</td>
<td>0.8</td>
<td>17.0</td>
</tr>
</tbody>
</table>
Lifetimes

- There is evidence that (simple) life existed on Earth 3.5 billion years ago!
- O, B, and A type stars do not survive long enough for life to evolve.
- Only F, G, K and M stars survive long enough.

Where to look for life

- To find life as we know it:
  
  Look around F, G and K stars.
  
  - They have
    - relatively long lives,
    - put out photons with right energy, and
    - have moderately large ecospheres.
The solar system from afar.

- **α Cen**, a nearby star (1.3 pc = 4.3 lyr)
  - G2 V star, \( m_v = 0.0 \)
- How would the solar system appear if it were there?

<table>
<thead>
<tr>
<th>Planet</th>
<th>Separation from ( \alpha ) Cen</th>
<th>( m_v )</th>
<th>Factor fainter than ( \alpha ) Cen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth</td>
<td>0.76&quot;</td>
<td>24</td>
<td>( 4 \times 10^9 )</td>
</tr>
<tr>
<td>Jupiter</td>
<td>3.9&quot;</td>
<td>22</td>
<td>( 6 \times 10^8 )</td>
</tr>
</tbody>
</table>

How do we find other planets?

**Four Possible Methods**

- Direct observation
  - Reflected light from star
  - Intrinsic infrared radiation
- Search for brightness variations
- Measure wiggles on the sky
- Doppler spectroscopy
Analogy to binary stars

- These techniques are similar to those used for binary stars.

<table>
<thead>
<tr>
<th>Search Technique</th>
<th>Binary Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct observation</td>
<td>Visual</td>
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<tr>
<td>Brightness variations</td>
<td>Eclipsing</td>
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<td>Doppler shifts</td>
<td>Spectroscopic</td>
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