Name: ________________

Date: ________________

Section: ________________

Astron 104 Laboratory #10
Solar Energy and the Habitable Zone

Introduction

The Sun provides most of the energy available in the solar system. Sunlight warms the planet and helps create the conditions for life, as we know it. In this lab, you will explore how solar energy determines the location and size of the **Habitable Zone**: the portion of the solar system where conditions could support life, as we know it.

Learning Objectives

1. Define the concepts of energy flux and albedo.
2. Describe the equilibrium temperature, T_{eq}, of a planet based on energy balance.
3. Describe the greenhouse effect and its role in setting the surface temperature of the Earth.
4. Define and describe the Habitable Zone with respect to T_{eq} and liquid water.

Equilibrium Temperature (70 points)

All organisms on Earth require liquid water for at least some part of their life cycle. At the pressure of Earth's atmosphere, water can be in liquid form in the temperature range of **0 to 100 degrees Celsius**. Astronomers use the **Kelvin** scale for temperature, where:

$$\text{Kelvin} = \text{Celsius} + 273$$

1. What is the range of temperatures for liquid water on the Kelvin scale? [**5 pts**].

2. What happens to water at colder temperatures? What about at hotter temperatures? [**5 pts**].

The surface temperature of a planet is the result of energy balance. Energy coming in from sunlight is absorbed, warming the planet.

3. Imagine your friend holds a flashlight in a dark field. How does the appearance of the flashlight change as you walk away from them? [**5 pts**].

4. Say you stood still and the flashlight began to appear brighter. How would you explain this observation? What if you knew your friend was not moving? [**5 pts**].

The apparent brightness of the light source depends on a quantity called the **energy flux**. Higher flux makes a light source appear brighter to your eye. The energy flux depends on two quantities:

- the rate of energy emitted by the source and
- the distance to the source

A light source emits energy at a rate given in Watts (W). The Sun emits energy at 4×10^{26} W, which is called the **luminosity** L of the Sun. As this energy radiates away from the Sun, it is spread out over a larger and larger area. The energy flux F follows a so-called **inverse square law** because it depends on the inverse square of the distance d:

$$F \propto \frac{L}{d^2}$$

5. Imagine two asteroids: Asteroid A is 2 AU from a star and Asteroid B is 4 AU from the same star. If the energy flux of starlight is $400\,\mathrm{W/m^2}$ at Asteroid A, what is the energy flux of starlight at Asteroid B? [**5 pts**].

A planet does not absorb all of the sunlight that falls upon it. Some of it is reflected by the surface. The fraction of light reflected by the surface is called its **albedo** (A):

- A high albedo (near 1.0) surface reflects a large fraction of the incident light, and appears bright when seen from far away.
- In constrast, a low albedo (near 0.0) surface absorbs a large fraction of the incident light, and appears dark and dull when seen from far away.

6. Rank the following surfaces in order of increasing albedo, from the most absorbent (1) to most reflective (4) [**10 pts**].:

   Charcoal: Ocean Water: Fresh Snow: Desert Sand:

The fraction of sunlight absorbed by a surface is simply $(1-A)$. For example, if ice has albedo of $A = 0.80$, then the ice reflects 80% of incident sunlight and absorbs $1-0.80 = 0.20$ or 20% of incident sunlight.

A planet emits some of the energy it receives from its star to space through **thermal radiation**, cooling the planet. The planet's temperature is determined by the equilibrium condition, where the rate of energy out equals the rate of energy in. The thermal energy emitted by a planet is proportional to the fourth power of its surface temperature, $F \propto T^4$. We can solve the energy balance equation for the equilibrium temperature T_{eq}. The formula below gives the equilibrium temperature for a planet (in Kelvin) based on the flux of sunlight (F) and the planet's albedo (A):

$$T_{\text{eq}} = 45.8[F(1-A)]^{1/4}$$

8. Based on this formula, would an increase in the albedo increase or decrease the temperature of the planet? Can you explain this effect?[**5 pts**].

9. What happens to the temperature of a planet if we move it farther away from the Sun? What would the larger distance change on the right-hand side of the formula?[**10 pts**].

10. Complete the table below to find the equilibrium temperatures of these three planets. The Solar flux at Earth is given and you can use the equations for T_{eq} and F to find the Solar flux at the other planets [**20 pts**]. The temperature conversion from Kelvin to Fahrenheit is:

$$T(\text{F}) = \frac{9(T(\text{K}) - 273)}{5} + 32$$

	Distance from Sun (AU)	Solar Flux (W/m^2)	Albedo	F(1-A) (W/m^2)	T_{eq} (K)	T_{eq} (F)
Venus	0.72		0.75			
Earth	1.00	1367	0.29			
Mars	1.50		0.22			

Feedback in the Atmosphere (45 points)

The average surface temperature on Earth is 288 K (59 F). This is much warmer than the equilibrium temperature you found above. We assumed the planet has no atmosphere, when in reality an atmosphere acts like a blanket, trapping energy and warming the planet. This is known as the **greenhouse effect**, and without it life on Earth would be impossible.

1. Say you park your car outside of the grocery store on a sunny day and leave the windows closed while you shop. What happens to the temperature inside the car? How does it compare to the temperature of the outside air when you return? [**5 pts**].

Window glass transmits visible light (sunlight), but is opaque to **infrared light**. Visible light from the Sun is absorbed by the car's interior, which emits a **thermal spectrum** in infrared light. The window glass prevents the infrared light from escaping the car, causing the change you notice when you return with your groceries. In this analogy, the window plays the role of gases in Earth's atmosphere. Carbon dioxide and water vapor play significant roles as **greenhouse gasses**.

2. Based on the analogy, do carbon dioxide and water vapor absorb or transmit visible light? Do these gasses absorb or transmit infrared light?[**5 pts**].

Earth's atmosphere is a very complex system, where changing one variable affects many other variables. Those variables can then affect the first one. This loop is known as **feedback**. Feedback can either be **positive** or **negative**:

- Positive feedback means that the original variable keeps changing faster (it runs away from where it started)
- Negative feedback means that the original variable goes back to where it started

Several feedback loops are involved, so let's consider a few.

In the following questions, fill in the blanks with **increase** or **decrease** to complete the carbon feedback loop:

3. Earth's oceans are able to absorb carbon dioxide from the atmosphere, leading to formation of limestone on the ocean floor. The water in the oceans would freeze if the temperature on Earth suddenly ________. Without liquid oceans, carbon dioxide absorption would ________ and the amount of carbon dioxide in the atmosphere would ________. The amount of infrared radiation escaping Earth to space would ________, causing the temperature of the surface to ________, melting the oceans. [**5 pts**].

4. Is the carbon feedback cycle a positive or negative feedback loop? Explain your reasoning. [**5 pts**].

5. If the temperature on earth suddenly increased, evaporation from the oceans would ________, causing the amount of water in the atmosphere to ________. The amount of infrared radiation escaping Earth to space would ________, causing the temperature of the surface to ________________. [**5 pts**].

6. Is this process a positive or negative feedback loop? Explain your reasoning. [**5 pts**].

7. Venus experiences a higher solar flux than Earth, but its equilibrium temperature is actually lower (refer to the previous table). How can this be true? Explain. [**5 pts**].

8. Measurements of the surface temperature of Venus are an incredible 737 K. Most hypothesis suspect that this was the result of a **runaway greenhouse effect**.

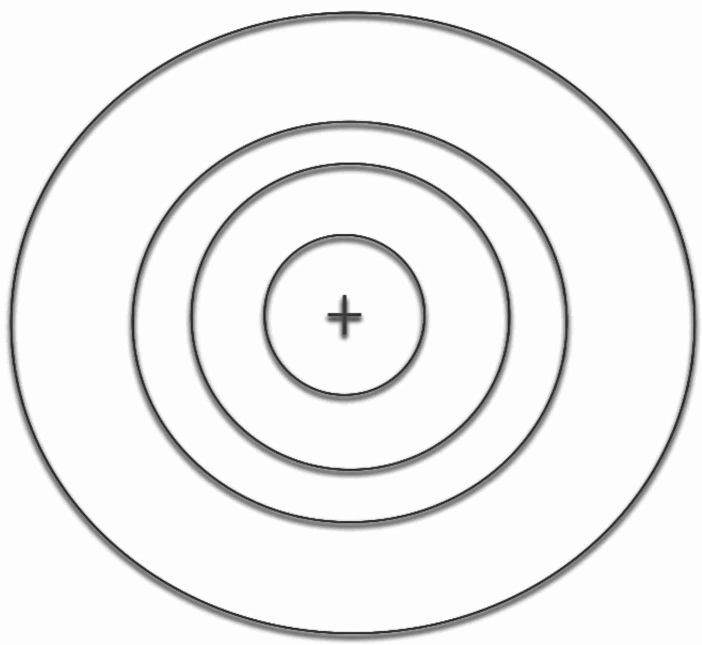
   What if Venus once had oceans of liquid water? How would an increase in the energy flux of sunlight change the evaporation rate of liquid water? What would this do the amount of water vapor in the atmosphere of Venus? [**5 pts**].

9. Continue this line of reasoning until you find a feedback loop. Is it positive or negative? [**5 pts**].

The Habitable Zone (10 points)

The fact that all life on earth is known to require liquid water leads to the definition of the **Habitable Zone**: a region around a star where the surface of a planet can have liquid water.

1. The chart below shows the orbits of the inner planets: Mercury, Venus, Earth and Mars. Based on your work in this lab, shade in the Habitable Zone around the Sun (the Sun is indicated by a + sign), showing the inner and outer boundaries. Which planets are in the Habitable Zone? [**5 pts**].



2. The sketches below show the Habitable Zones around three different types of stars: The Sun, the hotter star F, and the cooler star K. Label the three stars according to type. [**5 pts**].