Planetary Surface Temperatures & Greenhouse Effect – Benjamin Farr

Note: This lesson assumes the teacher has access and is familiar with Mathematica. Learn more about Mathematica here: https://www.wolfram.com/mathematica/

Purpose

The purpose of this activity is for students to gain an understanding of what factors determine the surface temperature of a planet. They will be using a basic model for this, that takes into account the planet's radius, orbital radius, albedo, and the strength of the greenhouse effect on the planet.

Overview

This activity is centered around the use of a computer model made using Mathematica, that models the surface temperature of planets, including a basic model for the greenhouse effect.

Student Outcomes

AAAS 1A:

- **P2:** Science investigations generally work the same way in different places.
- **E2:** Science is a process of trying to figure out how the world works by making careful observations and trying to make sense of those observations.
- **H1:** Science is based on the assumption that the universe is a vast single system in which the basic rules are everywhere the same and that the things and events in the universe occur in consistent patterns that are comprehensible through careful, systematic study.

AAAS 4A:

- **H4:** Mathematical models and computer simulations are used in studying evidence from many sources in order to form a scientific account of the universe.

AAAS 4E:

- **P1:** The sun warms the land, air, and water.
- **M1:** Whenever energy appears in one place, it must have disappeared from another. Whenever energy is lost from somewhere, it must have gone somewhere else. Sometimes when energy appears to be lost, it actually has been transferred to a system that is so large that the effect of the transferred energy is imperceptible.

M2: Energy can be transferred from one system to another (or from a system to its environment) in different ways: 1) thermally, when a warmer object is in contact with a cooler one; 2) mechanically, when two objects push or pull on each other over a distance; 3) electrically, when an electrical source such as a battery or generator is connected in a complete circuit to an electrical device; or 4) by electromagnetic waves.

M6: Light and other electromagnetic waves can warm objects. How much an object's temperature increases depends on how intense the light striking its surface is, how long the light shines on the object, and how much of the light is absorbed.

Time

10-15 minutes opening discussion
20-25 minutes working with computational model
5 minutes wrap-up discussion

Level

11-12 Grade Astronomy

Materials and Tools

Mathematica Player
Greenhouse model Mathematica player file
Greenhouse model activity sheet

Preparation

Ensure the free Mathematica player program is downloaded and installed on classroom computers, and that the Greenhouse model player file is accessible.

Prerequisites

Some previous discussion of energy and equilibrium would be helpful, but not necessary.

Background

In this lesson, you will learn how the ideas of equilibrium and energy conservation can be used to develop a model for the surface temperature of planets. You will also use a basic model for the greenhouse effect, in order to develop an understanding of how the greenhouse effect can impact the surface temperature of a planet.

Teaching Notes

Students are first introduced to new topics in a 10-15 minute discussion at the beginning of class. The concept of equilibrium is revisited, now for the case of thermal equilibrium. The concept of flux is introduced to explain why a planet's temperature depends on its distance from the Sun. Albedo is also introduced in order to determine how much incoming energy a planet will absorb. Black body radiation is reviewed to show how planets are able to radiate away energy. The class then has a short discussion about the greenhouse effect, and what effect that has on the surface temperature of a planet. Students are then shown a model for these processes, and a small discussion is had on what all of the parameters mean, and how they affect the planet's temperature. Students then go through a worksheet using a computer program that uses the models discussed in class to determine the planetary temperatures. The class is ended with a short discussion of what values students found for the greenhouse parameters of Earth, Venus, Mercury, and the Moon, and how this affects their surface temperatures.

Assessment

Assessment is done by checking answers to the questions on the activity sheet. The final discussion is also meant to test students' understanding of planetary surface temperatures and what affects them.

Planetary Surface Temperatures & Greenhouse Effect

After the lesson, you should have a clear understanding of how the equilibrium between incoming and outgoing energy for planets can be used to determine their surface temperature. You should also have a basic understanding of the greenhouse effect, and how this can affect the surface temperature of a planet.

Element	**1**	**2**	**3**
Eqiulibrium for Surface Temperatures	Understands that equilibrium is a balance, but not what is being balanced.	Understands that incoming energy from the sun and outgoing radiation from the planet must balance.	
Albedo	Doesn't understand what albedo is.	Understands that albedo is a measure of the reflectivity of a planet, but not what effect this has on the surface temperature.	Understands albedo measures reflectivity of a planet <u>**AND**</u> that lower albedos mean more energy absorption.
Greenhouse Effect	Doesn't know what the greenhouse effect is.	Understands that the greenhouse effect raises planetary surface temperatures, but can't explain it in terms of energy.	Understands that the greenhouse effect raises planetary surface temperatures <u>**AND**</u> can explain it in terms of energy.
Greenhouse Model	Doesn't know why the model includes the greenhouse effect.	Understands how the greenhouse effect is included in the model, but doesn't know what value corresponds to no greenhouse effect.	Understands how the greenhouse effect is included in the model, <u>**AND**</u> knows what value corresponds to no greenhouse effect.

Planetary Surface Temperatures

Element	**1**	**2**	**3**
Interpretation of Results	Wasn't able to determine greenhouse parameters for Mercury, Venus, Earth, and the Moon.	Has values for greenhouse parameters of Earth, Venus, Mercury, and the Moon. Doesn't understand what these numbers mean in terms of surface temperatueres.	Has values for greenhouse parameters of Earth, Venus, Mercury, and the Moon **AND** understands that the greenhouse effect on Venus is much more substantial than Earth, and that even moving Earth to the orbit of Venus would not make up for the temperature difference between the planets.

Total: ____ / 14

Name ____ Period __________ Date _____________

Planet Surface Temperatures

Introduction

To develop a model for the surface temperature of a planet, we must consider many factors. Since planets are in thermal equilibrium, we must figure out the case where the energy coming in from the sun is balanced by the thermal energy being emitted by the planet. The temperature at which we achieve this equilibrium is the surface temperature of the planet.

Albedo

The albedo α of a planet is a parameter between 0 and 1 that describes how much of the incoming radiation is reflected, where an albedo of 1 means a planet reflects all incoming radiation, and an albedo of 0 means it absorbs all radiation.

If we think of albedo as the percentage of energy reflected by the planet, then 1-α is the percentage absorbed. This means the energy 'absorbed' by the planet can be written as

$$E_{\text{in}} = (1 - \alpha)E_{\text{sun}}(a, R)$$

1. If we increase the albedo of a planet, what happens to the amount of energy it absorbs from the sun?

Greenhouse Effect

The greenhouse effect is caused by the presence of molecules in the atmosphere of a planet that absorb the thermal radiation traveling outward from the surface, and reradiate equally in all directions. This has the net effect of reducing the amount of energy the planet would normally radiate thermally. When we talked about black body radiation, we learned that the energy emitted by a black body is given by the Stefan-Boltzmann Law:

$$E_{\text{SB}} = \sigma T^4 4\pi R^2$$

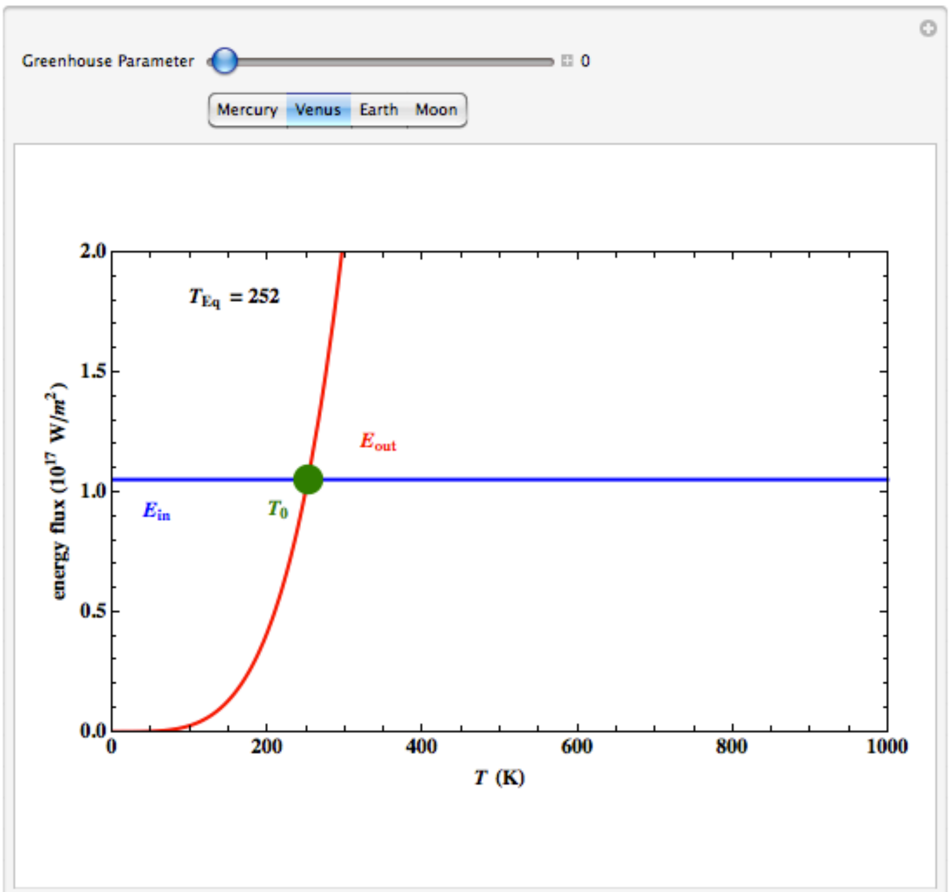
We can develop a simple model for the effect of greenhouse gases by introducing a greenhouse parameter *g*, with a value between 0 and 1 (much like albedo) that corresponds to the percentage of energy "retained" due to the greenhouse effect. Using this model, the energy output by the planet would be:

$$E_{\text{out}} = (1 - g)\sigma T^4 4\pi R^2$$

2. What happens to the thermal energy radiated by the planet as the greenhouse parameter g increases?

Surface Temperature

If a planet is in equilibrium, then E_{in} and E_{out} are equal. Please open the applet titled "Planet Surface Temperature." After initializing, this window should appear.



The plot includes E_{in} and E_{out} as a function of the surface temperature T (in Kelvin) of the planet. The slider at the top of the window controls the value of the greenhouse parameter g of the planet. The temperature T_0 where the two energies are equal is the point of equilibrium, and corresponds to the surface temperature of the body with the specified g.

3. If the surface temperature of Venus is already known to be 735K, what is the approximate greenhouse parameter?

4. Choosing a surface temperature for Earth of 287K, what is Earth's greenhouse parameter?

5. If the greenhouse parameter for Earth is set to that of Venus (from question 3), what would the surface temperature of Earth be?

6. Based on what you know about the Moon, what do you think the greenhouse parameter is? Why?

7. Set the greenhouse parameter for the Moon to this value. What is the surface temperature?

8. Based on what you know about Mercury, what do you think its greenhouse parameter is? Why?

9. Set the greenhouse parameter for Mercury to this value. What is the surface temperature?

10. Using your book or the internet, find the measured values for the surface temperatures of the Moon and Mercury. How do these values compare to what you found in questions 7 and 9?

Above and Beyond

The flux from the sun is defined as the energy per unit time per unit area at a given radius from the sun:

$$F_\odot(a) = \frac{L_\odot}{4\pi a^2}$$

where,

$$L_\odot \approx 3.839 \times 10^{26}\mathrm{W}$$

Using this, we can define the E_{sun} found on page 1 of this activity:

$$E_{\mathrm{sun}}(a, R) = F_\odot(a)\pi R^2$$

Based on these equations, what is the equation for T_0.