Planet Designer: Kelvin Climb

High School Grades

Lesson Summary

Students create a planet using a computer game and change features of the planet to increase or decrease the planet's temperature. Students will explore some of the same principles scientists use to determine how likely it is for a planet to maintain flowing water.

Prior Knowledge & Skills

- Introductory understanding of the greenhouse effect
- Experience with variables
- Ability to use data tables
- Experience interpreting data to form arguments

AAAS Science Benchmarks

The Physical Setting

The Earth

NSES Science Standards

- **Science as Inquiry:** Abilities necessary to do scientific inquiry
- **Earth and Space Science:** Energy in the Earth System

Teaching Time: One-to-two 50-minute periods

Materials

Each student will need:

- Copy of Student Directions
- Access to a computer with Flash

Advanced Planning

Preparation Time: 20 minutes

- Make copies of the student pages
- Prepare a computer room to run the Flash interactive (if Flash is supported) or download the executable file on each computer if Flash is not available. The interactive can be found here: http://lasp.colorado.edu/home/education/k-12/project-spectra/
- Open the Flash Interactive, "Planet Designer: Kelvin Climb"

Why Do We Care?

The Mars Atmospheric and Volatile EvolutioN (MAVEN) mission will collect data to help scientists trace Mars' atmospheric history to determine what happened to the flowing water.

Why do we care about water? Every known life form on Earth requires water to survive, and wherever we find water on Earth, we find life. Finding liquid water on another planet is exciting, not because it means life does exist, but that it *could* exist. It's that possibility that motivates missions like MAVEN to keep searching for clues about Mars' early history.

Suggested background reading

MAVEN website:
http://lasp.colorado.edu/maven/

Laboratory for Atmospheric and Space Physics
University of Colorado Boulder

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Activity Dependency "Goldilocks and the Three Planets"

Expendable Cost per Group US$0.30

Engineering Connection (See also Engineering Connection for "Martian Makeover")

Mars has a thin atmosphere today, but it likely had a thicker atmosphere early in its history, creating surface temperatures warm enough to sustain liquid water at the surface. At some point, around 3.6 to 3.8 billion years ago, a large part of the atmosphere went away, along with the flowing liquid water. The Mars Atmosphere and Volatile EvolutioN (MAVEN) mission to Mars will launch in the fall of 2013. MAVEN is equipped with instrumentation designed to explore Mars' upper atmosphere and how it interacts with the space environment. MAVEN will measure the amount of atmosphere Mars loses today, so that we can estimate how much atmosphere Mars had in the past. This will help us understand whether and how the Mars climate evolved from warm and wet to cold and dry.

Learning Objectives

After this activity, students should be able to:

- Define albedo
- Explain how distance to the Sun, albedo, and atmospheric properties affect planetary temperature

Introduction / Motivation

The MAVEN mission, launching in 2013, will explore the upper atmosphere of Mars. There is quite a bit of evidence that liquid water flowed on the surface of Mars in the past. MAVEN will collect data to help scientists trace Mars' atmospheric history to determine what happened to the flowing water. Today, you will be exploring some of the same principles scientists use to determine how likely it is for a planet to maintain flowing water.

Why do we care about water? Every known life form on Earth requires water to survive, and wherever we find water on Earth, we tend to find life. Finding liquid water on another planet is exciting, not because it means life does exist, but that it *could* exist. It's that possibility that motivates missions like MAVEN to keep searching for clues about Mars' early history.

Today, you are going to explore the basics of planetary temperature. You'll start by creating your own planet without an atmosphere or surface features on the computer. To calculate planetary temperature, the computer uses a blackbody temperature estimate. A blackbody is a surface that perfectly absorbs and emits all parts of the electromagnetic spectrum equally. Once you add surface features to your planet, it will reflect some of the sunlight (electromagnetic radiation) that hits it and absorb the rest. The albedo of a planet tells us what percentage of sunlight it reflects. For example, a planet with an albedo of 0.5 (or 50%) reflects half the electromagnetic radiation that hits it and absorbs the other half. An albedo of one reflects 100% of the electromagnetic radiation, and an

albedo of zero reflects 0% (absorbs everything). The absorbed light heats the surface of the planet, and the planet radiates infrared light (heat) back into space.

A planet might also have an atmosphere that absorbs and emits over parts of the electromagnetic spectrum. When we look at a spectrum of light reflected from an atmosphere, we see dips (absorption) and peaks (emission) from different atoms and molecules. Greenhouse gases in an atmosphere allow visible light to pass through, but absorb infrared light. Visible light from the Sun heats the surface. The heated surface radiates infrared light (heat) out. The greenhouse gases in the atmosphere absorb and reemit some of the infrared light radiated from the surface. Some of it is emitted to space, but some emits toward the surface of the planet, heating it up more. You will add a greenhouse atmosphere to your planet to try to increase the temperature.

Part of your challenge today is to figure out what planetary conditions are necessary for liquid water to exist on the surface of a planet.

Vocabulary / Definitions

Word	Definition
Albedo	The percentage of incident (incoming) light that is reflected from a surface. A perfectly white object would have an albedo of one, indicating that 100% of the light reflects off of the surface. A perfectly black object would have an albedo of zero, indicating that none of the light reflects off of the surface, but all is absorbed.
Astronomical Unit (AU)	The average distance between the Earth and the Sun, or approximately 150,000,000 kilometers (93 million miles)
Blackbody	An ideal body or surface that completely absorbs all light falling upon it with no reflection, and emits a thermal spectrum dependent upon its temperature
Kelvin (K)	A unit of temperature defined as ^{o}C + 273 (approximately). Absolute zero is defined as zero K.
Luminosity	The amount of power radiated by a star (or any object) in the form of light. This can be expressed in watts.
Planetary Surface Pressure	The atmospheric pressure at the surface of a planet

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Procedure

Background (See also Background for "Planet Designer: Retro Planet Red" and "Goldilocks and the Three Planets")

Absorbed light heats a surface, and any object with heat radiates light at wavelengths that depend on its temperature. Objects at room temperature and people, for example, radiate light in the infrared. Much hotter objects (embers, for example) begin to glow in the visible part of the spectrum. In astronomy, a blackbody is an idealized object that absorbs all incident light (albedo of zero) and radiates with perfect efficiency. When visible light shines on a planet, it will heat up and radiate increasing amounts of energy in the infrared. At a certain temperature, the planet reaches an equilibrium, where the amount of visible light absorbed is balanced by the amount of infrared light radiated.

Students will use a computer interactive to explore the blackbody temperature of a planet before considering what contribution greenhouse gases make to the surface temperature. The fundamental rule of a planet's energy budget, simply stated, is, "What goes in must come out." To calculate blackbody temperature, we will use this information:

- The Sun produces a certain amount of energy (luminosity).
- Energy from the Sun travels outward in every direction. Since the Sun is a sphere, the energy travels outward in a sphere. See Image 1.
- The planets travel around the Sun on elliptical orbits with the Sun at one focus. These ellipses are nearly circular, so we will use the average distance to simplify the equations.
- The amount of energy received by an object decreases with distance from the Sun.
- The planets are spherical, but only the hemisphere facing the Sun gets exposed to the energy. We will approximate the area that is directly exposed to be a circle.
- All of the energy that hits a planet is either reflected or absorbed. We know the amount reflected, because we can measure the albedo of the planet. Students will calculate the blackbody temperature of a non-reflective, black planet before moving to this step.
- In equilibrium, the amount of infrared light that the planet radiates must be equal to the amount of visible light that it absorbs.
- The equilibrium temperature of the planet is the temperature the planet must be to balance the equation (what goes in comes out).

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Image 1

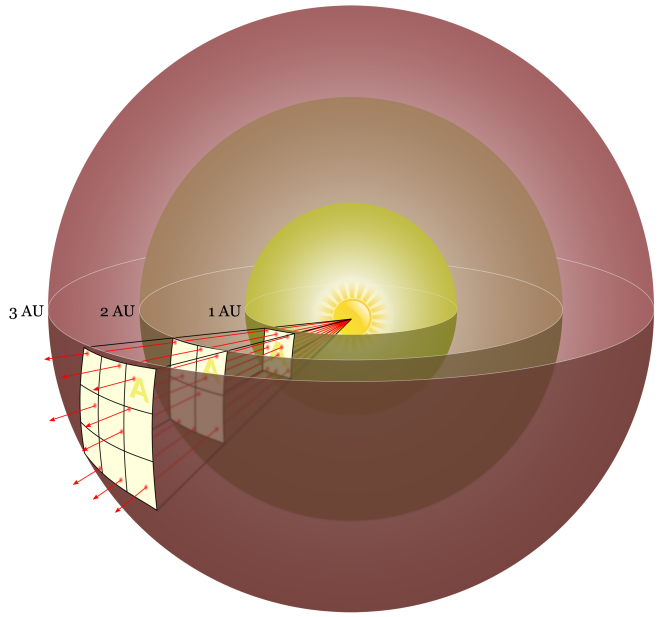

Image 1: The luminosity of Sun is constant, and distributed uniformly in every direction. Light spreads out proportionally over the distance squared, so that at 2 AU, the amount of light an object receives is a quarter of the amount received at 1 AU.

Warning: Math ahead!

Disclaimer: This section provides details of the math used to create the interactive, and is not intended for direct instruction to students who are not at an advanced level. It is also not necessary to understand the math behind the interactive in order to teach the content, so it may be skipped entirely.

The total power output, or luminosity, of the Sun is a known value from satellite measurements. Stefan-Boltzmann's law states that power, "*P*," emitted by a body (from every square meter) is represented by the expression, where "*T*" is temperature:

Eq. 1

$$P = \sigma T^4$$

Where Stefan-Boltzmann's constant is:

$$\sigma = 5.7 \times 10^{-8} \frac{Watts}{m^2 K^4}$$

Eq. 2

$$L = 4\pi R^2 \sigma T_s^4$$

Luminosity (power output) of the Sun

Area of the Sun, where R is the radius of the Sun

from Stefan-Boltzmann's law: Power emitted by the Sun from every square meter (given the blackbody temperature of the Sun).

From these pieces, we can establish a relationship for the amount of energy from the Sun that reaches a planet and set it equal to the amount emitted by the planet (since the amount of energy going in must equal what comes out), seen in Eq. 3.
From here, we can calculate the blackbody temperature, "T_b," if we know the other variables. The

Eq. 3

$$\frac{L}{4\pi D^2}\pi r^2(1-\alpha) = 4\pi r^2 \sigma T_b^4$$

Luminosity (power output) of the Sun

Subtract the amount of light reflected (albedo) off the planet, where alpha is the albedo

from Stefan-Boltzmann's law: Power emitted by the planet from every square meter (given the black body temperature of the planet)

Area of the whole planet

Area of a sphere (how the sunlight spreads out into space) where D is the distance from the Sun to the planet

Area of a circle (the planet) that receives sunlight, where r is the radius of the planet

luminosity of the Sun can be calculated from Eq. 2, given that the blackbody temperature of the Sun is about 5,800 degrees Kelvin. A planet's albedo is known from measurements. Note that the radius of the planet will not affect the blackbody temperature (the radius of the planet will cancel when solving Eq. 3 for "T_b"), since a larger planet absorbs more energy, but also emits more energy from

its larger surface area. Substituting Eq. 3 into Eq. 2 gives a simplified equation that relates planetary temperature, solar temperature, and distance from the Sun, seen in Eq. 4.

Eq. 4

$$T_b = T_s (1-\alpha)^{1/4} \sqrt{\frac{R}{2D}}$$

Blackbody Temperature of the Sun

Radius of the Sun

Blackbody Temperature for a planet

Albedo of the planet

Distance from the Sun to the planet

This doesn't give a full picture of a planet's temperature because greenhouse gases warm up a planet's surface by absorbing long wavelength infrared radiation. Students will find that planets are really chilly without a greenhouse atmosphere.

Here's where we get to cheat a little. We know the actual average surface temperature of each planet. We've measured it. We use Stefan-Boltzmann's law to equate the power emitted through black body radiation to the actual emission by the planet, where "N" is a multiplier, and "T_a" is the actual surface temperature, giving:

Eq. 5

$$\sigma T_a^4 = N \times \sigma T_b^4$$

Eq. 6

$$\left(\frac{T_a}{T_b}\right)^4 = N$$

The multiplier "N" includes many factors influencing a planet's temperature, including greenhouse warming (See Table 1 for "N" values). For simplicity, we will call this the "Greenhouse Strength." It is important to note that doubling "N" does not double the amount of greenhouse gases. You might recall from "Goldilocks and the Three Planets" that Venus has approximately 220,000 times the amount of CO_2 as Earth, but "N" is not 220,000 times greater than Earth's or even close to it.

In the computer interactive students will use during this activity, an "N" value is assigned for a strong and weak Greenhouse Strength, but that isn't a direct indication of the composition of the atmosphere. Planetary surface pressure is also based upon the student's input of atmospheric

thickness and not from gravity, because the composition of the atmosphere and exact volume of atmosphere can't be determined here. However, students should walk away with the understanding that a weak greenhouse effect on a planet leads to lower temperatures, and conversely, that a strong greenhouse effect leads to higher temperatures. A student's planet might support liquid water on the surface if the distance from the Sun, planetary surface pressure, and surface temperature are adequate. Any one of these factors could influence whether or not a student is able to create a planet with liquid water on the surface. Note that because a planet *could* have water on the surface does not necessarily mean that it does! You may want to discuss this subtlety with students, and explain that the interactive shows only one possible scenario.

A real planet is more complicated. Certain areas might be more reflective (clouds, oceans, ice etc.), and the albedo can vary over days (cloud patterns), seasons (winter snowfall), or geologic time scales (ice ages). A real planet has surface interactions with the atmosphere that might make a predicted temperature higher or lower than this calculation could possibly give. On Earth, for example, if the temperature increases, the amount of snow and ice will decrease in some areas, but the amount of cloud coverage would presumably increase. Both things will change our planetary albedo, which factors into the final surface temperature—and that's just one possible change. This is called a feedback effect—when one small change gives rise to other changes in a system. To factor in all of the potential changes, huge supercomputers running almost non-stop are used to predict climate change outcomes.

Table 1: Planetary Parameters

	Venus	**Earth**	**Mars**
Mass (Earth Masses)	0.815	1	0.107
Density (kg/m^3)	5250	5520	3930
Radius (Earth Radius)	0.95	1	0.53
Distance from Sun (AU)	0.723	1	1.524
Albedo	0.75	0.29	0.16
Greenhouse Strength (N)	106.75	1.62	1.15
Surface Pressure (bars)	90	1	0.007
Average Surface Temperature (Kelvin)	743	288	223

With the Students

1. Take students to the computer room, and instruct them on how to begin building planets.
2. Walk around the room clarifying any questions students may have.

Assessment

Pre-Activity Assessment

Ask: What do you know about the phases of water? What conditions are necessary on Earth for liquid water to exist?

Post-Activity Assessment
Poster presentation: Have students create posters explaining what the conditions are like on their planet, and whether life as we know it could be possible.

Discussion: Discuss feedback effects with students, and record student ideas about what would actually happen to the albedo if a planet's temperature increased or decreased. Have students consider the implications of a positive feedback, where an increase or decrease in temperature leads to a decrease or increase in albedo. Students can consider the "snowball Earth," where a slight decrease in temperature leads to increases in ice and snow corresponding with an increased albedo that feeds the cycle. Another scenario they might consider is a "runaway greenhouse," where an increase in temperature leads to snow and ice melt corresponding to a decreased albedo. This could lead to a long-term research project.

Activity Extensions
"Planet Designer: Retro Planet Red" activity

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