PLANETARY TEMPERATURES, ALBEDOS, AND THE GREENHOUSE EFFECT

“Mars is essentially in the same orbit. Mars is somewhat the same distance from the Sun, which is very important. We have seen pictures where there are canals, we believe, and water. If there is water, that means there is oxygen. If oxygen, that means we can breathe.” - D. Quayle

SYNOPSIS: In the next two lab sessions we will explore the factors that contribute to the average temperature of a planet using the EARTH/VENUS/MARS module of the Solar System Collaboratory.

EQUIPMENT: Computer with internet connection to the Solar System Collaboratory

LENGTH: Two lab periods.

The module provides the tools you need to attack one of the grand questions of planetary science. In this case, the grand question of the EARTH/VENUS/MARS module can be phrased in two different but related ways:

• Why can Earth support abundant life but Venus and Mars cannot?
  - or -

• What determines the habitable region around a star?

Although both questions are truly grand (meaning that it would probably take a number of major research projects to answer them in detail) they can be broken down into a number of component parts, each one of which is quite accessible. The module concentrates on a few of these parts; planetary temperature, albedo, and greenhouse effect.

Why temperature? Of all the factors that affect the presence of abundant life on a planet (chemistry, radiation, biology, etc.) the presence of liquid water is of paramount importance, and liquid water can only exist in a narrow temperature range.

In the Computer Lab, launch the Netscape browser (be sure that the window is not maximized).

Now go to the website http://solarsystem.colorado.edu/cu-astr/ . Click on either the Low Resolution or High Resolution link, depending upon which is appropriate for your monitor. Then click on the Modules option, and finally, select the Earth/Venus/Mars module.

Part I. Distance from the Sun

This is the simplest and most obvious way to determine a planet's temperature. Like hikers who build a fire and huddle around it at night, the inner planets huddle around the central fire in the solar system. The closer you get to the fire, the warmer you get. Notice that the “model” used to calculate the temperature of a planet in this applet is displayed at the bottom of the applet. It should be set on “fast-rotating, dark planet”. The “fast-rotating” part of this just ensures that the planet rotates fast enough that day-vs.-night temperatures are not too terribly different. The “dark” just means that the planet absorbs (rather than reflects) all the sunlight that hits it.
The PHYSICS PAGE link provides background information on the physical processes that go into the model. SHOW ME THE MATH provides the mathematical formulation that is programmed into the computer.

Select the "Fast rotating dark planet" model from the menu at the bottom of the applet. Let’s explore how the distance of a planetary orbit from the Sun affects the planet’s temperature.

I.1 Move Planet X to the orbit of the Earth (1 AU). What is the temperature of Planet X?

I.2 We know that if we move the planet to a larger orbit, its temperature will go down. But by how much? Make a prediction: what do you think will happen if you double the size of the Earth’s orbit? Think about it before you move Planet X! Here are some possibilities:

(a) If the temperature follows an inverse law, doubling the radius should cause the temperature to drop by a factor of 2.

(b) If the temperature follows an inverse square law, doubling the radius should cause the temperature to go down by a factor of 4.

(c) If the temperature follows an inverse square-root law, doubling the radius should cause the temperature to drop by a factor of “square root of 2” which is about 1.414.

Your prediction: ____________________________________________

I.3 Now go ahead and move Planet X to 2 AU (twice Earth’s orbital distance) - what is the temperature?

Which of the above laws does temperature follow?

I.4 Do you think the temperature of a planet depends on the size of the planet in this model? Explain why (or why not).

I.5 How good is this model? Does it calculate the average temperature of a dark body correctly? State your conclusion and show all the steps you took to reach it.

HINT: The FACT SHEET from the quick navigation frame (the gray frame on the left) gives temperature data for some of the bodies in the inner solar system. Use this information to evaluate the accuracy of the model.
I.6 Now look at the SHOW ME THE MATH applet again. This formula applies only to a fast rotating dark planet. Why?

Assume that you have a slow rotating dark planet. How does this change the temperature relation?

Part II. Adding Albedo to the Model

Albedo (represented by the symbol A) is the fraction of sunlight falling on a surface that is reflected back into space. (The word albedo comes from the Latin word for "white" - albus.) The albedo represents the average reflectivity over the entire visible surface; hence it differs slightly from the reflectivity of different portions of it. For example, the surface of the Moon has an albedo of 0.07 (on average, 7% of the incident sunlight is reflected, 93% is absorbed), even though there are bright and dark regions that have reflectivities different from the average.

We can measure the albedo of a planet or moon by comparing its brightness to how much sunlight it receives. We know how much sunlight it receives because we know its distance from the Sun (remember the $1/R^2$ rule!); and we can measure how much light is coming from the object with a photometer on a telescope. If the object has an albedo of 100% it will reflect all the sunlight incident upon it. Note: We are assuming that all of the light coming from the object is reflected sunlight; i.e. the object is not producing its own light. Planetary scientists are interested in knowing the albedo of a planet or moon because it provides information on the composition of the object. By comparing the albedo of a planet or moon to the albedos of substances found here on Earth we can learn what substances may or may not be on that object.

But first let's consider how the planet's albedo affects its temperature. If you haven't done this already, you may want to get more background information on the physics behind this applet. Click on the PHYSICS PAGE link in the quick navigation frame (the gray strip on the left) and look up albedo.

Select the "Fast rotating dark planet with adjustable albedo" model from the menu at the bottom of the applet.

II.1 What happens to the temperature of Mars if you increase its present day albedo by 0.05?

The temperature goes from _________________ to ____________

II.2 What happens to the temperature of Mars if you increase its albedo from 0.999 to 0.9999?

The temperature goes from _________________ to ____________.

II.3 In general, if you increase the albedo, you _________________ the temperature. Explain why this is the case.

II.4 Now evaluate this model like you did for the previous one.
Part III. Greenhouse Gases

Think of the planets as hikers who try to keep warm at night. The first thing they do is build a fire and huddle around it. The closer you are to the fire, the warmer you are. Like the hikers, the planets huddle around the central fire in the solar system. We saw last time that the closer a planet is to the Sun, the warmer it is. Extending the hikers-around-the-fire analogy, if you want more warmth than the fire can provide, you get a blanket. That is what the atmosphere does. In fact, an atmosphere is better than a blanket. It allows most of the sun's radiative power (which is at visible or “optical” wavelengths) through to the surface, but absorbs the radiation from the planet (which is at infrared wavelengths) and prevents the planet’s heat from being radiated back into space. This is the principle of the greenhouse effect. We will use two new applets, the “Greenhouse Effect” applet, and the “Radiative Transfer” applet to explore the way the greenhouse effect affects the temperature of a planet.

III.1 Define a greenhouse gas. Discuss absorption and transmission of visible, infrared, and ultraviolet light in your definition.

The main greenhouse gases for the planets are water vapor (H$_2$O), carbon dioxide (CO$_2$) and methane (CH$_4$).

III.2 What is the main greenhouse gas for Earth's atmosphere? *(Hint: take a look at the FACT SHEET.)*

III.3 What is the main greenhouse gas for Venus' atmosphere?

III.4 Use the Greenhouse Effect applet to compare the Terrestrial, Venusian and Martian atmospheres:

(a) Which planet has the most *total amount* of atmosphere?

(b) Which atmosphere has the largest *percentage* of greenhouse gasses?

(c) Which atmosphere has the highest greenhouse *effectiveness*?

(d) What is the major difference between the atmospheres of Mars and Venus?

III.5 The net *greenhouse strength* depends on these three factors together (see SHOW ME THE MATH). Write down the net greenhouse strength for the three planets:

Earth: ___________  Venus: ___________  Mars: ___________
We can now go back to the “Planet Temperature” applet and use the “Fast rotating planet with adjustable albedo and greenhouse strength” model.

III.6 What is the effect of adding greenhouse strength to the model of the planet temperature? (Fill in the blanks in the table below.)

<table>
<thead>
<tr>
<th></th>
<th>Average Temperature (look in the FACT SHEET)</th>
<th>Model Temperature with albedo only</th>
<th>Model Temperature with albedo and greenhouse strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>EARTH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VENUS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MARS</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

III.7 Try to make Mars habitable. (i.e., examine the temperature of Mars by changing the atmosphere but keeping the albedo of the planet the same). First you will need to come up with criteria for habitability (Think about what sustains life on Earth but is not present on Venus or Mars). Then come up with some scenarios that will help you meet this criteria. Be sure to list all of the steps you took and all of your data in your lab report. *(Hint: You are not adding any new components to Mars’ atmosphere, just changing the amounts of what is there.)*

III.8 Now try to make Venus habitable.

III.9 We have kept albedo the same while changing the atmosphere. Is this likely to be realistic? Why or why not?

III.10 Go back to the “Planet Temperature” applet. Using the albedo and greenhouse strength of Earth, determine the range of orbital radii that allow for liquid water on the planet’s surface. Does this surprise you? Discuss the importance of an atmosphere in the habitability of a planet.

**Part IV. One-Layer Atmospheric Models**

We will now use the “Convective Equilibrium Radiative Transfer” applet to study in a little more detail the models that lie behind the “Greenhouse Effect” applet that you have just been using. You are now getting into some pretty sophisticated physics. The applet will take care of the hairy math for you, but you should read the physics page (use the "PHYSICS PAGE" button on the left) to get an idea of the principles involved. The main point that you should get out of this applet is that we can model a physical system (in this case Earth's atmosphere) in several different ways. Each model has its advantages and its limitations, and you have to be aware of both before you try using a particular model to answer a question.
Note that the calculations behind the “Radiative Transfer” applet apply ONLY to the Earth. The physical principles still apply to all of the planets, but the formulations inside the applet would need to be changed.

The simplest of all atmospheric models is the one-layer semigray model. It assumes that the atmosphere is thin enough that a typical photon emitted by the ground will be absorbed only once (hence single-layer). The model also assumes that the visible wavelengths radiated by the Sun are not absorbed by the atmosphere, but the infrared wavelengths radiated by the ground are absorbed with a uniform absorption coefficient. (Hence the term semi-gray: “semi” because the atmosphere does not absorb visible radiation, and “gray” because the IR radiation is absorbed uniformly across the IR wavelength range.)

IV.1 Choose the semigray model, and set the absorption coefficient to 0.0%.

(a) What temperature does the model give for the Earth?

(b) Refer back to the “Planet Temperature” applet (you may want to use the EXTRA WINDOW button on the left, so that you can have both applets running at the same time) and choose the third model from the menu, “adjustable albedo and greenhouse strength”. Put in the appropriate albedo for the Earth (check the FACT SHEET). To what value of greenhouse strength do you think an absorption coefficient of 0.0% corresponds?

(c) Set the absorption coefficient to 1.0 (100%). What temperature does the model give for the Earth?

(d) Now look up the measured average temperature for Earth (check the FACT SHEET). Approximately what value of the absorption coefficient gives the measured temperature for the Earth?

Now let's look at the semigray model with one spectral window. This model is a simple improvement on the previous one. It attempts to address the fact that the Earth's atmosphere does not really have a uniform absorption coefficient over the entire infrared region of the spectrum, by allowing for a “radiative window”. Think of the absorption spectrum of the atmosphere as a “blanket” that covers the entire infrared spectrum. A radiative window is a “hole” in that blanket that allows part of the Earth's IR radiation to escape directly to space without being absorbed by the atmosphere. The absorption curve for this model resembles the absorption curve of the semigray model except for the hole.

IV.2 Keeping the absorption coefficient at 100%, find the two approximate locations in the IR spectrum of the radiative window (in micrometers, 1 um = 1 millionth of a meter) that will give you the measured temperature of the Earth.
Finally, for the three gas model, approximate absorption curves of three greenhouse gasses (water vapor, carbon dioxide, and methane) have been incorporated into the applet. By moving the sliders, you can change the relative concentration of these gasses in the Earth's atmosphere, and see what effect that has on the atmosphere's absorption curve (at the middle) and on the Earth's temperature. (Remember the limitations of the model - it is still a single-layer model). The sliders have been scaled to the present-day average concentrations of these gasses, so that a value of “2.0” for the carbon dioxide slider for example corresponds to doubling the amount of carbon dioxide in the atmosphere over current levels.

IV.3 (a) Set all three concentration values to “1.0” (present-day values). Does the applet give the measured temperature for the Earth? If not, how many degrees off is the model?

(b) With all three concentration values set to one, look at the absorption curve. Where is the position of the biggest “dip” in the absorption curve? Does the position of that dip correspond to the position of the radiative window that you found with the “semigray with one spectral window” model?

IV.4 Which of these three gases is the most effective greenhouse gas? (Hint: try increasing/decreasing the concentration of each gas relative to present values and see which gas changes the temperature the most). Be sure to give evidence to support your choice.

IV.5 (a) Now double the amount of CO$_2$ in the atmosphere. What does the model give for the temperature of the Earth?

(b) How many degrees warmer is this than the current measured average temperature?

(c) Do you think this is a good prediction? That is, if the amount of CO$_2$ in the atmosphere were to actually double over the next few years, would you expect the actual temperature of the Earth to be higher, lower, or the same as that predicted by this model? Can you explain why the actual temperature might differ from your prediction using this model?
Part V. Measuring Colors and Albedos

The albedo and colors of a planet or moon provide valuable information about its composition as well as temperature. To get a feel for the process, you will measure and analyze the colors and albedos of various soil and rock specimens.

A photometer (light meter) with a sunshade can be used to measure the reflectivity of different materials, as shown below. The measurements are made as follows:

- Measure the brightness of white paper illuminated by sunlight. We consider an albedo of 1 to represent the color white and an albedo of 0 to represent the color black. Therefore we will measure reflectivity of the white paper and use those values to normalize subsequent measurements thus giving a convenient standard against which to compare the reflectivity of other surfaces. Be sure that nothing (including you or the photometer) is casting shadows onto the area under observation!

- Measure the brightness of the sample. Be sure to hold the photometer close enough to the sample so that its detector only "sees" the sample, not the surrounding area.

- Divide your sample reading by the value you obtained for the white paper. The resulting fraction is the reflectivity of the material. In short:

  \[ \text{Reflectivity} = \frac{\text{Sample}}{\text{White}} \]

If we use an unfiltered lightmeter, the process measures the average reflectivity of the sample over the entire visible spectrum. However, if we make separate measurements through red (R), green (G), and blue (B) filters, we will have determined the red, green, and blue reflectivities of the sample instead - a quantitative way to measure its color!

V.1 Measure the RGB reflectivities of the various specimens provided by your lab instructor. Enter your results in the table below. For each filter record the brightness of the paper in the first column and the brightness of the sample in the second column. Calculate the reflectivity and record your answer in the third (shaded) column. Also note the visual color of each specimen. For the remaining spaces of the table, choose other surfaces (e.g. table, carpet, sidewalk, grass, etc.).

What pattern of RGB values combine to produce a strong visual impression of "red"? Which produces "some shade of gray"?
<table>
<thead>
<tr>
<th>Geological Specimen Identification</th>
<th>Color Reflectivities</th>
<th>Visual Color Description</th>
<th>Visual Albedo (R+G+B)/3</th>
<th>Color Index (R)/(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loam</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basalt</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charcoal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sandstone</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

V.2 Now average your measured RGB reflectivities of each sample (shaded column) to come up with an average measurement of the sample's reflectivity, or albedo, over the entire visible spectrum. Add these figures to the table.

Which sample has the highest overall albedo? Which has the lowest? Does this match your visual impression?

V.3 Finally for each sample divide the value of the red reflectivity (R) by the value of the blue reflectivity (B), and enter the resultant ratio (R)/(B) in the final column of the table.

Explain how this **color index** numerically describes the sample's *hue* (color balance) independent of its overall brightness or albedo.

What visual color might correspond to a color index of 2.00? A color index of 1.00? An index of 0.50?
Part VI. Martian and Lunar Analysis

Ideally, we would like to be able to provide you with real-life soil specimens from, say, Mars and the Moon, and have you compare those with the earthly samples you've just analyzed. Unfortunately, rock samples from Mars have yet to be retrieved, and those from the Moon are far more precious than gold. As a result, we have to resort to the next-best thing: using simulated samples, developed here on Earth to be as identical as possible to the "real thing". These samples were developed after extensive color imaging and spectrographic analysis of the actual lunar and martian soils.

VI.1 Using the same procedure that you used in Section V, measure the red, green, and blue reflectivities of the simulated soils, visually describe its color, calculate its albedo and a color index. Record your work in the table below.

<table>
<thead>
<tr>
<th>Geological Specimen Identification</th>
<th>Color Reflectivities</th>
<th>Visual Color Description</th>
<th>Visual Albedo (R+G+B)/3</th>
<th>Color Index (R)/(B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOON SOIL (simulated)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MARS SOIL (simulated)</td>
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<td></td>
</tr>
</tbody>
</table>

Assume that the lunar and martian soils are composed of one or more of the materials you analyzed in Part V. (Obviously, this is an unrealistic and very simplistic assumption, and to do the job well we would have had to have investigated many, many more candidate materials.)

VI.2 Based only on the albedo determinations, which specimen is most similar to (simulated) Mars soil?

Which specimen's albedo is most like that of the (simulated) lunar soil?

VI.3 Now, using just the color index, which specimen’s hue most resembles martian soil?

Which most resembles the lunar material?
VI.4 Now analyze the **combined effects of the RGB colors**; which, if any, materials might be likely candidates for explaining the colors we see in the Martian landscape?

How about for the Moon?

VI.5 Attempt to make a reasonable conjecture about the composition of the soils of the two celestial objects. If you had to choose among one (or more) of our (very limited) selection of measured materials, suggest what you feel would be the most probable composition of the martian and lunar soils. Consider what you know about the histories of these bodies in addition to your answers to questions VI.2-VI.4. (Don't worry about getting the "right answer" - there isn't one). However, you should be able to explain the reasoning behind your conclusions:

VII. **Follow-up Questions**

VII.1 In the lab (and in class) we have told you that the color white represents an albedo of 1. Go back to the measurements you made on the reflectivity of the white paper and ask yourself – did the white paper truly have an albedo of 1? Explain your answer and use it to justify our *normalization* of all the subsequent measurements.

VII.2 Most people are surprised to find that the Moon has such a low albedo, meaning that it is very dark. Why, then do you suppose the Moon appears to be so bright in the nighttime sky?

On Earth we see basalt in several forms. When it is first created (i.e. when it comes out of the Earth in the form of lava) it is very dark; however, over time it gets “weathered” - exposure to oxygen oxidizes the iron in the basalt and turns it reddish.

VII.3 What planet do you think might have oxidized basalt based upon its color?

What would this suggest about that planet’s atmosphere?

Would you expect to find basalt on this planet, i.e. is there evidence that volcanism has occurred/is occurring?

VII.4 Returned lunar samples from the Apollo missions shows that the Moon contains very old basalt in its maria regions. Why hasn't it turned red?
VII.5 Aldebaran (the eye of Taurus the bull) has a surface temperature of 4000K and a radius of $2.76 \times 10^7$ km.

Assume that there is a planet orbiting Aldebaran at 1 AU with the same albedo as Earth ($A = 0.3$). What is the planet’s surface temperature?

Now assume the planet has the same average surface temperature as Earth without any greenhouse effect ($T = 255$ K). What would the planet’s albedo be?

If we wanted to find an Earth-like planet around Aldebaran (i.e. $A = 0.3$ and $T = 255$ K), how far from the star must the planet orbit? Express your answer in AU. Which planet in our solar system orbits about this distance from our Sun?

VII.6 Now, consider the questions posed to you at the beginning of the lab. Why can Earth support abundant life but Venus and Mars cannot? and What determines the habitable region around a star? Use what you have learned in this lab to answer these two fundamental questions about our place in the solar system.

VII.7 Extra Credit: Since 1995 scientists have been discovering planets orbiting other Sun-type stars. So far, two planets have been found orbiting the star called HD37124. The inner planet has an orbital radius of 0.54 AU. Use the “Planet Temperature” applet to determine whether or not you can make this planet habitable by adjusting the atmosphere. Try different scenarios (e.g. do you need an abundance of greenhouse gases or can you do it with none at all?) NOTE: Remember, the applet assumes that the central star is our Sun. HD37124 is slightly smaller ($R = 6.44 \times 10^5$ km) and a little cooler ($T = 5658$ K) than our Sun so you will need to scale the planet temperature value that the applet gives you.
VIII. Planetary Atmospheres Follow-up Questions

The exercise you did in Part V is a rudimentary form of imaging spectroscopy. Imaging spectroscopy is a technique where an image of a surface is taken in multiple wavelengths at the same time. Each pixel in the image has its own reflectance spectrum associated with it. To determine the composition of the materials in area included in each pixel, the reflectance spectrum is matched to a laboratory-measured spectrum of materials expected to be present. This technique has been used to infer the compositions of other bodies such as Mars and the Galilean satellites.

In our exercise, we used only three wavelengths: red, green, and blue (R,G,B). We also took measurements over only a single pixel (we didn’t take separate measurements of different areas of the image). The measurements we took are similar to the experiments that gave scientists the idea to try imaging spectroscopy in the first place.

As you saw in Section VI, there are pitfalls in using spectral data to make inferences about the composition of planetary surfaces. In this section you will be asked to plot your reflectance spectrum data; quantify error bars on your measurements; and reflect upon the validity of the inferred compositions you determined in Section VI.

 Hint: These questions will be very easy if you input your reflectance values into Microsoft Excel or a similar spreadsheet program.

VIII.1 Determine the errors on the (R,G, B) reflectance values you calculated in the tables on p.132 and 133. Estimate the errors on these measurements by comparing (R,G,B) reflectance values for each material with the values measured by one or two other groups in your lab. Make a table similar to the table on p. 132 with the reflectances, but this time list the errors. To do this, include in each box of the table the uncertainty that you have determined. For example, if you have a measured value for the reflectance of sand of 0.3 but you believe that this value could lie anywhere in the range from 0.28 to 0.4, then your entry should be 0.3 (+0.1,-0.02).

VIII.2 Plot reflectance spectra (reflectance on the y-axis, wavelength or color on the x-axis) for each material you measured and listed in the tables on pp. 132 and 133 (including Mars and Moon soil simulants). Include error bars on each measurement on the graphs. If you can’t get Excel to plot the error bars, just estimate them using a ruler. Put each material on a separate graph, and make a series of small graphs on a single page in Excel. (Make sure, though, that the axes and labels are large enough so that your lab instructor can read them!)

VIII.3 Plot the reflectance spectra (with error bars) of the Mars simulant and two of the “likely candidate” materials you picked in question VI.4 on the same axes. Do the same for the Moon simulant and the “likely” Moon materials.

VIII.4 Given the error bars on your reflectance spectra, are you confident that the materials you chose in VI.4 are “good” matches to the spectra of the Moon and Mars? Are there other materials among those we measured that might fit the Moon or Mars spectra better?