Earth's Heat Budget   Update June 2015

Written by Roy Plotnick, Gene Harris, and Sara Loiacono

Contact information:

Roy Plotnick

Earth and Environmental Sciences

University of Illinois at Chicago

845 W. Taylor St.

Chicago, IL 60607

plotnick@uic.edu

14. Earth's Heat Budget

This exercise is an introduction to how Earth is heated by the Sun, a critical factor in understanding our weather, the seasons, and the nature and causes of climate and climatic change. The lab has five parts and will take two laboratory periods to complete if all parts are assigned. Part A is a series of experiments that deal with the intensity of solar energy at changing distances from the Sun, how much reaches Earth, and how that varies throughout the year and from place to place on Earth's surface. The experiments in Part B investigate how the reflection and absorption of solar energy by earth materials can influence both local and global temperatures. Part C is concerned with the power output of the Sun, the solar flux for other planets in the solar system, and the effect of atmospheres on planetary temperatures. Part D consists of problems summarizing and expanding on some of the topics from Parts A and B. Part E is a demonstration of the Coriolis Effect. Parts C and D do not require laboratory access and may be assigned as homework.

A basic scientific calculator is necessary for this lab (and others). If you are unfamiliar with the use of scientific notation (a compact way to write and manipulate very large or very small numbers) or with basic geometry and trigonometry, please refer to pages A-4 and A-5 in the Appendix. For help with converting metric units of distance and energy as you work through the problems in this lab, refer to page A-3.

A. Earth in the Sun's Rays

> Materials: bench with lamp, solar cell apparatus, digital multi-meter with microamp ranges, translucent screen, globe, solar angle goniometer, metric ruler, protractor

1. The Solar Flux

The Sun's energy is produced by the transmutation of hydrogen into helium via nuclear fusion (as discussed in Part C). Some of this energy reaches the planets in the solar system and the amount of energy each planet receives depends on its size and its distance from the Sun. The energy received by a planet is called its ***solar flux*** (*F*), defined as *units of energy falling on a unit area per unit of time* (usually as calories/square centimeter/second [cal/cm^2/sec], or as Watts/cm^2).

Experiment 1: How does solar energy vary with distance?

The apparatus for this experiment consists of a bench with a centimeter scale along its length and a lamp, which projects a well-focused beam of light upon a movable, translucent white screen. By measuring the areas of the spots projected on the screen at different distances from the lamp, we will see how the amount of solar radiation that a planet receives is determined by its distance from the sun.

[　]　　1) Set up the apparatus as shown by your instructor. Make sure that the spot of light is centered on the plastic screen. Begin with the screen at the 50cm mark. (Use the screen itself to set the distance, not the front of the wooden block.)

[　]　　2) Measure the spot diameter at a screen distance of 50cm (rounding to the nearest centimeter), and record this value in Table 1, Column 3. Repeat the measurement at 100 cm and 200cm. **[Move only the screen, not the lamp.]**

　　　　To simplify calculations and plotting of data, we have defined the 1 meter position as 1 "Distance Unit" (DU). Other distances are then simple proportions of that unit.

[　]　　3) Calculate the **areas** of the spots (rounding to the nearest cm^2), and enter the values into Table 1, Column 4. (Recall that the area of a circle is the square of the radius (**r**) times π (**pi**): A = π**r**^{2} and $\pi \approx 3.142$.)

[　]　　4) Compare the spot areas at 50cm and 200cm with the spot at 100cm by dividing each area by the area of the 100cm spot. Enter the proportions into Table 1, Column 5.

Table 1: Illuminated Areas vs. Distance from Source						
1	2	3	4	5	6	7
Distance (cm)	DU	Spot Diameter (cm)	Spot Area (cm^2)	Area proportional to spot at 1 DU	Intensity (per cm^2)	DU^2
50	1/2					
100	1			1	1	
200	2					

Has the lamp brightness changed during the experiment? No. Of course not. ***The same amount of energy falls on the screen at each distance.*** But how has the brightness of the spot (the <u>energy per square centimeter</u>, or ***intensity***) changed as you moved the screen farther from the lamp?

Since the intensity of the light at each distance is equal to the energy produced by the bulb divided by the area over which that energy is spread (the spot area), we can determine the relative intensity of the light at each screen distance.

⇒ **To simplify calculations, we'll define the standard intensity (intensity of the light at a distance of 100cm) as 1 unit per cm^2.**

[   ]   5) Calculate the relative intensity of the light at 50cm and 200cm by dividing the standard intensity (intensity at 100cm) by each proportional spot area (Table 1, Column 5). Record the intensity at each distance in Table 1, Column 6.

[   ]   6) Now, calculate the *square* of the distance (in DU) for each of the three positions and enter the values in Column 7.

If the intensity increases as the distance increases, we would say that the intensity is ***directly*** proportional to the distance. If the intensity decreases as the distance increases, we would say that the intensity is ***inversely*** proportional to the distance.

1   Is the relationship between intensity and distance an inverse or direct relationship?

2   a. How much smaller is the spot area at ½ DU than at 1 DU?

b. How much larger is the spot area at 2 DU than at 1 DU?

c. Since the same amount of light is falling on each spot, the intensity for ½ DU is _____ times the intensity at 1 DU, and the intensity at 2 DU is _____ times the intensity at 1 DU.

3   HYPOTHESIS -

The solar flux (intensity) is inversely / directly (circle one) proportional to the distance —— (to what power?).

Or, stated mathematically: Intensity ∝ _____

Experiment 2: Testing your hypothesis

Now we will measure the current produced by a solar cell (which converts light directly into electricity). The current produced is proportional to the area of the cell and the intensity of light falling on it.

IMPORTANT! READ THIS!

The solar cell apparatus is delicate. Handle it carefully. Lift it only by the handle on top. To start, the **LATITUDE** dial must be at 0°and the **SOLAR ANGLE** dial at 90°. *If you cannot __easily__ adjust the angle ask your instructor for help. NEVER use force to rotate the angle indicators.*

[   ]   1) Place the solar cell box **1 meter** from the light source: align the white index mark on the side of the base with the 1 meter mark on the bench. Make sure the solar cell is directly facing the light, and that the spot of light is centered around the opening at the front of the box. The "Solar Angle" dial should indicate 90°, and the "Latitude" dial should read 0°.

$\Rightarrow$ **To simplify calculations and graphing, we will also define 1 "Intensity Unit" (IU) as the electrical current measured at 1 Distance Unit.**

[   ]   2) Switch the lamp to its highest setting. Read the current on the digital meter. (Ask your instructor if in doubt about which scale to use.) Enter this value (including the appropriate units) in the "Current" column in Table 2 for 1 Distance Unit (1 meter).

[   ]   3) Based on your hypothesis from Experiment 1 (Question #3, p. 2), **predict** what you expect to measure (in IU) at 0.50 DU and 2.00 DU. Record your predictions in Table 2, Column 2.

[   ]   4) Move the solar cell to 0.50 DU. Record the *measured* electrical output in Table 2, Column 3a.

[   ]   5) Convert your electrical output measurement to IU (Column 3b) by dividing the current at 0.50 DU by the current at 1.00 DU. Is this answer consistent with your hypothesis (predicted intensity)? (Record your answers in Table 2.)

[   ]   6) Repeat steps 4 & 5 for 1.50 DU and 2.00 DU.

[   ]   7) Based on your measurement at 1.50 DU, **predict** what you expect to measure (in IU) at 0.75 DU. Then, repeat steps 4 & 5 for 0.75 DU to determine the actual flux (electrical output) for 0.75 DU.

[   ]   8) Enter the class average for IU at each distance in Column 4.

Table 2: Light Intensity vs. Distance from Source					
1	2	3a	3b	4	5
Distance Units (DU) (meters)	Predicted Intensity (IU)	Current (μA or mA)	Intensity Units (IU)	IU (Class Avg.)	Consistent with hypothesis?
(2nd) 0.50					
(do last) 0.75					
(do 1st) 1.00	1.00		1.00	1.00	
(4th) 1.50	XXXXXXXXXX				
(3rd) 2.00					

4   *Does the intensity vs. distance relationship agree with your predictions?*

What would be the intensity at 0.25 DU? _____ at 4 DU? _____

5   *Plot the class averaged intensities (Table 2, Column 4) versus distance from 0.50 DU to 2 DU on the graph below. Also plot a curve for your intensity <u>predictions</u> (Table 2, Column 3b). Make sure you clearly label your curves or include a legend.*
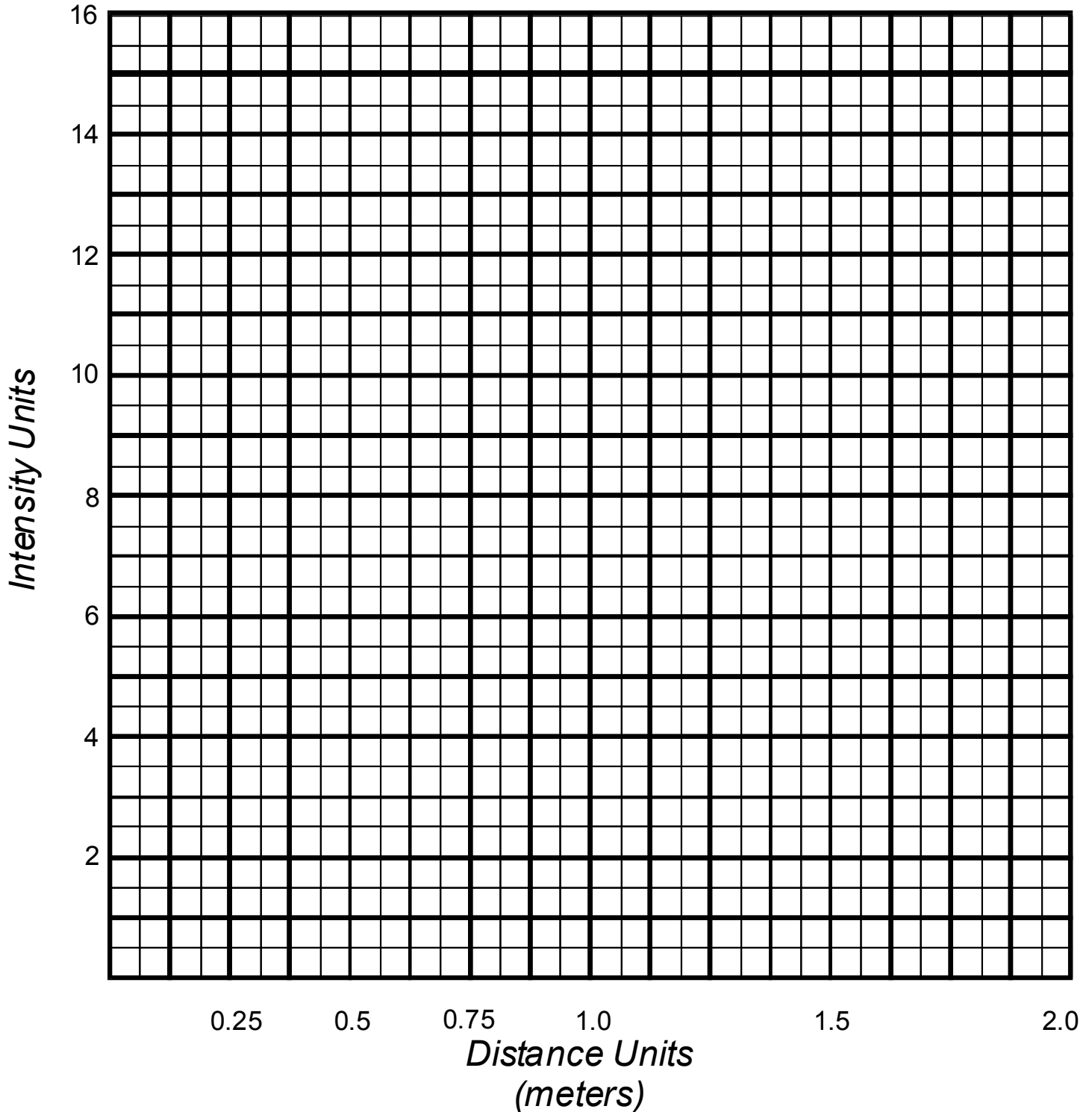
2. The Geometry of the "Inverse-Square" Relationship

Our hypothesis is only as good as the experiments it is based on, so an important question is how well do those experiments model what actually happens to the sun's energy as it travels through space? One way to answer this question is to consider the geometry of our experiment. Think of the lamp as being at the center of an imaginary sphere with a radius of 1 DU. When the screen is 1DU from the lamp the circle of light represents a small portion of the surface of this sphere. Since the radius of this imaginary sphere is 1 DU the total surface area a_1 of the sphere is:

$$a_1 = 4\pi \cdot 1^2$$
<div align="right">Eq. 1a</div>

Now imagine a point on a second sphere with twice the radius of the first. The distance from the lamp to this point is 2 DU and the radius of this sphere is 2 DU. The surface area of the second sphere is:

$$a_2 = 4\pi \cdot 2^2$$
<div align="right">Eq. 1b</div>

6   The surface area a_2 is how many times greater than a_1? _____

Now imagine Earth situated on the outside of a sphere with the sun at its center. The radius of this sphere is 150×10^6 km. (Astronomers call this radius 1 AU ("Astronomical Unit") to simplify calculations). So the surface area of this "Sun-Earth sphere" is:

$$a_E = 4\pi \cdot 1AU^2$$
<div align="right">Eq. 2a</div>

7   Imagine another planet, Z, the same size as Earth but twice as far from the Sun. It would occupy a sphere with a surface area: (Fill in the missing value in the equation below.)

$$a_Z = 4\pi \cdot [\ \ ]AU^2$$
<div align="right">Eq. 2b</div>

The important point to remember here is that the solar flux (F) for any planet (the amount of energy received ***per unit area per unit time***) is inversely proportional to the surface area of the Sun-planet sphere, which in turn is proportional to the square of the distance from the Sun, R. Geometry thus forces this simple rule: the energy a planet receives varies by 1/(the square of its distance from the Sun): $1/R^2$. This, ***the inverse-square rule***, applies to many forms of radiation as well as to the force of gravity! We can use this rule to find the ratio between the energy flux at two locations at distances R_1 and R_2. If $R_1 < R_2$ then:

(pay special attention to the subscripts) $$\boldsymbol{F_1/F_2 = R_2{}^2/R_1{}^2}$$
<div align="right">Eq. 3</div>

Check your experimental values for any 2 distances against those predicted by Eq. 3. They should agree.

3. Variations in Solar Flux due to the Eccentricity of Earth's Orbit

Planetary orbits are not perfectly circular, but slightly elliptical, so the distance of a planet from the sun will vary somewhat throughout its solar year. The radius of Earth's orbit (R) varies from 147.5×10^6 km at *perihelion* (around January 4), its closest approach to the Sun, to 152.5×10^6 km at *aphelion* (around July 4) when Earth's distance from the Sun is greatest. (See Figure 1.)
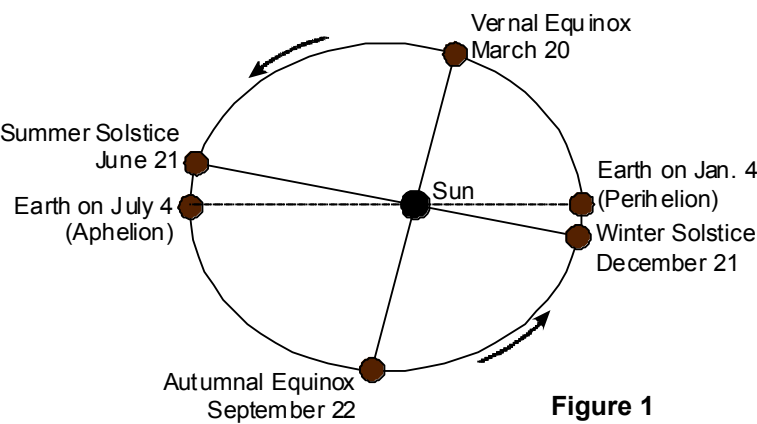

Figure 1

Experiment 3: The solar flux at perihelion and at aphelion

Is this variation in distance the cause of our seasons? First we'll try to answer this question with an experiment.

[   ]   1) Set up your lab equipment to measure the energy received by the photocell at 147.5 cm (perihelion; Jan 4), which is marked with a 'P' on the bench scale. (Make sure you <u>align the white mark</u> on the side of the solar cell, <u>not the front</u> of the solar cell, with the appropriate distance.) Record the current output (energy) with the appropriate units (µA or mA) in Table 3.

[   ]   2) Repeat the measurement for 152.5 cm (aphelion; July 4), which is marked with an 'A' on the bench scale.

Table 3: The Solar Flux at Perihelion vs. Aphelion		
	"Perihelion": 147.5cm (January 4)	"Aphelion": 152.5cm (July 4)
µA or mA		

8   **What is the % difference between the current generated at 147.5cm and at 152.5cm? Use the equation below in your calculation.**

$$\left[\frac{p - a}{p} \right] \times 100$$

(where p = perihelion reading, and a = aphelion reading)

9   **Based on these results, should Earth be WARMER or COLDER in January than in July?**

10   **The experimental values should agree well with those predicted by Eq. 3. Do they?**

We Earth dwellers do not seem to notice these small but real changes in solar flux. One reason is that the variations affect the planet as a whole: they are distributed over the entire surface of Earth, so their effects in any one location are masked by the very much larger seasonal changes that are strongly dependent on where we live. For example, while we may be skiing in January in the Northern Hemisphere, Australians are sweltering in the sun. Does it seem reasonable that there must be another mechanism besides our distance from the sun which accounts for the seasonal changes we experience?

4. Seasonal Variations in the Solar Flux

The large variations we know as seasons have nothing to do with changing distances from the sun but depend instead on the fact that Earth's axis is inclined to the plane of its orbit. The following experiments will demonstrate how the seasons are a result of this "tilt".

Experiment 4: Sun-Earth orientation at the EQUINOXES

There are 4 events each year that mark the beginnings of the seasons, two **EQUINOXES** (around March 21 and September 23), and two **SOLSTICES** (around June 22 / December 22). On either equinox (which means "equal night") the day and night are equally long, each 12 hours, because the plane of Earth's rotational axis is perpendicular to the Sun's direction. (See Figure 2.)
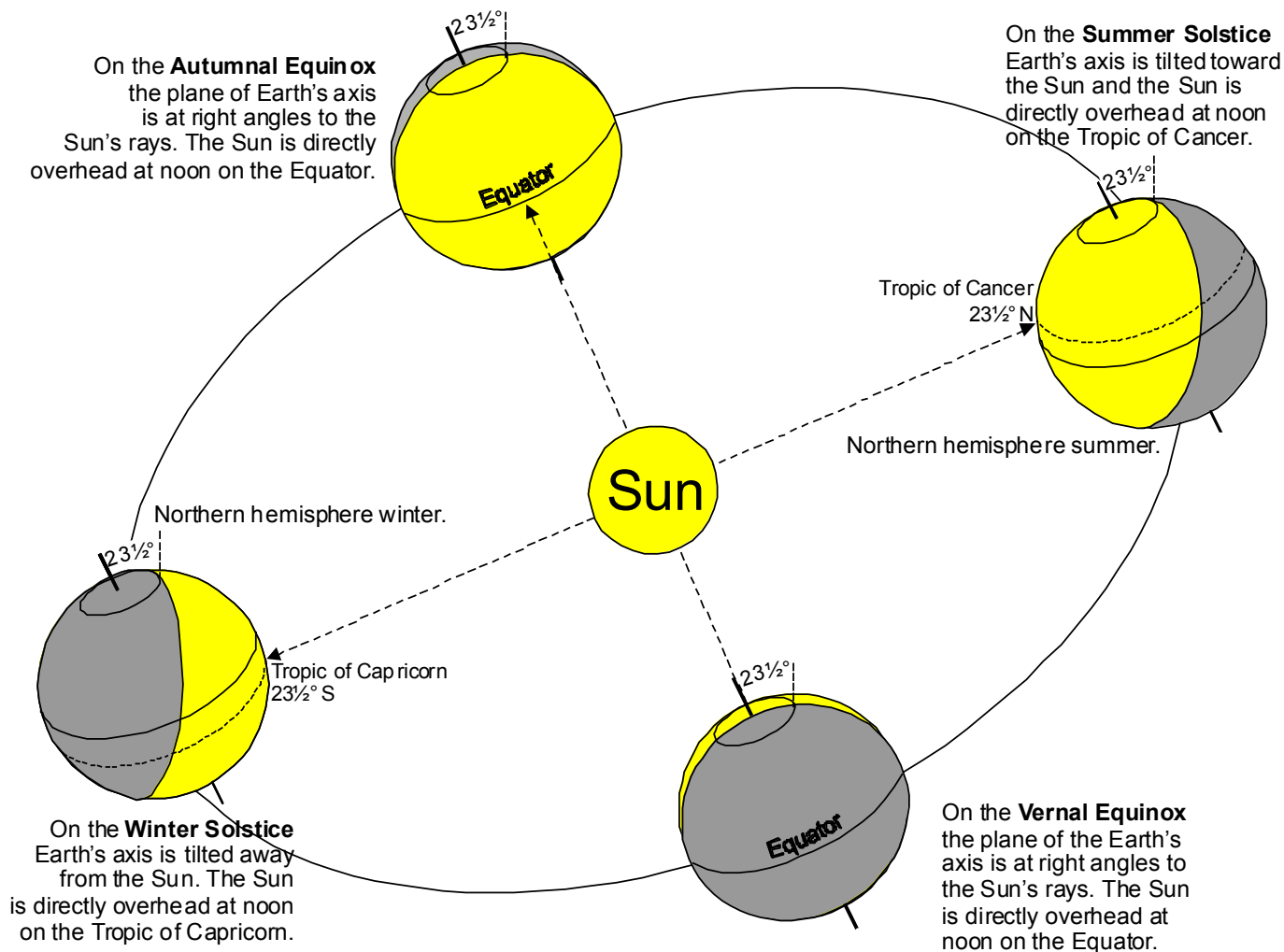

On the **Autumnal Equinox** the plane of Earth's axis is at right angles to the Sun's rays. The Sun is directly overhead at noon on the Equator.

23½°

Equator

On the **Summer Solstice** Earth's axis is tilted toward the Sun and the Sun is directly overhead at noon on the Tropic of Cancer.

23½°

Tropic of Cancer 23½° N

Sun

Northern hemisphere summer.

Northern hemisphere winter.

23½°

Tropic of Capricorn 23½° S

On the **Winter Solstice** Earth's axis is tilted away from the Sun. The Sun is directly overhead at noon on the Tropic of Capricorn.

23½°

Equator

On the **Vernal Equinox** the plane of the Earth's axis is at right angles to the Sun's rays. The Sun is directly overhead at noon on the Equator.

Figure 2

[   ]   1) Replace the cell assembly with a globe. Place one of the flat wooden blocks beneath the globe to support it. Orient the globe so that the plane of its axis is at a right angle to the direction of the lamp. (The meridian, the metal ring around the globe, is in the plane of the axis, so should be oriented perpendicular to the lamp.) This is the orientation of Earth relative to the Sun on the first day of Spring (the Vernal Equinox) and on the first day of Fall (the Autumnal Equinox).

[   ]   2) Rotate the globe, keeping the meridian stationary. Notice that there is a point that is always in the center of the spot of light on the globe. As you rotate the globe, this point defines a line along which the sun (at approximately noon local time) will always be directly overhead (that is, at 90°) somewhere.

 11   What is this line called?_____ **Its latitude is** _____**°.**

The maximum elevation angle or "solar angle" (we'll call it α*)* is the angle between the earth's surface at any point and the sun "at transit" (that is, at its highest point in the sky). This occurs at approximately noon local solar time (see Figure 3), and varies depending on *the day of the year*, and *the latitude.*

>>*Of course in Chicago the sun is never directly overhead (why?).*<<
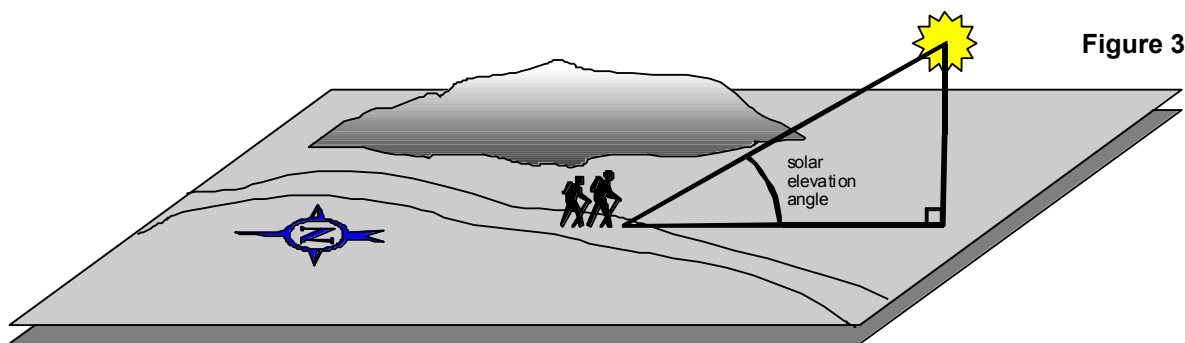
Figure 3

[   ]   3) Rotate the globe so that Chicago is exactly half way between the two sides of the meridian. This is the position of Chicago relative to the sun at solar noon on the equinox. (See Figure 4a, p. 14-10.)

[   ]   4) Find the solar angle for Chicago at Equinox using the following methods.
  [   ]   a) **Measure it directly on the globe** with the "solar angle goniometer" (a modified protractor). Your instructor will show you how to do this. **Enter the measured solar angle for Chicago at the EQUINOX in the appropriate space in Table 4.**
  [   ]   b) Check your measurement by **calculating it from this formula: α = 90° - latitude**. **Record your calculated solar angle in the appropriate space in Table 4.**

Experiment 5: Sun-Earth orientation at the SOLSTICES

On the **SUMMER SOLSTICE**, approximately June 22, Earth's axis is tilted toward the Sun in the Northern Hemisphere.

[   ]   1) Turn the globe so that the North Pole is tilted directly towards the lamp. This is Earth's position on the Summer Solstice. Rotate the globe as before.

 12   Now the sun is directly overhead along another line, not the Equator. What is this line called and what is its latitude? _____ .

[ ]   2) Rotate the globe so that Chicago is facing the lamp (nearly underneath the meridian). This is the position of Chicago relative to the sun at solar noon on the Summer Solstice. (See Figure 4b, p. 14-10.)

[ ]   3) Find the solar angle for Chicago at the Summer Solstice using the following methods.
     [ ]   a) **Measure it directly on the globe** with the "solar angle goniometer" (a modified protractor). Your instructor will show you how to do this. **Enter the measured solar angle for Chicago at the SUMMER SOLSTICE in the appropriate space in Table 4.**
     [ ]   b) Check your measurement by **calculating it from this formula: α = 90° - latitude + 23.5˚**. (Why do we add the tilt of the axis? See Figure 4b.) **Record your calculated solar angle in the appropriate space in Table 4.**

On the **WINTER SOLSTICE**, approximately December 22, Earth's axis is tilted away from the Sun in the Northern Hemisphere.

[ ]   4) Turn the globe so that the North Pole is tilted directly away from the lamp. This is Earth's position on the Winter Solstice. Rotate the globe as before.

13 What is the name and latitude of the line where the Sun is directly overhead?

[ ]   5) Rotate the globe so that Chicago is facing the lamp (nearly underneath the meridian). This is the position of Chicago relative to the sun at solar noon on the Winter Solstice. (See Figure 4c, p. 4-10.)

[ ]   6) Find the solar angle for Chicago at the Winter Solstice using the following methods.
     [ ]   a) **Measure it directly on the globe** with the "solar angle goniometer" (a modified protractor). Your instructor will show you how to do this. **Enter the measured solar angle for Chicago at the WINTER SOLSTICE in the appropriate space in Table 4.**
     [ ]   b) Check your measurement by **calculating it from this formula: α = 90° - latitude - 23.5˚**. (Why do we subtract the tilt of the axis? See Figure 4c.) **Record your calculated solar angle in the appropriate space in Table 4.**

Experiment 6: Solar Flux vs. Seasons

Now you will compare the solar radiation in Chicago at the start of each of the seasons, based on the solar angles you just found. **Use the value at the Winter Solstice as a standard.**

[ ]   1) Place the solar cell assembly at 1 Distance Unit from the lamp. Align the apparatus as before, making certain that the solar cell is perpendicular to the light beam to start.

[ ]   2) Tilt the cell using the ***SOLAR ANGLE INDICATOR*** on the left side of the solar cell box. Set it to the angle you found for the Winter Solstice in Chicago.

[ ]   3) Measure the current received at the Winter Solstice solar angle and record the value in Table 4.

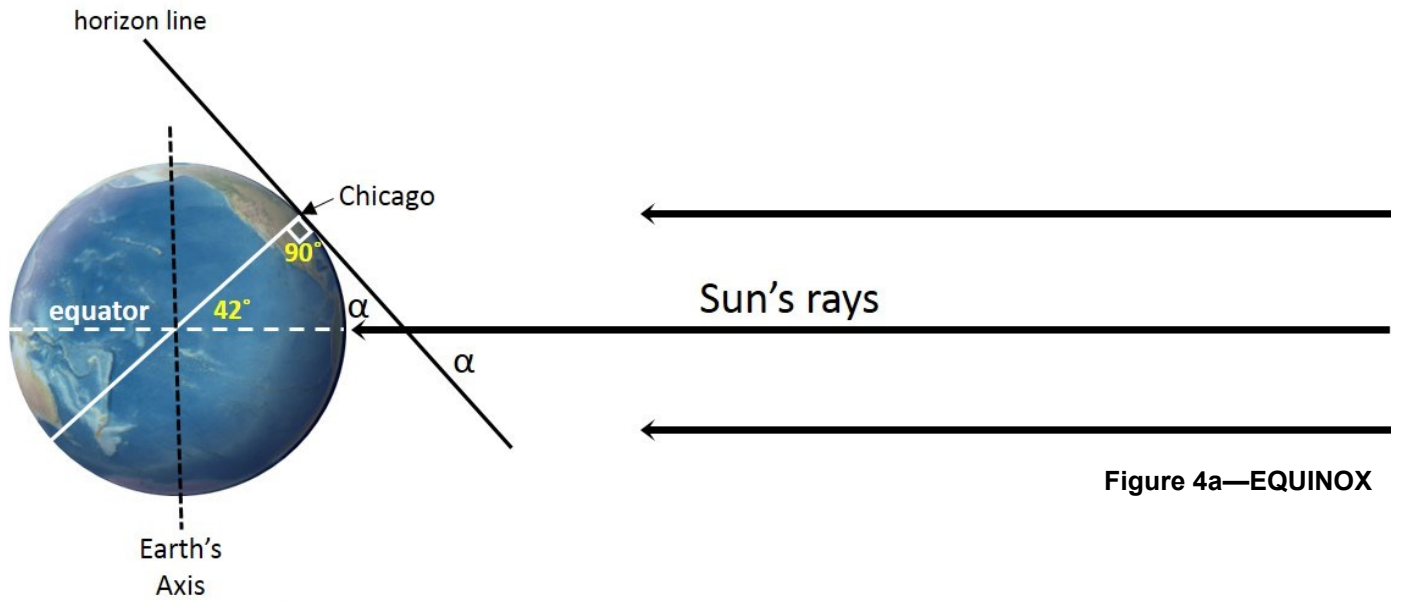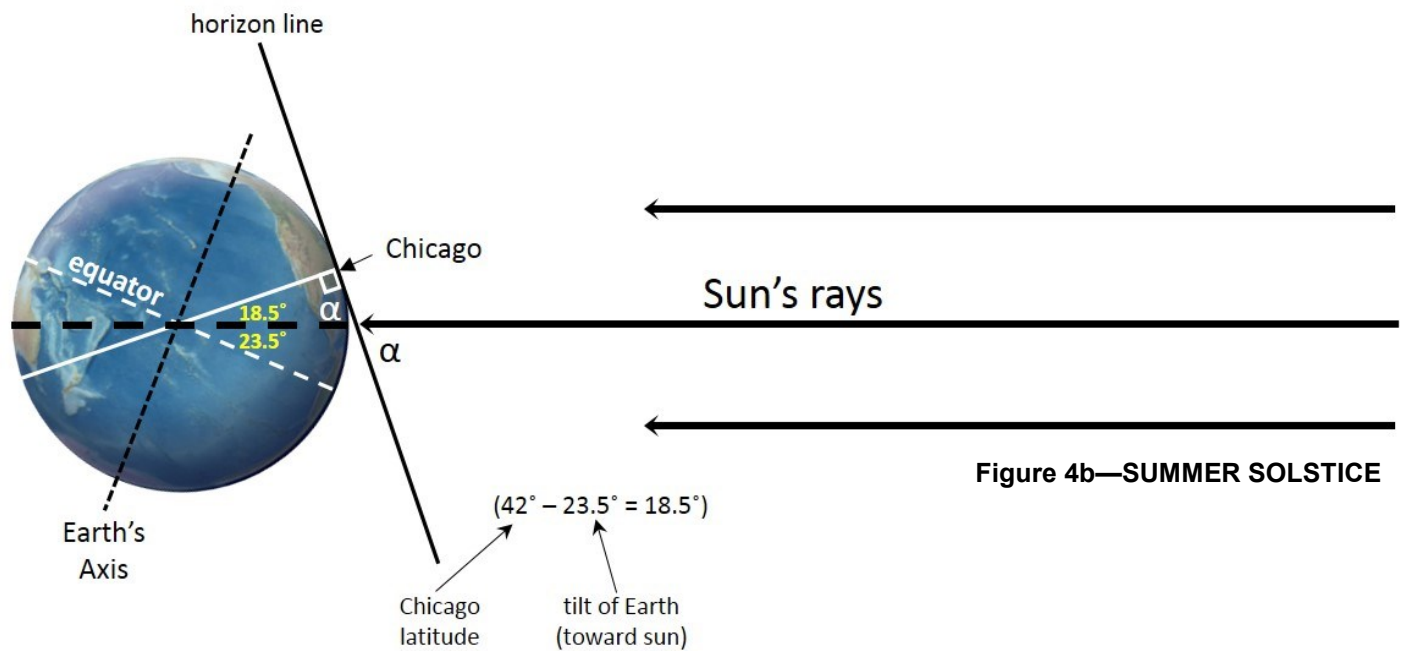[ ]   4) Repeat steps 2-3 for the Summer Solstice and Equinox solar angles.

horizon line

Chicago

90°

equator **42°** α

α

Sun's rays

Figure 4a—EQUINOX

Earth's
Axis

horizon line

equator

Chicago

18.5° α
23.5°

α

Sun's rays

Figure 4b—SUMMER SOLSTICE

Earth's
Axis

(42° − 23.5° = 18.5°)

Chicago   tilt of Earth
latitude   (toward sun)

horizon line

Chicago

90°

42°
23.5°

α

equator

α

Sun's rays
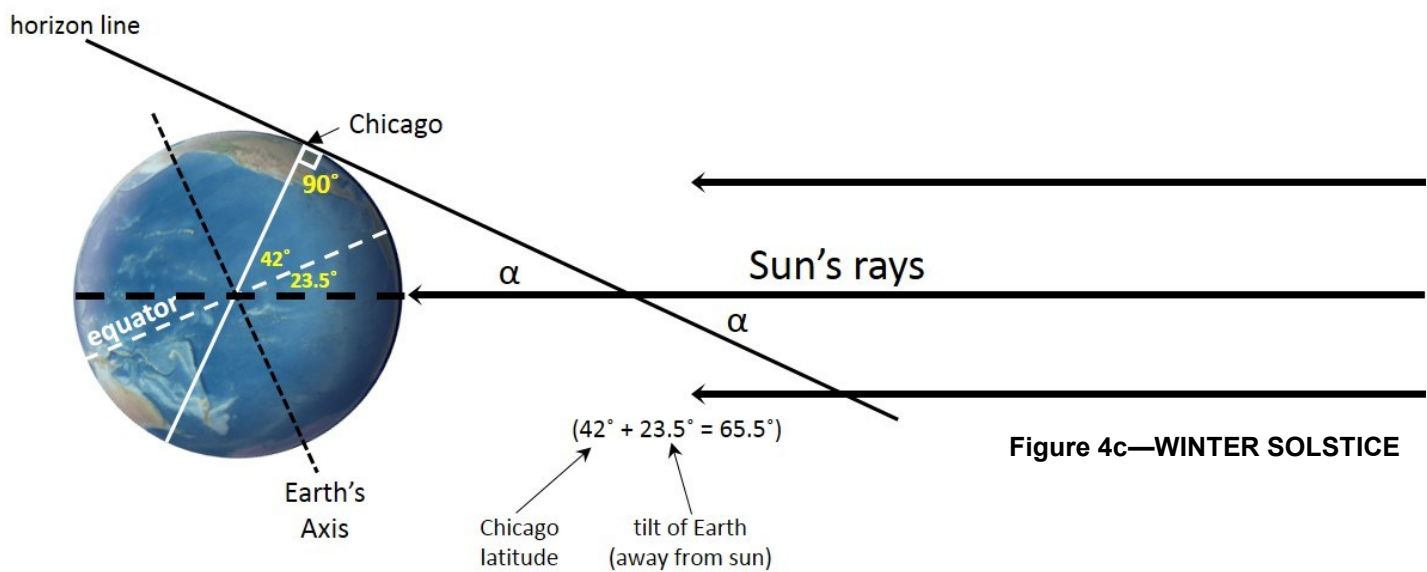
Figure 4c—WINTER SOLSTICE

Earth's
Axis

(42° + 23.5° = 65.5°)

Chicago   tilt of Earth
latitude   (away from sun)

14- 10 Earth's Heat Budget

[   ]   5) Compare the energy received at our latitude on the Winter Solstice with that for the Vernal and Autumnal Equinoxes, and for the Summer Solstice. Consider the energy measured for the Winter Solstice as 100%. Using the equation below, calculate the percent energy received for each relative to the Winter Solstice. Record your answers in Table 4.

$$\textbf{\textit{Percent relative to Winter}} = \frac{\textbf{\textit{Energy at Equinox or Summer Solstice}}}{\textbf{\textit{Energy at Winter Solstice}}} \times 100$$

Table 4: Seasonal Changes in Solar Flux at the Latitude of Chicago (41°50′N)			
Time of Year	Winter Solstice (~Dec. 22)	Vernal and Autumnal Equinoxes (~Mar. 21, ~Sep. 23)	Summer Solstice (~June 22)
Solar Angle (measured)			
Solar Angle			
Measured Current			
% vs. Winter Solstice	100%		
Sun is overhead at this			

14   What is the percent difference for the Summer Solstice compared to the Winter Solstice? (See Question #8 on p. 14-6 for the equation for percent difference.) How does this compare to your calculation for the percentage difference from aphelion to perihelion? (Experiment 3)

15   Based on your results for Experiments 3-6, which has a greater control over the seasonal temperature variations on Earth: the distance of the Earth from the Sun or the tilt of the Earth relative to the Sun?

5. Variation in Solar Heating with Latitude

Next we consider the effect of latitude on the intensity of solar radiation. It is obvious that the tropics (the portion of the earth between 23.5°N and 23.5°S) are the warmest year round while the polar regions are coolest. It may also be obvious that this has something to do with the decrease in solar angle as we travel from the Equator towards the Poles. But how exactly does the flux vary? Can this variation be expressed mathematically so that we could predict the relative amounts of radiation received at various places on Earth's surface (or on the surface of any planet)?

Experiment 7: Solar Flux vs. Latitude

[　] 1) Position the solar cell assembly at 1 meter from the lamp and make certain the cell is perfectly vertical (**LATITUDE** dial = 0°, **SOLAR ANGLE** dial = 90°). The current generated here represents the energy falling on the Earth at the Equator when the Sun is directly overhead. Record this current in Table 5 in the 0° latitude column.

[　] 2) Rotate the solar cell so the latitude is 15˚ and the solar angle is 75˚. Measure the current generated at this latitude/solar angle combination and record the value in Table 5.

[　] 3) Repeat step 2 for the other latitude/solar angle combinations listed in Table 5.

Table 5: Variations in Solar Flux with Latitude							
Latitude	0°	15°	30°	45°	60°	75°	90°
Current							
Proportion of Current at 0°	1.00						
Cosine of the latitude							
Max. Solar Angle at Equinox	90°	75°	60°	45°	30°	15°	0°

[　] 4) Calculate the proportion of current at each latitude based upon that measured at the Equator (proportion of current at Equator = 1.00). Record your answers in Table 5.

[　] 5) Calculate the *cosines* for each angle of latitude and enter them in Table 5.

*16　Why does the flux decrease with latitude?*

17　Formulate a "rule" to predict the solar flux relative to the equator. (Look at the values recorded in Table 5. How do the proportions for current relate to the latitude?)

Part B: The Reflection and Absorption of Solar Energy

Materials: 75W flood lamp on ring stand; 45° solar cell block with digital multi-meter; 3" × 5" trays of surface materials as listed in Table 6; black and white foam-board squares with embedded thermometers

1. Albedo

Albedo is the ratio of the total light reflected from a surface to the light incident (received) on that surface. (The fraction that is absorbed by a surface is then [1 - albedo]). A planet's total (or *astronomical*) albedo is the sum of the *terrestrial* albedos of its various terrains and of clouds in its atmosphere, and is partly responsible for the brightness of a planet in the night sky as viewed from Earth (the other factors being the planet's size and distance from Earth). Earth's astronomical albedo is approximately 0.30.
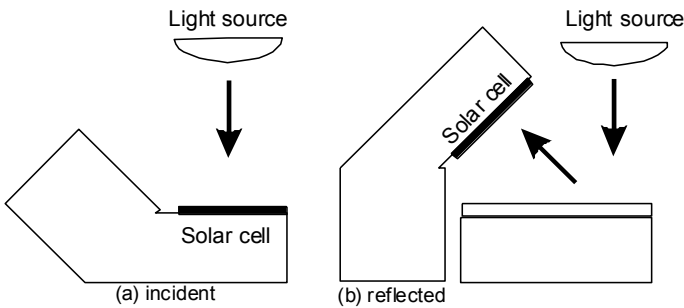
Do not touch the bare surfaces of the solar cells!

Experiment 8: What is Albedo?   **Figure 5**

In the following experiment you will determine the relative albedos of various earth materials by measuring their reflectivity with a solar cell. To see how albedo affects heating of the Earth's surface, you will also measure the temperature change for two surfaces that differ only in brightness.

[   ]   1) Make sure the multimeter is set to read mA; then, measure the *incident* energy as shown in Figure 5a. Record the value in Table 6.

[   ]   2) Describe the color of each surface listed in Table 6. Then, rank the texture of each surface on a scale of 1 - 5, with 1 being the smoothest and 5 the roughest. Record your observations in Table 6.

[   ]   3) Now, measure the *reflected* energy (see Figure 5b) of each surface listed in the table. *For accuracy, it is important that the surface of the solar cell be at the same distance from the lamp as the reflecting surfaces.* Read the generated current and enter the values in Table 6. **Turn off the lamp when you are finished.**

[   ]   4) Calculate the energy of the reflected light as a percentage of the incident light and record your answers below.

Table 6: Albedos of Various Earth Surfaces				
Incident energy: _____milliAmps				
Surface	Color	Texture (1=smoothest, 5 = roughest)	Reflected Energy (mA)	% Reflected (Albedo)
A. Very Fine Sand				
B. Beach Sand				
C. Fine Gravel				
D. Coarse Gravel				
E. Glacial Till				
F. "Snow"				
G. Volcanic Glass				

Earth's Heat Budget 14-13

18 Which surface has the highest albedo?

19 … the lowest albedo?

20 Which characteristic of the materials seems to have the LARGEST effect on albedo? (Circle one.)
     TEXTURE / COLOR / TYPE OF MATERIAL

21 Which characteristic has a smaller but still measurable effect on albedo? (Circle one.)
     TEXTURE / COLOR / TYPE OF MATERIAL

22 Which characteristic has the LEAST effect on albedo? (Circle one.)
     TEXTURE / COLOR / TYPE OF MATERIAL

Experiment 9: How does albedo affect surface temperatures?

We will measure the temperatures of two pieces of foam-board after they are exposed to a lamp for a few minutes. These foam-boards have embedded thermometers to measure their temperature. They differ only in their color, and both are the same size, shape, and mass.

[   ]   1) Read the initial temperature of each foam-board using the embedded digital thermometer; record it in Table 7.

[   ]   2) Place the two foam-boards side-by-side on top of the wooden blocks, and move them so that they are underneath the lamp. Allow the boards to warm for *no more than 10 minutes*, then record the final temperature of each board in Table 7.

[   ]   3) Calculate the increase in temperature for each board (ΔT) and record it below.

Table 7: Temperature Differentials of Black and White Surfaces			
Color	T (°C) initial	T (°C) maximum	ΔT (difference)
White			
Black			

23 Which board has the larger increase in temperature?_____ Why?

2. The Absorption and Retention of Heat by Earth Materials

The instructor will begin this experiment at the start of class. It requires about 90 minutes to complete.

One of the major factors affecting local and global climates is the ability of solid earth materials (rocks, soils, and vegetation), water, and atmospheric gases to absorb and retain heat. This ability is called ***heat capacity***. A useful way to think of heat capacity is as the amount of heat a substance can absorb before its temperature increases. The next experiment is a demonstration of the difference in the heat capacities of water and sand.

Experiment 10: Do land and water heat and cool at the same rate?

We will use an infrared lamp to heat a container of sand and a container of water. The containers are identical and each hold equal masses of sand and of water. To eliminate albedo as a variable, both containers are black; thus any difference in heating and cooling rates should be due only to the inherent heat capacities of the sand and the water. The experiment will be started when class begins. The heating stage will last for 15 minutes, then the lamp will switch off automatically and cooling will continue for another 75 minutes. Because of the length of the experiment, you may have to complete this section after class. <u>You will receive a printout of the temperature vs. time plot from the experiment before the end of class. When you turn in your lab report, include the plot.</u>

A quality related to heat capacity, the **specific heat**, is defined as the number of calories required to raise 1 gram of a substance by 1 degree Celsius. A standard definition of the **calorie** is that it is **the amount of heat required to raise the temperature of 1 gram of water by 1 degree Celsius**. Thus it follows that **the specific heat of water is defined as 1**, and values for other substances are then expressed as ratios compared to the specific heat of water. For example, a gram of material that responds to a heat input of 1 calorie by a 2° rise in temperature has a specific heat of 0.5. The important point to remember is that <u>substances with low specific heats respond to heating more rapidly than those with high specific heats</u>.

From this experiment we will obtain a reasonable estimate of the specific heat of sand relative to water by comparing the slopes of their heating curves on the graph.

[   ]   1) Using the plot, record the **starting temperatures** for water and sand in Table 8, Column 1.

[   ]   2) In Column 2, record the **maximum temperature of the water and of the sand** .

[   ]   3) In Column 3, record the **temperature difference** (ΔT) between the starting temperature and the maximum temperature.

[   ]   **Divide ΔT for water by ΔT for the sand** to obtain **the specific heat of sand**. Record this value in Column 4. of the table.

<table>
<tr><th colspan="5">Table 8: Heating and Cooling of Sand vs. Water</th></tr>
<tr><th></th><th>1</th><th>2</th><th>3</th><th>4</th></tr>
<tr><th></th><th>T (°C) @ start</th><th>T (˚C) @ 15 min.</th><th>ΔT</th><th>Specific Heat</th></tr>
<tr><td>Water</td><td></td><td></td><td></td><td>1.00</td></tr>
<tr><td>Sand</td><td></td><td></td><td></td><td></td></tr>
</table>

24 **Based on these results, explain the moderating effect Lake Michigan has on our local temperatures, both seasonally and over the course of a single day.**

25 **Explain why sea surface temperatures, in comparison to the very wide fluctuations that occur on land, range only about 15°F (~8°C) in any locality over the course of a year.**

C. More about the Sun's Energy and Planetary Temperatures

1. How Does the Sun Produce Energy?

The Sun's energy is produced largely by the fusion of hydrogen (H) nuclei into helium (He). This is a complex process with several intermediate steps but may be summarized as: 4H → He.

26 The mass of a hydrogen atom is 1.67265 × 10^{-24} gram. The mass of a helium atom is 6.64552 × 10^{-24} gram. Is the mass of 4 H atoms equal to the mass of 1 He atom? _____ How much mass is "missing" from each 4H → He fusion reaction? _____grams

What has happened to the "missing" mass? According to Einstein's mass/energy equivalence:

$$E = mc^2 \hspace{4cm} Eq.\ 4$$

the mass m (in grams) lost, multiplied by the square of the velocity of light c (3.0 × 10^{10} cm/sec) equals the energy E produced (in ergs).

27 The mass of hydrogen converted to helium by nuclear fusion in the Sun every second is about 5.4×10^{11} kg, (600,000,000 tons!)—equivalent to 3.3×10^{38} H atoms. Use Eq. 4 to calculate the energy released by the sun each second as a result of the fusion reaction 4H → He. [First solve Eq. 4 using the mass obtained for Q26 in order to determine how much energy is produced (in ergs) from each 4H → He fusion reaction. Then multiply that result by the number of H atoms consumed per second divided by 4, since each fusion reaction consumes 4 H atoms.]

_____ergs/sec

2. How Much of the Sun's Energy is Radiated into Space?

The spectrum of radiation emitted by a body depends on the temperature of the body, and this provides us with a more straightforward way to calculate the energy output of any body, including stars. A common example of this principle: when a bar of iron is heated it first emits infrared radiation, which is invisible but can be felt. As the iron increases in temperature it emits visible radiation, first red, then orange, then yellow, and as temperature increases the frequency (λ) and the energy (E) of the emitted radiation also increases. This idea is expressed mathematically as the **Stefan - Boltzmann Law (Eq. 5).**

$$E = \sigma T^4 \hspace{4cm} Eq.\ 5$$

This equation allows us to calculate the energy emitted by a warm body if we know its surface temperature. Here E = the energy flux, in calories / cm^2 /sec (the amount of energy given off every second over a square centimeter), σ (sigma) = 1.36 x 10^{-12}cal/cm^2/ K^4/sec is the **Stefan - Boltzmann Constant**, and T is the temperature of the body on the Kelvin Scale, where 0K = -273.15°C. In brief, it states that a heated body radiates energy that is proportional to the 4th power of its temperature. For example, a body at 2000K (1727°C) will radiate 16 times as much energy as a body at 1000K (727°C).

28 Find the energy output of the sun (in cal/cm^2/sec) using the Stefan - Boltzmann law. For T use 6000K , the approximate temperature of the sun's photosphere (its outermost layer): _____

29 The sun's diameter is 1.4 × 10^6 km (1.4 × 10^{11}cm). Find the total emitted energy (Ê) output of the sun in cal / sec.

3. How Much Solar Energy Reaches Earth?

Here we can apply the inverse-square rule we derived in Part A. First, calculate the solar flux for Earth. At Earth's distance the total energy output ($\hat{E}$) of the Sun has spread out over the surface area (S) of a sphere with a radius (R) of 150 million (1.5×10^8) km (our average distance from the Sun). The *solar flux* (F) for Earth is then

$$F = \hat{E} / S = \hat{E} / 4\pi \cdot R^2 \, .$$ *Eq. 6*

»   To express F in cal / sec / cm^2, R must be in **centimeters**: *1.5 x 10^8 km* = _____ *cm*

30   Calculate F, the solar flux for Earth. Show your work. F = _____ cal / sec / cm^2

To calculate the total amount of radiation received by Earth, note that we can disregard the fact that Earth is a sphere. That is, for this calculation *the area over which Earth receives solar energy is equal only to the area of a disk with the same radius as the Earth*. Do you understand why? (Recall the results of the latitude experiment in Part A5.) If not, your instructor can do a simple demonstration to illustrate this.

31   Earth's radius is 6378 km (6.378 x 10^8 cm). Calculate the energy received by Earth, in cal / sec, and in Watts. (A calorie/second is equivalent to 4.18 Watts.)

4. How Much Solar Energy is Absorbed by Earth?

Here we must take into account Earth's albedo, the proportion of solar energy reflected back into space. Overall, Earth's albedo is approximately 0.33, meaning that [1-albedo] or about 2/3 of the energy intercepted by Earth is absorbed.

32   How much solar energy is <u>absorbed</u> by Earth every second? _____ cal

5. Does Earth Emit Energy, and How Much?

If Earth only absorbed energy it would keep heating up (and eventually melt), so an equal amount of energy must be radiated back into space. (Note that this is not the same as the amount *reflected*, which is accounted for by the albedo.)

33   (a). First, find the total surface area of Earth in cm^2.

(b). Using the amount of solar energy absorbed by Earth every second that you calculated above (in Q32), how much radiation does each cm^2 of Earth's surface emit every second?

Now if we return to the Stefan - Boltzmann relationship and rearrange its terms we can find what is known as the **effective temperature (T_{eff})** of Earth:

$$T_{eff} = (E/\sigma)^{1/4}$$

34 Calculate the T_{eff} for Earth using Equation 7. (Calculate the temperature in K and convert to °C. Note that the power ¼ can be obtained by taking the square root of a square root.)

Since T_{eff} takes into account the albedo, it can also be calculated more directly from the following equation. Note that with this equation we do not have to consider the size of Earth!

$$T_{eff} = \left[\frac{(1-albedo) \times solar\,flux}{4\sigma} \right]^{1/4}$$

T_{eff} is a theoretical temperature calculated from the energy radiated by a simple warm body. But Earth's actual average surface temperature is 288K (15°C / 59°F)!

35 How can we explain this discrepancy? What critical property of Earth have we so far neglected?

We will return to this issue after looking at the solar flux and T_{eff} for other planets.

6. Surface Temperatures of the Terrestrial Planets

Table 9 contains data for the inner planets of our solar system. We might expect that the temperatures of the planets would be based on the solar energy they receive per cm^2, according to the inverse-square rule.

Enter your calculated value for Earth's solar flux into the appropriate cell in Table 9, Column 5; then calculate the solar flux for Mercury, Venus, and Mars as a proportion of Earth's, and enter those values into Column 6. Use the data in Columns 3 and 6 to plot the solar flux for each planet against its distance in AU from the Sun in Figure 6.

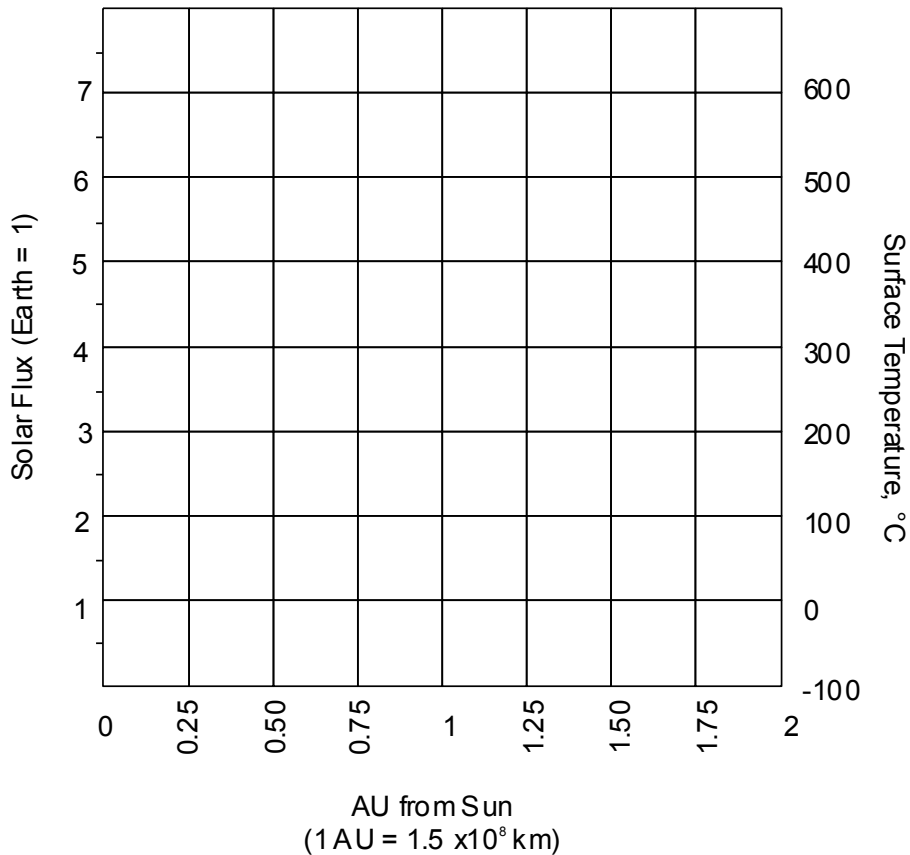|									
Table 9: Solar Flux, Albedo, and Average Surface Temperature for the Inner Planets									
1	2	3	4	5	6	7	8	9	10
Planet	Radius (km)	AU from Sun	1/AU^2	Solar Flux (cal/sec/ cm^2)	Solar Flux (Earth =1)	Albedo	Effective Temp (°C)	Atmospheric Pressure, (Earth =1)	Avg. Surface Temp (°C)
Mercury	2439	0.387	6.68	0.250		0.12	177	~0	-180 to +430
Venus	6050	0.733	1.86	0.071		0.75	-32	100	480
Earth	6378	1	1		1	0.33	-12	1	15
Mars	3398	1.533	0.426	0.016		0.16	-50	0.006	-23

AU from Sun
(1 AU = 1.5 x10^8 km)

Figure 6

36 *The solar flux plot should be consistent with the inverse-square relationship you observed in lab. Is it?*

Now plot the surface temperatures (Column 10) against the distances (for Mercury use the maximum temperature).

37 *Are the planets generally WARMER or COLDER than predicted by the inverse-square rule?*
Which planet is the exception?
Of the planets that are warmer than the inverse-square rule predicts, which deviates most strongly?

Note that Mercury, with its low albedo and nearly non-existent atmosphere, has a daytime temperature that conforms quite closely to the inverse-square plot. Now look at Venus—it reflects 3 times more solar energy than it absorbs (albedo = 0.75), and as a consequence its has a T_{eff} *lower* than Earth's, though it is closer to the Sun than Earth. Yet, at the same time, its atmosphere is much denser than Earth's and its actual surface temperature is substantially higher. It seems as though the presence of an atmosphere simultaneously increases the amount of reflected energy *and* increases the planet's average temperature. How is this possible?

7. The "Greenhouse Effect"

As we learned when discussing the Stefan - Boltzmann Law, a warm body radiates energy across the width of the electromagnetic spectrum. However, it is also important to know the *distribution* of energy across the spectrum. For example, the distribution of the Sun's emitted energy is about 9% in the ultraviolet, 41% in the visible spectrum, and 50% in the infrared, and its peak emission is within the range of visible light. The wavelength of this emission peak, called the ***wavelength of maximum intensity*** (λ_{max}), shifts with the temperature of the body. This shift is described by ***Wien's Displacement Law***,

$$\lambda_{max} = A / T \qquad\qquad Eq.\ 9$$

which states that as temperature increases the intensity of emission at λ_{max} increases and its wavelength becomes shorter. The constant $A = 2.9 \times 10^6$. For example, the λ_{max} of the sun falls in the blue range of the visible spectrum (see Figure 7):

$$\lambda_{max} = 2.9 \times 10^6 / 6000K = 480nm$$

Because gases in Earth's troposphere are transparent to wavelengths in the ultraviolet and visible parts of the spectrum, most of the sun's radiation (minus the one-third that is reflected) reaches the surface where it warms the oceans and continents. These surfaces, in turn, continually re-radiate this energy back into the atmosphere, a process known as *ground radiation* or *terrestrial radiation*.
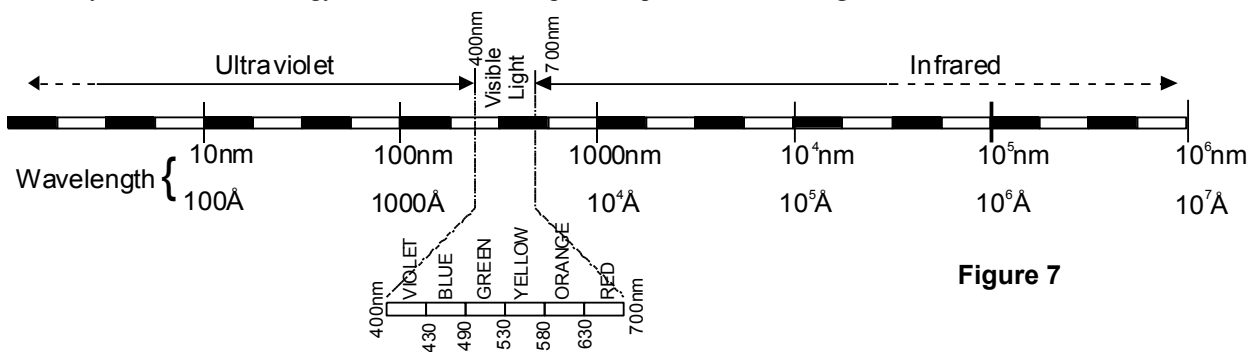

Figure 7

38 *What is the wavelength of maximum intensity for ground radiation? Calculate λ_{max} for Earth (for T, use 288K).*

39 *This is in what region of the electromagnetic spectrum?*

D. Follow-up Problems

40 *Earth's atmosphere is transparent to the shorter wavelengths in the UV and visible spectrum, but is more opaque to infrared radiation. Although all atmospheric gases (N, O, Ar, CO_2, and H_2O) absorb infrared to an extent, some of these, the so-called "greenhouse gases" (CO_2, H_2O, and also methane CH_4), are much more efficient absorbers of these longer wavelengths. Discuss how the presence of an atmosphere can make a planet warmer than would be predicted from the simple application of the inverse-square rule.*

41 *The solid earth absorbs about 55% of solar radiation reaching it. What percentage of the Sun's energy reaching Earth is absorbed by the atmosphere?*

42 *The albedos of the Northern and Southern Hemispheres are very similar though the hemispheres differ markedly in the relative proportions of land mass to ocean (there is much more land north of the Equator than to the south). However, average annual cloud cover is much the same for both hemispheres. What does this suggest about the role of clouds in Earth's radiation balance?*

43 *On sunny winter days the air temperature often remains low if there is widespread snow cover, and little melting occurs. On the other hand, any bare spots in the snow cover will tend to enlarge even though the air temperature does not increase. Explain.*

44 *Many natural systems are homeostatic. That is, they respond to external stresses in such a way as to keep within "normal" limits. Planetary temperature regulation is one such system. Consider what you have learned today and complete the diagram on the right to show how an increase in surface temperature can initiate a series of events, which eventually lead to a temperature decrease. The first events are filled in for you. There are 4 empty steps in the flow chart. Add more if you wish but all must logically precede a temperature decrease.*

temperature increases

↓

melting of snow and ice

↓

[ ]

↓

[ ]

↓

[ ]

↓

temperature decreases
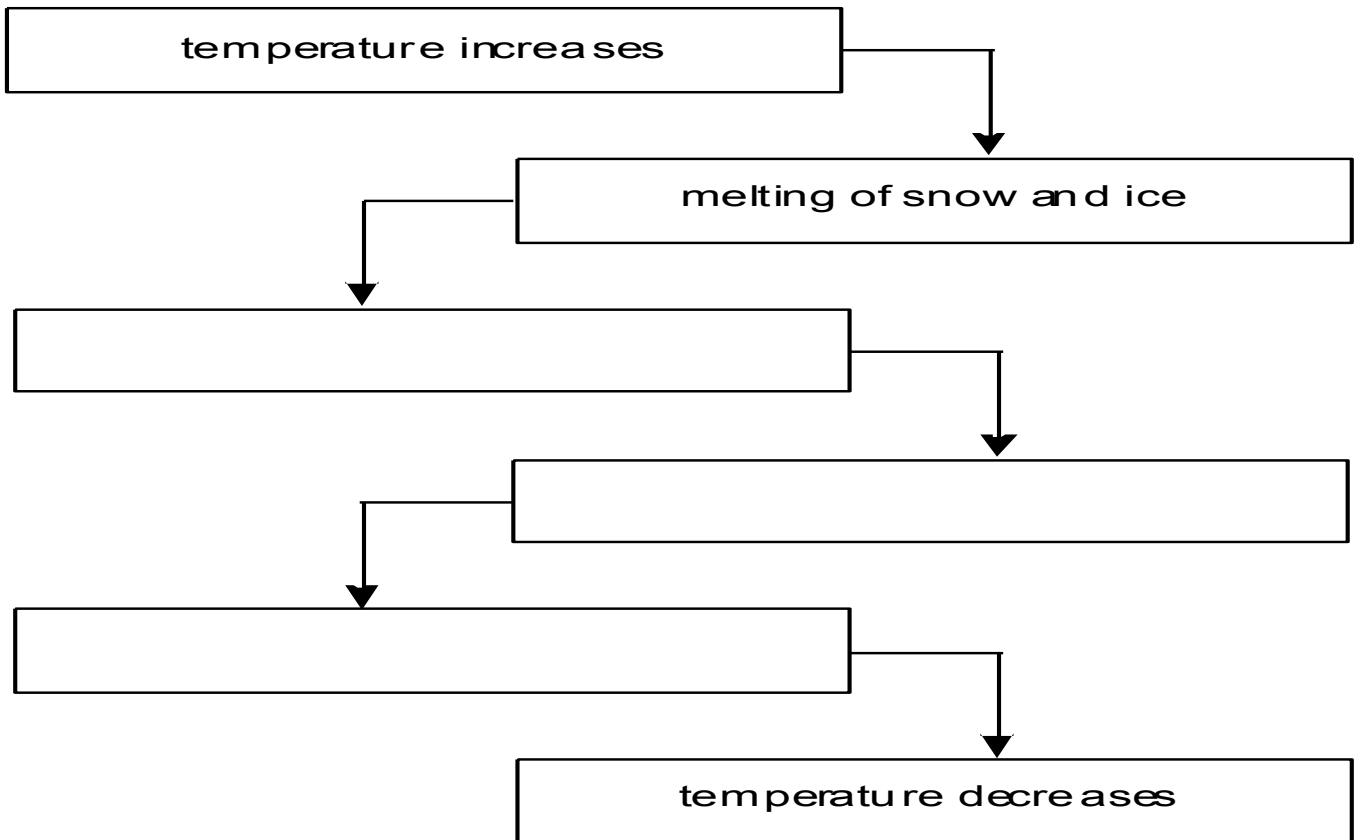
E. The Coriolis Effect

The planetary temperatures we have discussed are averages. Polar regions receive much less radiation than temperate zones and Equatorial regions receive most of all. Because of this differential heating, Earth's atmosphere undergoes convective heat transfer from the Equator to the Poles. This produces prevailing wind patterns, which are in turn influenced by the rotation of the Earth. This exercise is a demonstration of the Coriolis Effect, a consequence of Earth's rotation.

Our apparatus consists of a remote-controlled missile launcher positioned at the center of a turntable and aimed at a target at the end of a long extension arm attached to the turntable. For our purposes, we will consider the center of the turntable as one of the Poles with the target's location as the Equator. In the figures below the arrows represent the path of the missile when the turntable is stationary.
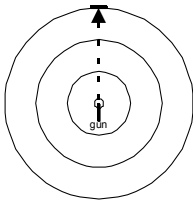
Trial 1: Stationary platform
Does the missile hit the target?
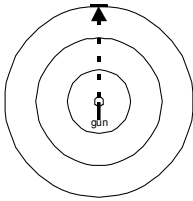
Trial 2: Platform rotates counter-clockwise (CCW)
Draw the direction of rotation and the path of the missile.
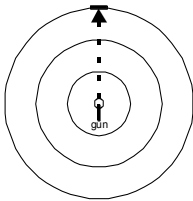
Trial 3: Platform rotates clockwise (CW)
Draw the direction of rotation and the path of the missile.

45 Wind is simply air moving from a region of higher pressure to a region of lower pressure. Based on our Coriolis demonstration, illustrate how winds circulate around atmospheric "highs" and "lows" in the Northern Hemisphere.

H   L

46 The Coriolis Effect is sometimes called the "Coriolis Force". Why is this incorrect?