Lab Budget

Name ______________________________

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. 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. T.

A basic scientific calculator is necessary for this lab.

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. 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**): $A = \pi r^2$ 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.

Lab adapted from Plotnick, Harris, and Loiacono, Earth and Environmental Sciences, University of Illinois at Chicago
http://nagt.org/nagt/teaching_resources/teachingmaterials/9266.html

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*** $\propto$ ____________________

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°.

⇒ **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.

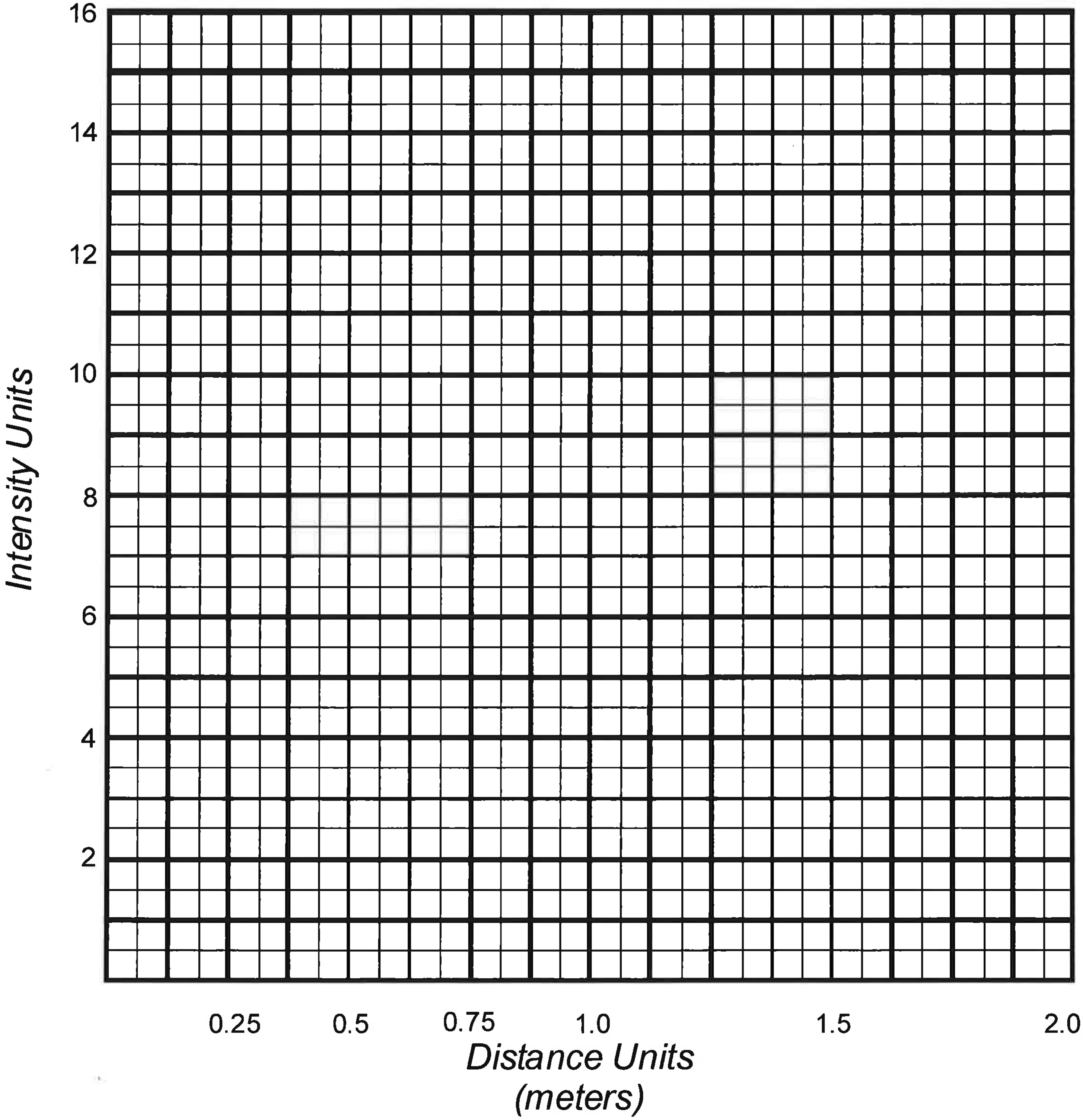
Table 2: Light Intensity vs. Distance from Source

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 $\mathbf{a_1}$ of the sphere is:

$$a_1 = 4\pi \cdot 1^2 \quad \textit{Eq. 1a}$$

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:

$$a_2 = 4\pi \cdot 2^2 \quad \textit{Eq. 1b}$$

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:

$$a_E = 4\pi \cdot 1AU^2 \quad \textit{Eq. 2a}$$

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.)***

$$a_Z = 4\pi \cdot [\ \ ]AU^2 \quad \textit{Eq. 2b}$$

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)

$$F_1/F_2 = R_2^2/R_1^2 \quad \textit{Eq. 3}$$

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.)

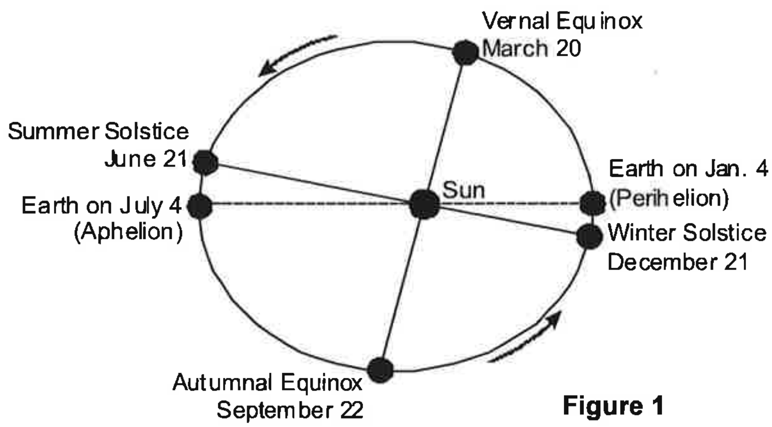


Figure 1

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 align the white mark on the side of the solar cell, not the front 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.)

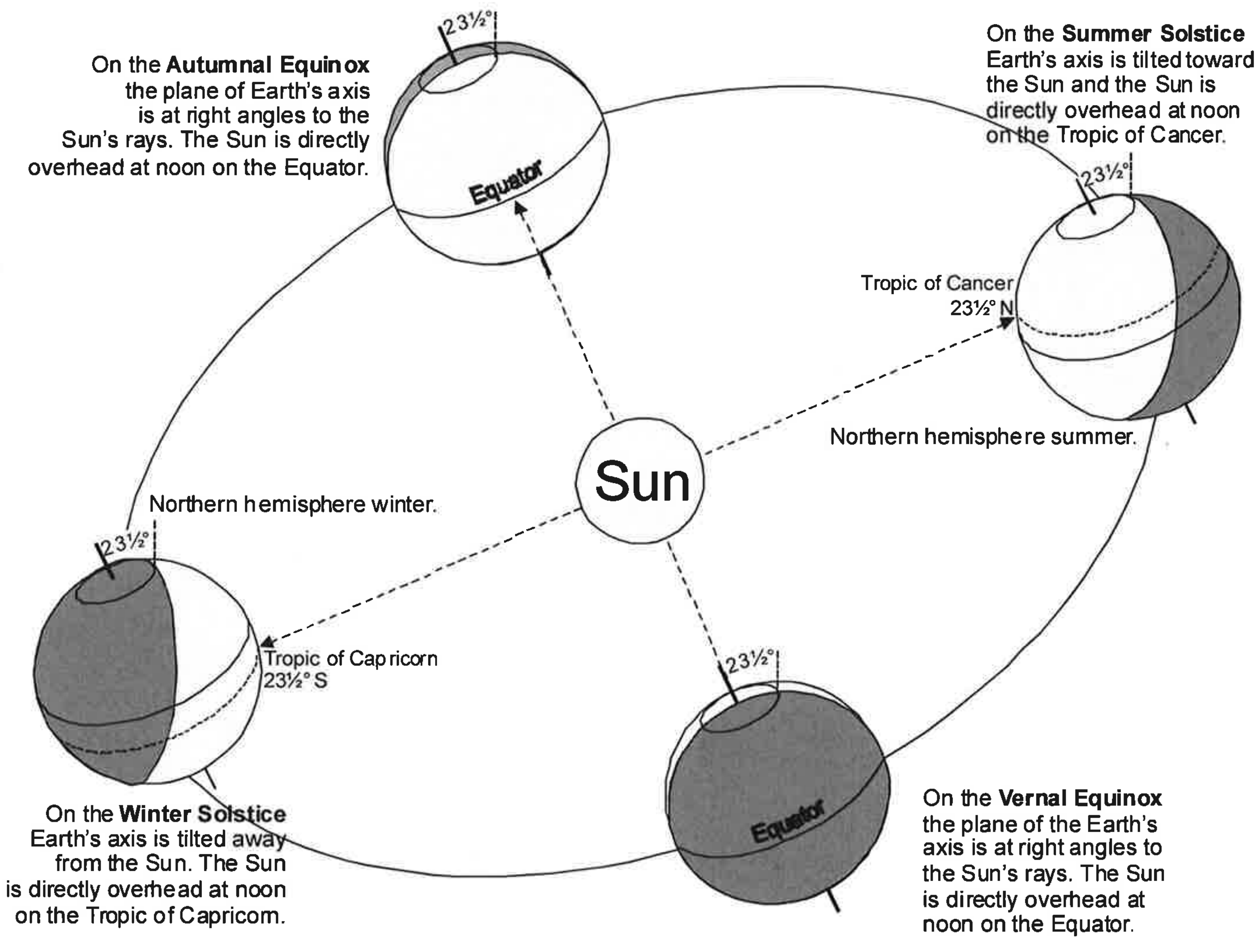


Figure 2

[ ] 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 San Diego the sun is never directly overhead (why?).<<

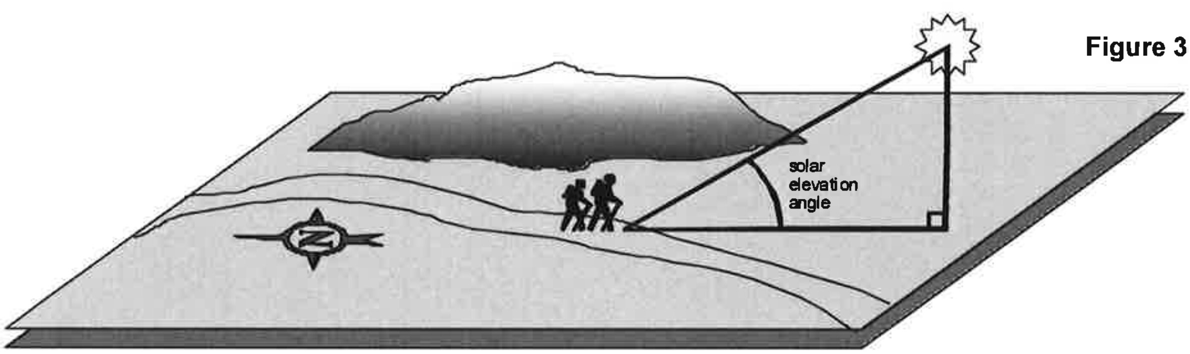


Figure 3

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

[ ] 4) Find the solar angle for San Diego at Equinox using the following methods.

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

<u>Experiment 5: Sun-Earth orientation at the SOLSTICES</u>

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 San Diego is facing the lamp (nearly underneath the meridian). This is the position of San Diego relative to the sun at solar noon on the Summer Solstice. (See Figure 4b, p. 14-10.)

[ ] 3) Find the solar angle for San Diego 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 San Diego at the SUMMER SOLSTICE in the appropriate space in Table 4.**

[ ] b) Check your measurement by **calculating it from this formula: $\alpha = 90° - \text{latitude} + 23.5°$**. (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 San Diego is facing the lamp (nearly underneath the meridian). This is the position of San Diego relative to the sun at solar noon on the Winter Solstice. (See Figure 4c, p. 4-10.)

[ ] 6) Find the solar angle for San Diego 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 San Diego at the WINTER SOLSTICE in the appropriate space in Table 4.**

[ ] b) Check your measurement by **calculating it from this formula: $\alpha = 90° - \text{latitude} - 23.5°$**. (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 San Diego 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 San Diego.

[ ] 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.

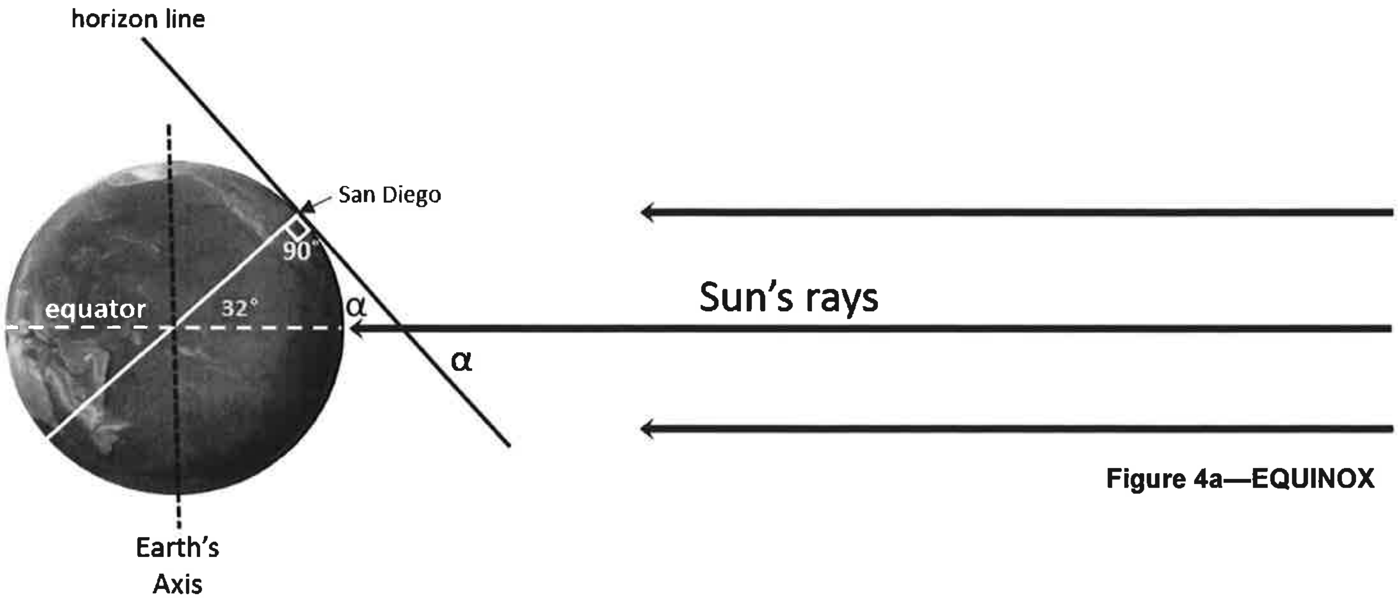


Figure 4a—EQUINOX

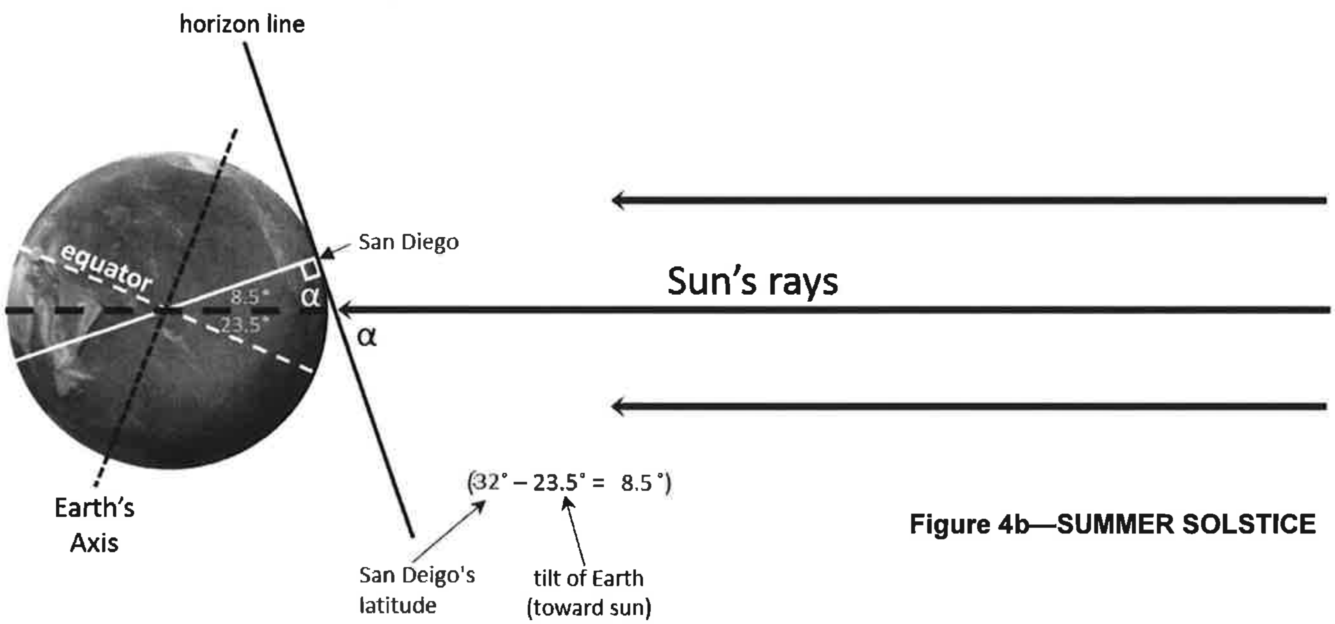


Figure 4b—SUMMER SOLSTICE

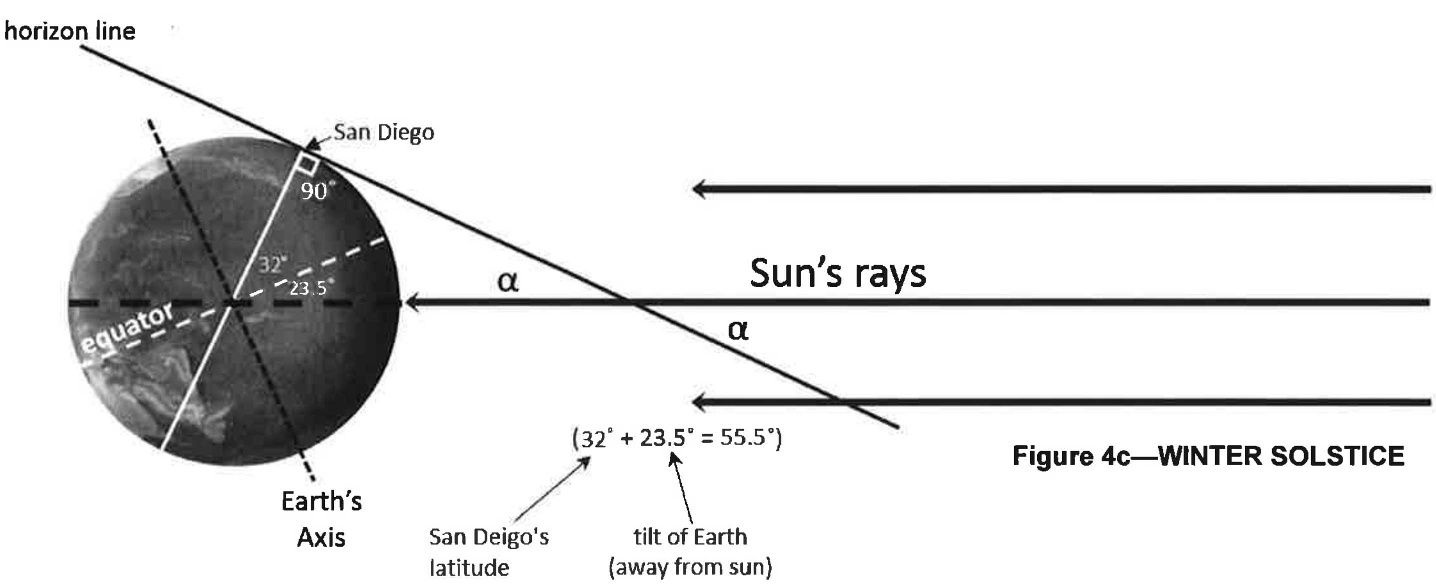


Figure 4c—WINTER SOLSTICE

[ ] 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.

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

Table 4: Seasonal Changes in Solar Flux at the Latitude of San Diego (32°42′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?)