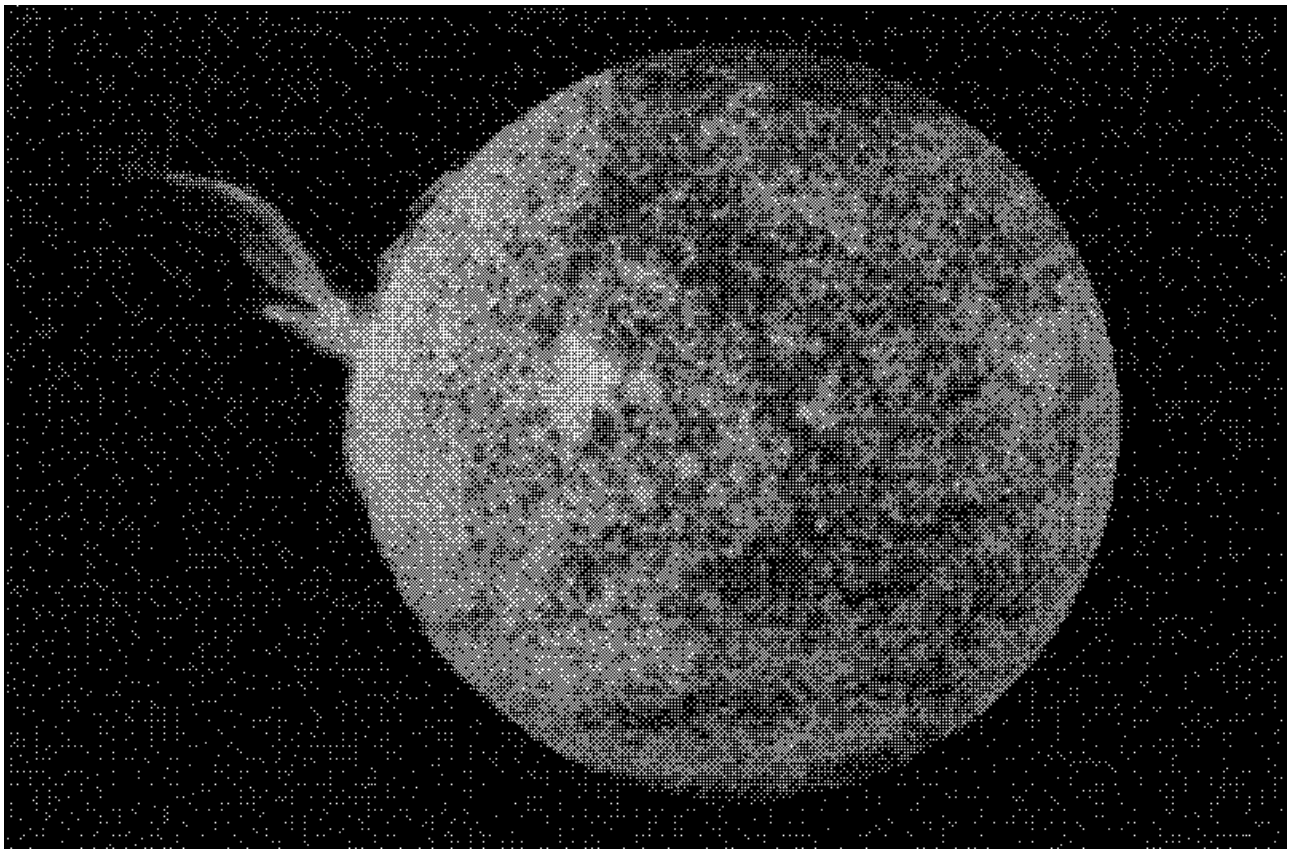
THE FLOW OF ENERGY OUT OF THE SUN

STUDENT MANUAL

A Manual to Accompany Software for
Introductory Astronomy Lab Exercise
Document SM 5: Version 1



Department of Physics
Gettysburg College
Gettysburg, PA 17325

Telephone: (717) 337-6028
email: clea@gettysburg.edu

Contemporary Laboratory
Experiences in Astronomy

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Goal:

Using the computer simulation, you will explore the interaction of photons with gas atoms.

Objectives:

If you learn to . . .

Recognize the effects of absorption and re-emission by individual atoms.

Recognize the effect a photon's energy has on the rate of absorption by a particular gas.

Observe and describe the effects of diffusion and its dependence on the number of layers of gas in the star.

You should be able to . . .

Understand how the absorption and emission lines we see in stellar spectra are produced.

Understand why it takes a photon a long time to travel from the center to the surface of the Sun.

EQUIPMENT:

Simple pocket calculator, pencil, graph paper, Windows Computer, this exercise and the CLEA Computer Program Energy Transport.

Share the use of the computer and the program with your partner to collect data. All calculations and graphing, as well as your narratives, must be your own original work.

INTRODUCTION:

Absorption In The Atmosphere

The program that you will use today is designed to teach you how photons travel from the core of the Sun to the surface and how they interact with matter on their way into space. They interact in two general regions with two different effects:

1. The **solar atmosphere** is a thin layer of gas that makes up the outermost skin of the Sun. It is largely transparent so it has little effect on most of the photons. But some photons are absorbed and re-emitted by atoms in the atmosphere producing **absorption lines** or **dark lines** in the Sun's spectrum.

2. Before reaching the atmosphere, photons generated in the core of the Sun, travel through the main body called its **interior**. They travel a zig-zag path on their way out, as they are scattered back and forth by particles (mostly electrons). So many interactions occur, that it literally takes hundreds of thousands of years for a typical photon to travel form the center to the surface.

The Solar Atmosphere

The computer program you will use includes several simulations of how photons behave as they interact with atoms of gas. You will find that when the energy of a photon matches the excitation energy of an atom or gas, the photon is easily absorbed, only to be re-radiated sometime later in some direction. If the photon energy is not properly matched to the atom, the photon passes through the gas largely unaffected. This affects our perception of photons when viewed through a cloud of gas producing the features we see when we spread out the light and look at its spectrum.

A sub-microscopic simulation, **Interaction**, allows you to study how an individual line or continuum photon interacts with atoms.

Other simulations demonstrate how the interaction of a photon passing through a thinner gas cloud depends largely on the energy of the photon. Photons that have just the right amount of energy to kick an electron of a gas atom to a higher energy state are absorbed by the atom. These types of photons are called **line radiation photons** and are studied in the **Line Formation** simulation.

Other photons, called **continuum photons**, do not have the precise energy required to be absorbed and pass through a cloud of gas easily except for occasional scattering and are studied in the **Continuum** simulation.

A final gas cloud simulation, **Experiment**, allows you to experiment with matching a photon's energy with various gas clouds to determine the wavelengths of absorption lines. This permits you to plot a line spectrum similar to what you might observe using a spectrograph attached to a real telescope.

The Solar Interior

In the **Flow** simulation, a two dimensional slice of the interior of a simulated star (hot dense gas), is used to study how a photon diffuses outward from the core, and how the numbers of layers of atoms in the model affect the amount of time it takes for a photon to escape.

STARTING THE PROGRAM

Run the Energy Transport program. Select Log In... from the menu. Enter your name, and those of your lab partners. Do not use punctuation marks. Press return after each name, or to skip to the next entry. Enter the Table Number you are seated at for this experiment. Once you have moved to the next entry, you cannot change your response unless you rerun the program again. When all the information has been entered to your satisfaction, click OK to continue.

EXERCISES

EXERCISE 1: INTERACTION OF THE SUB-MICROSCOPIC STUDY OF SOME PHOTON/ATOM INTERACTIONS.

Select **Interaction** from the **Simulation** menu to start. The display portrays many atoms in a gas. You see the electron cloud about the atom, its nucleus invisible and buried deep in the center. These simplistic pictures are for reference only. They are not drawn to scale. Atoms are seldom so round because electrons orbit the nucleus in complex levels called shells which are rotationally symmetric but not necessarily spherical. You can change the scale by selecting **Close-Up** or **Large-Scale** from the **View** menu.

Select **Line** (or **Continuum**) from the **Photon** type menu to choose the type of photons to be sent through the gassy region. Line photons have precisely the right amount of energy to be absorbed by the atoms. Absorbing a photon adds energy to the electrons in the atom, and they are kicked into higher orbits. After a brief moment, they fall to a lower energy state and release a photon in some random direction. These photons are said to be undergoing bound-bound transitions, since the electrons remain attached to the same atom even when excited. Continuum photons are the wrong energy to interact easily with the atoms, and often pass through them without incident. Occasionally, a continuum photon will scatter off of an electron, but not often.

Choose line photons and click on the **run** button to watch as many photons are sent from the left of the screen to pass through or interact with the atoms. Click on the **stop** button after 20 photons are sent.

1. How many line photons were scattered? _____

Repeat the demonstration with continuum photons.

2. How many continuum photons were scattered? _____

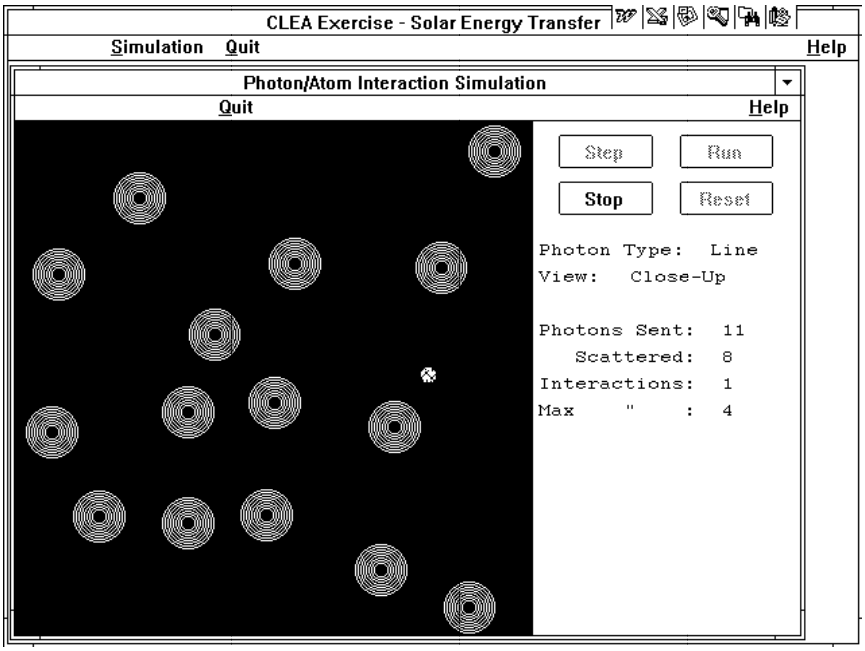


Figure 1

EXERCISE 2: LINE FORMATION

Select **Line formation** from the **Simulation** menu to start. Each time you run the simulation, photons are sent through a cloud of gas (the test-tube). Photons enter the cloud from the left having come from a bright but off-screen object like the Sun. Your detector is located at the right. Your detector views the Sun through the cloud. If a photon makes it through the cloud and is picked up by your detector the "Detected" counter increases. The photon may interact with the cloud and get redirected and miss the detector. This situation is scored "Not detected". If you want to start over, you can reset the numbers to zero by pushing the RESET button.

Line photons have just the right amount of energy to excite an electron of an atom into a higher orbit. When the electron drops back down to its lower orbit, a photon is emitted. There is no telling in which direction this photon will be emitted.

Select **# of Photons (for "Run")** from the **Parameters** menu and enter 20. Click on the **Run** button to send them through the cloud. Of the 20, what **percentage** were detected?

_____

Figure 2

Line photons are responsible for the lines in a spectrum (hence the name). If you observe them against a bright background such as a star's surface, they cause dark lines to appear, for as the simulation shows, most are scattered away. This is an absorption spectrum.

But if you observe line photons against an otherwise dark background, they cause bright lines in a spectrum. Such would be the case if you observed from a place which does not receive the direct photons, for instance if you put your detector at the bottom of the cloud instead of the right side. This is an emission spectrum.

EXERCISE 3: CONTINUUM

Select **Continuum** from the **Simulation** menu to start. The configuration is the same, but this simulation uses continuum photons instead of line photons. The energy level of continuum photons is not well matched to the atom of gas. The electrons of an atom are kicked into higher orbits only when exactly the right amount of energy is provided by the photon. Continuum photons provide either too much or too little energy to excite the electron. So most photons pass right through the electron orbits without interacting.

Send 20 photons through the cloud, as you did in Exercise 2. Of the 20, what **percentage** were detected? _____

Continuum photons give rise to the solid continuous rainbow of colors in a spectrum. They are the photons of various energies (and therefore colors) that can't easily interact with the electrons of the gas, save occasional scattering.

We observe a star's light through its atmosphere, so pure continuous spectra are not normally observed. Nearly all show tell-tale absorption lines characteristic of the cooler, less dense regions of the star's upper atmosphere.

EXERCISE 4: EXPERIMENT

Select **Experiment** from the **Simulation** menu to start. In the experiment mode you are challenged to determine the energy level of a photon necessary to excite the atoms of various gases. You can plot the number of photons that pass easily through the gas at different wavelengths to see where the dark absorption lines appear. Exercises 2 and 3 demonstrate that the photon must have just the right amount of energy to accomplish this. When many interactions are occurring, few photons get detected because most are scatters away into different directions. On the other hand, many photons are detected when there are few interactions because it's the interactions that cause a photon to change direction.

You have a number of atoms available for study. They include thin gaseous clouds of Calcium (Ca), Hydrogen (H), Magnesium (Mg), Oxygen (O), and Sodium (Na).

Choose a gas by selecting **Select Gas Atoms** and the gas from the **Parameters** menu. Enter the name of the gas in TABLE 3. Select **Change Photon Energy** from the **Parameters** menu to set the photon energy to 1.5 eV. As you change the photon energy, the wavelength (the color) changes automatically since the two are related[1]. You can reset the counters and statistics using the **Reset** button. Be sure to reset the counters if you switch to a new a gas or a different energy level.

Select **# of Photons (for "Run")** from the **Parameters** menu and enter 20. Click on the **Run** button to send them through the gas cloud at each energy level from 1.5 through 3.2 eV. Fill in the wavelength and number of detected photons for each energy level as you proceed. For example, of you send 20 photons through the gas at 2.3 eV energy level and 5 are detected, enter a 5 into the table. Be sure to RESET the counters each time you change photon energy.

[1] If you are curious or would like to calculate the wavelength (in meters) by hand, the equation is:

$$h=hc/E$$

Where h = Plank's constant = 4.14×10^{-15} eV second
c = speed of light = 3×10^{8} meters/second
E = energy of the photon in electron volts

Complete TABLE 3 and then make a graph of your results: The range of the x-axis (horizontal) should be from 350 nm to 900 nm and be labeled WAVELENGTH. The y-axis (vertical) should range from 0 to 20 and be labeled PHOTONS DETECTED. Plot the data from TABLE 3 on your graph. Connect the points on the graph with straight lines. Title the graph GAS ABSORPTION SPECTRUM. Although crude, you should be able to see a pronounced dip or several dips in the number of photons detected. The wavelength, and thus the energy of the dip, identify photon energies that easily energize the atom. Once energized, you know from Exercise 2 that most of the photons will be scattered away from an observer viewing the atom head on.

GAS TYPE: _____

eV	Wavelength	Number Detected	eV	Wavelength	Number Detected
1.5			2.6		
1.6			2.7		
1.7			2.8		
1.8			2.9		
1.9			3.0		
2.0			3.1		
2.1			3.2		
2.2					
2.3					
2.4					
2.5					

Photons Detected
TABLE 3

EXERCISE 5: FLOW

Select **Flow** and **1 photon** from the **Simulation** menu to start.

A photon trying to escape from deep in the solar stellar interior follows a tortuous path. In a hot dense gas, like the interior of the Sun , three primary mechanisms affect the photons generally outward path. They are:

1. Electron Scattering
2. Bound-Free Absorption
3. Free-Free Absorption

Most atoms in the Sun, and other stars, are said to be **ionized** because the intense temperatures have stripped off most of their electrons.

Electron scattering occurs when a photon encounters an electron and causes it to vibrate or oscillate. The energy stolen from the photon in this process is re-radiated by the electron in some random new direction as a new photon.

In Bound-Free Absorption, a photon can be absorbed by an atom. The extra energy absorbed into the atom can ionize it, causing the atom to eject an electron. This free electron can recombine with another ionized atom some time later giving rise to the release of a new photon in some random direction.

Finally, in Free-Free Absorption, a photon can transfer its energy to an already free electron thus making the electron more energetic. The more energetic electron may give up this extra energy at any time in the form of a new photon, again to be radiated in some random direction.

All of these processes play a role in affecting a photon in the Sun though the interior electron scattering is most effective. The result of these processes is that every time a photon interacts with matter, it is re-directed so that it travels in a new and complete random direction. The resulting zig-zag path is called a **random walk**. This is graphically demonstrated in the Flow simulation.

Use the Flow simulator to explore the number of interactions required for a photon to exit the surface of the simulated star. **Trails** can be selected from the **Parameters** menu to trace out the photons crooked path. Trails are visually interesting. but remember that photons crooked are not "eating" their way out of the Sun in any sense, they are just bouncing around. We generally do <u>not</u> turn on Trails.

Choose the # of Layers in the Sun by selecting **# of Layers** from the **Parameters** menu. Run the Flow simulation with stars created with 20, 30, 40, 50, 60, and 80 layers. Repeat three times, and average each column. Record your results in Table 1.

Layers	20	30	40	50	60	80
Trial 1						
Trial 2						
Trail 3						
Average						

Interactions

TABLE 1

Plot the **average** results on a sheet of graph paper. The horizontal X axis should be labeled LAYERS and run from 0 on the left to 80 on the right. The vertical Y axis should be labeled AVERAGE INTERACTIONS and run from 0 at the bottom to 6500 at the top. Give your graph a title.

Does a straight line or a curved line seem to fit your data best? Circle one: STRAIGHT / CURVED / HARD TO TELL. Sketch in a best fit line if you can.

It can be mathematically shown that the number of interactions needed to escape is very nearly n^2 where n is the number of layers in the model. Calculate n^2 for the layers you have used. Complete TABLE 2.

n=	20	30	40	50	60	80
n^2=						
your average						
hi/low						

n compared with n^2
TABLE 2

How do the calculated values of n^2 compare with the average results from the simulations? If they are different, why?

Write the number of interactions needed for the 50 layer model on the black board. When the whole class has done this, average the results. How does the class average compare with 2500 (which is 50^2)?

You may now quit the Flow Simulation.

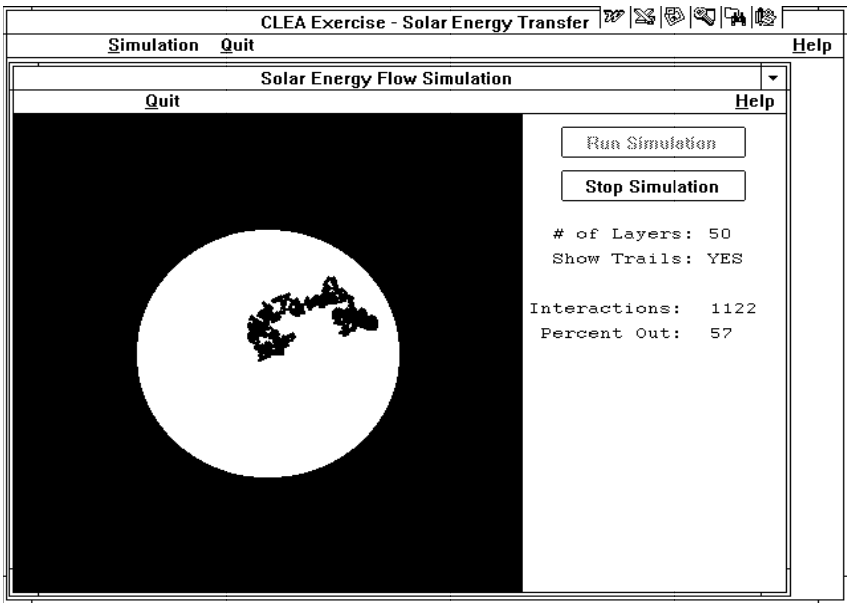


Figure 3

EXERCISE 6: PHOTON DIFFUSION (OPTIONAL)

Select **Flow** and **Diffusion** from the Simulation menu to start.

In Exercise 5 you watched the progress of individual photons as they followed a random walk from the core of the sun to its surface. The process was a statistical one, governed by chance, and you had to repeat the experiment several times to get an estimate of how many interactions, on the average, it takes for a photon to make it to the surface. Suppose that, instead of watching a single photon several times, you could watch several photons, you could watch several photons all at once.

That is what this simulation permits you to do. You can release from 1 to 1000 photons simultaneously from the center of sun and watch them make their collective trip to the surface. If you wait for them all to come to the surface, you can get a reliable estimate of how many interactions are required to travel through a star of **n** layers, and the simulated experiment takes far less time than running individual photons through **n** times.

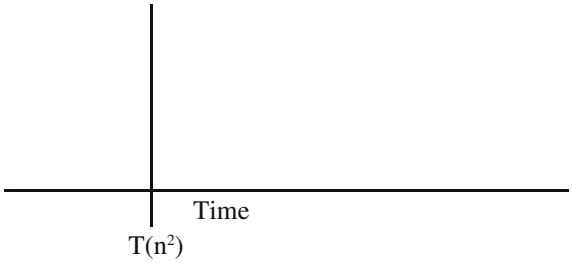
You can simply redo one of your experiments from Exercise 5 to see how well things agree. Set the simulation for 10 photons and a 50 layer model. Then run the simulation.

What is the average number of interactions required for a photon to reach the surface?
_____

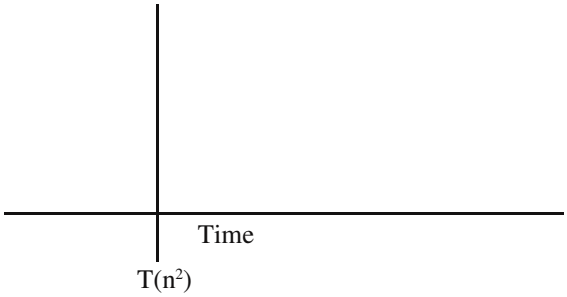
How does this compare with the class results in Exercise 5?_____
_____.

This simulation is not simply a short way of doing the experiment. It also illustrates a phenomenon called **diffusion**, which means the gradual "leakage" of photons through a material, like the solar interior, that scatters them. Note that all your photons began their journey at once—in a brief instantaneous pulse. Yet because they are scattered randomly on their way out, some take a long time to get out, and others a short time to get out. The graph at the lower right of the screen shows (on the Y axis) how many photons make it to the surface at a given time after the initial pulse of photons began at the center (increasing time on the X axis). Instead of a brief pulse of photons leaving the surface, you see them straggling their way gradually out of the star. The effect is to "muffle" the initial pulse—its energy doesn't come out all at once, but over an extended period of time.

To illustrate this qualitatively, set the simulation for a 25 layer star and send 100 photons out from the center. Sketch the shape of the curve below:



Try this again with a 5 layer star and 1000 photons



Are the two curves substantially the same shape?_____.

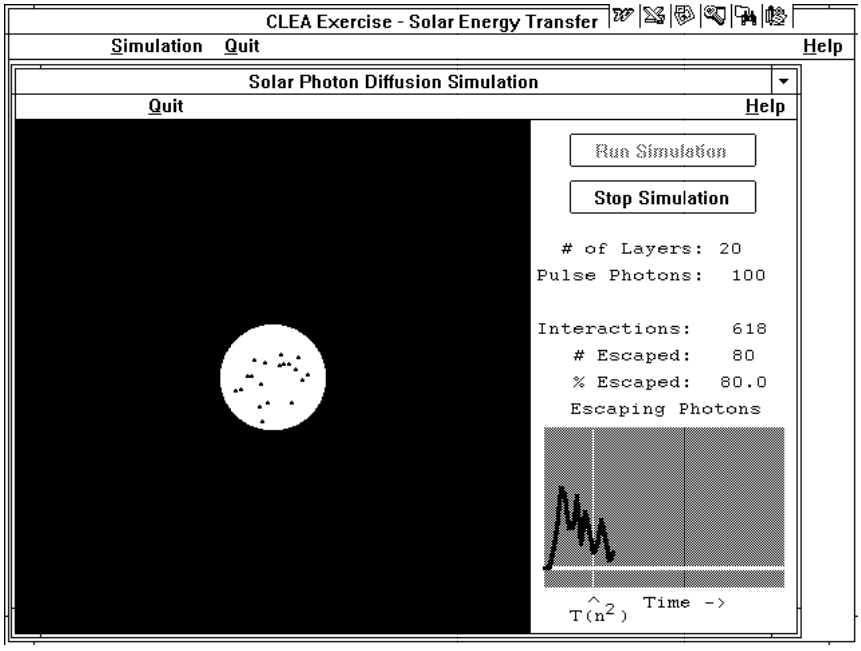


Figure 4

EXERCISE 7: ESSAY QUESTION

In the Sun, it takes several hundred thousand years for a photon released in the core to reach the surface.

Use the speed of light and the radius of the Sun to estimate the escape time for a photon from the center of the Sun if there were no interactions.

Using what you have learned in this lab, explain the apparent contradiction in a one page essay (Use the space below and if necessary, the back of this page).

EXERCISE 8 : EXTRA CREDIT (OPTIONAL)

Line photons are responsible for the bright lines in an emission spectrum as well as the dark lines in an absorption spectrum. How can this one type of photon give rise to two strikingly different spectra? Write a one page essay carefully explaining how this is possible. Use diagrams if possible to clarify your argument.

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