SOLAR SPECTROSCOPY

Objective:

In this experiment we will measure the solar spectrum at different times of day. From the measurements, we will determine the transparency of earth's atmosphere over a wide range of wavelengths, identify the molecules in the sun's atmosphere that produce prominent absorption lines, and measure the temperature of the sun based on its blackbody spectrum.

Background:

1) Read Chapter 8 in Taylor on least-squares fitting. Give special attention to pages 194-196 on exponential functions.
2) Almost any Modern Physics text on hydrogen's spectrum and blackbody radiation.
3) Sun's composition and spectrum.
http://www.oceanopticsbook.info/view/light_and_radiometry/level_2/blackbody_radiation

Theory and Apparatus:

The Sun: The sun is composed of hot gasses, 73.5% hydrogen, 25.0% helium, 1.5% heavier elements like iron, oxygen, carbon, etc. Nearly every element in the periodic chart is found in trace amounts. The reason for this is that the sun is made from the remnants of stars that died in supernovae explosions in the past. The nuclear processes in supernovae synthesized small amounts of the elements heavier than helium.

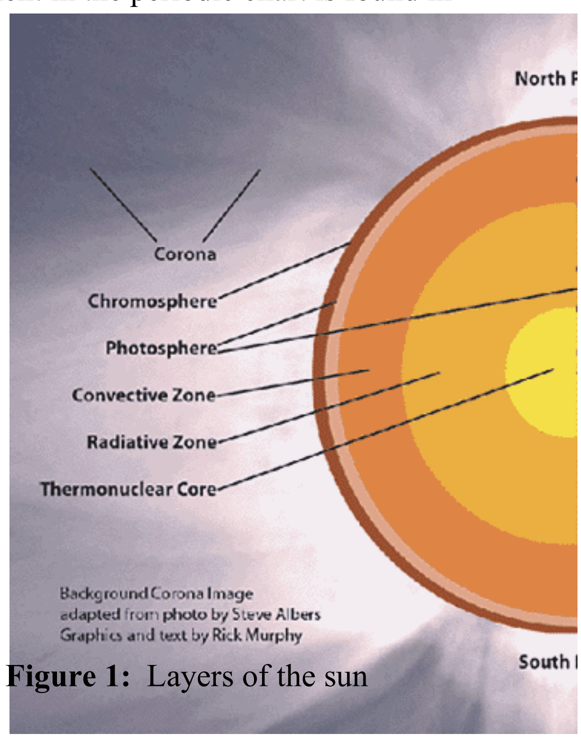

Figure 1: Layers of the sun

The sun is basically a big ball of gas, however, the physical processes at work within the sun change at different depths and lead us to label its layers. The Core is where the density and temperature are high enough to support thermonuclear fusion. Heat from the core is then transported through the Radiative Zone by the process of radiation. Photons are continually absorbed and re-emitted in random directions until they reach the Convective Zone. Heat is transported through the Convective Zone primarily by convection of the gas. Here the hot gas rises to the surface as a fluid, where it radiates heat, cools and then falls back downward. Figure 2 shows a close-up view of the granules created by this convection. The schematic view below the image explains the physical processes responsible for both the granules and the sunspots. The granules are constantly shifting on time scales of about 15 minutes. One thing people don't think about much is that this convection is loud. The surface of the sun is a very loud place.

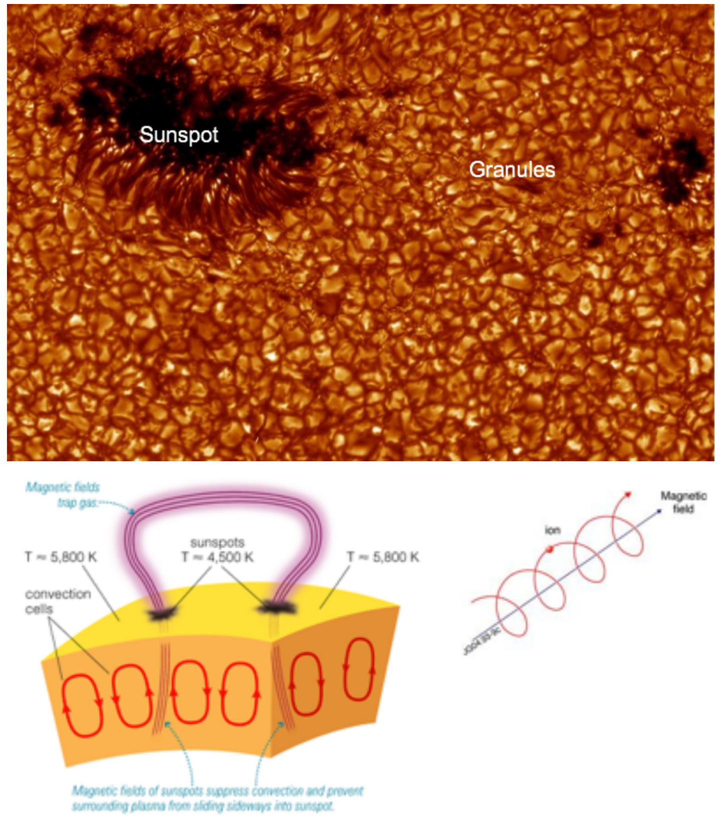

Figure 2: (Top) A close-up view of the Sun's surface. (Bottom) A schematic view of the convection that causes the granules and the magnetic fields that cause sunspots.

The light we see on earth is primarily emitted from the Photosphere which is optically thin. The gas density is low enough that a significant amount of the light emitted at the top of the Convective Zone passes through and exits the sun. The photosphere is approximately 400 km thick and starts at a radius of 696,000 km from the center of the sun.

The Chromosphere is the thick, but tenuous outer atmosphere where spicules, prominences, filaments, and Plages are observed as shown in Figure 3. These features are all related to the sun's magnetic fields and their distortion of the Chromosphere, or jets that protrude from the sunspots. The gas at the higher elevations is hot enough that its atoms emit spectral lines, but these are an insignificant part of the light that we will collect. The corona consists of material that has been ejected out of the gravitational pull of the sun and eventually becomes part of the solar wind.

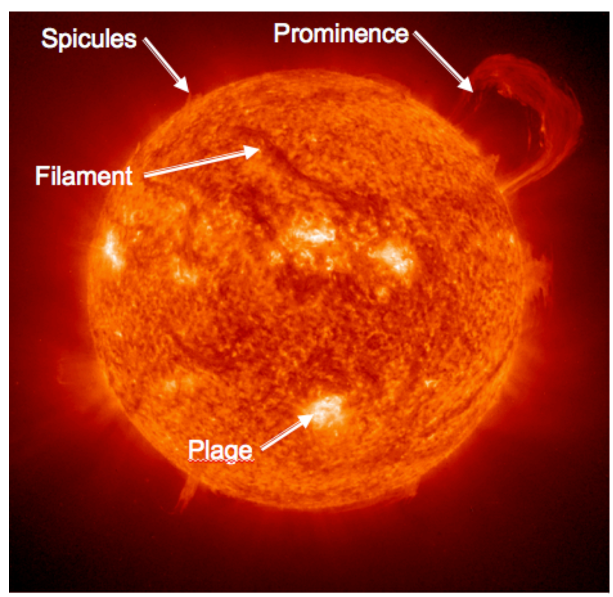

Figure 3: The sun's Chromosphere

The spectrum of the sun has two primary physical mechanisms, the blackbody radiation produced at the rather fuzzy boundary between the Convective Zone and the Photosphere

$$I_{BB} = \frac{2\pi hc^2}{\lambda^5}\left(\frac{1}{\exp(hc/\lambda k_B T)-1}\right), \tag{1}$$

and absorption lines produced when this blackbody radiation is absorbed by atoms in the atmosphere above, i.e. by the Photosphere and Chromosphere. The blackbody intensity at the "surface" of the sun is called irradiance and has units of (W/m^2nm). It uses both Planck's and Boltzmann's constants, h and k_B. It is the energy emitted per unit time in an area,

m^2 over a small range of wavelengths, $\Delta\lambda$. By the time the light reaches earth, it has spread out over a sphere centered on the sun. The distance between earth and the sun is $D_{Sun} = 1.496\times10^8$ km. Thus, the intensity that we observe at the top of Earth's atmosphere is scaled down by the ratio of the surface areas:

$$I_{TOA-BB} = I_{BB}\left(\frac{4\pi R_{Sun}^2}{4\pi D_{Sun}^2}\right) \tag{2}$$

where the radius of the sun is $R_{Sun} = 696{,}000$ km. The same geometric effect is responsible for the dimming of headlights that are far away. Headlights of a particular luminosity will be observed to have a smaller irradiance at an increased distance.

The Telescope: To detect the solar spectrum we need a solar telescope and a spectrometer. The telescope is constructed using two lenses arranged as shown in Figure 4. The first lens makes an image of the sun, and the second magnifies the image. The sun's diameter is 1.392×10^6 km located at a distance of 1.496×10^8 km. The image formed by the first lens with a 17.5 cm focal length (f_1) is therefore about 1.6 mm diameter which is too small to align accurately on the detector. The second lens (f_2 = 2.5 cm) is used to magnify the first image to a diameter of about 1.2 cm for easy alignment on the detector. In fact, it is large enough to investigate large sunspots that may be present on the day you do your lab as well as the dimming at the edge of the sun, called the limb. The limb has stronger absorption lines due to a thicker atmosphere. The magnetic fields that cause sunspots also broaden the spectral absorption lines due to the Zeeman Effect. There is also a small Doppler broadening that occurs because of the velocity (~10 km/s) of the rising and falling gas in the granules.

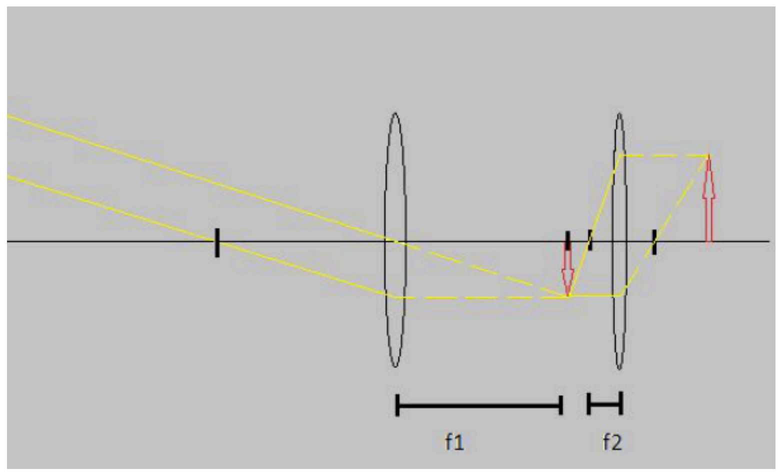

Figure 4. Solar telescope optics, light source on left

A picture of the telescope is shown in Figure 5. The Ocean Optics spectrometer is mounted to the optical cage to maintain a constant calibration throughout the experiment.

Light that reaches the solar telescope has been attenuated by Earth's atmosphere. Some of the light is absorbed by molecules in the atmosphere which create absorption lines in the spectrum. Some of the light is also scattered away from the primary direction of the sun, this Thompson scattering primarily affects blue light and is the reason the sky is blue in directions other than the direction of the sun. Light that reaches the telescope is attenuated further by the optical elements that make up the telescope and spectrometer. Our measured intensity is related to the solar intensity by two efficiency factors, one due to the transmission of the atmosphere ε_{Atm} and another due to the efficiency of the detector, ε_{Det}.

$$I_{meas} = I_{TOA}\varepsilon_{Atm}\varepsilon_{Det} \tag{3}$$

where I_{TOA} is the irradiance at the top of the atmosphere. The theoretical prediction for I_{TOA} is I_{TOA-BB} given in Eqn. 2 minus absorption lines from the sun's atmosphere. The detector efficiency includes the aperture of the telescope, the pinhole, and the entrance slit to the spectrometer, as well as the losses from the transmission of then optical elements such as the lenses, fiber optic cable, mirrors, gratings and finally the efficiency of the CCD detector in the spectrometer itself.

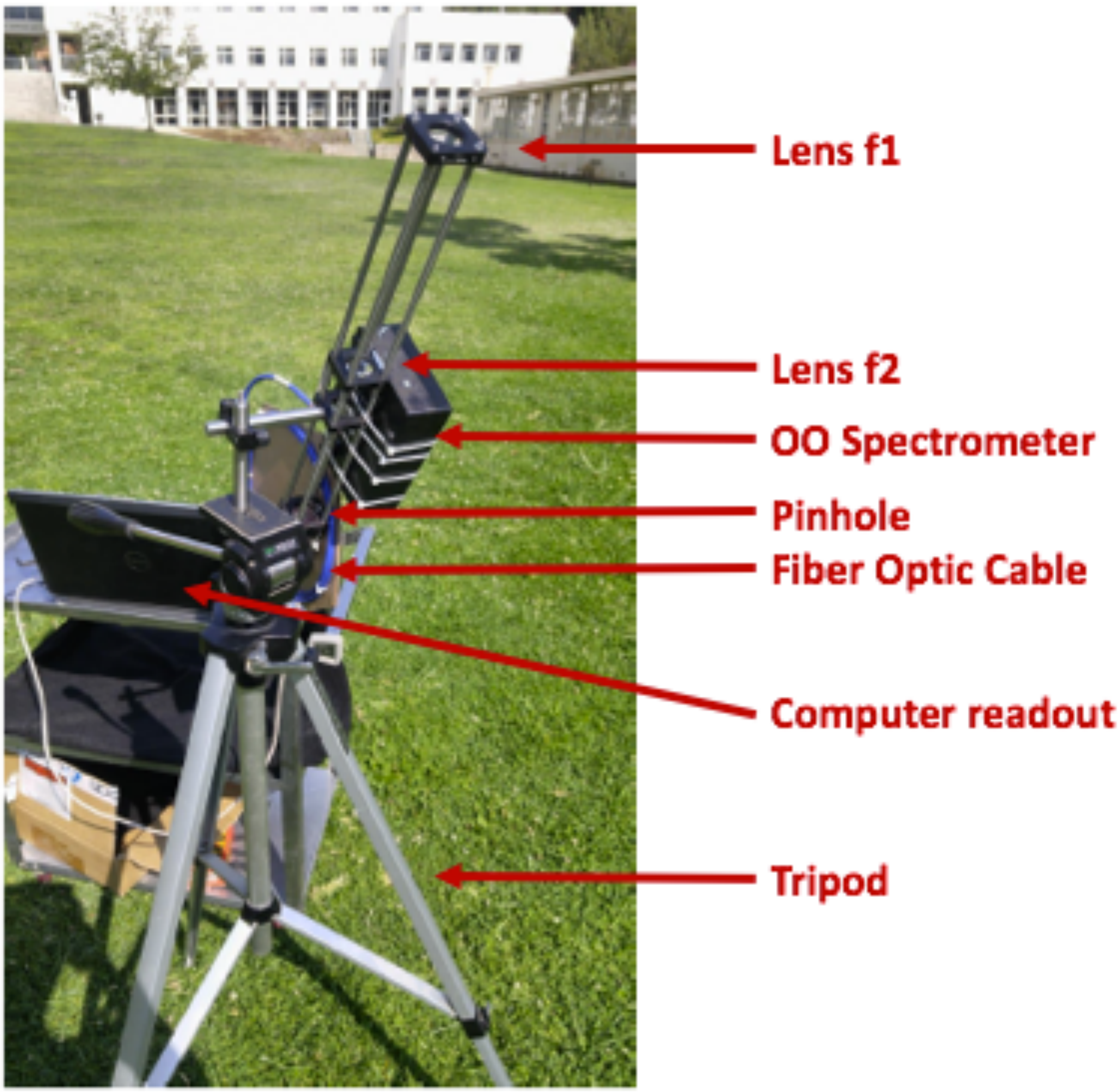

Figure 5: Our solar telescope mounted on a tripod.

Langley technique: Experimentally, we must tease out the different efficiencies and measure them separately. The Langley Technique is widely used by Atmospheric physicists. Astronomers tend to use different techniques since they can measure a variety of stars to determine the ε_{Atm} on a given night. The bottom line is that everyone who observes from the ground must correct for the transparency of the atmosphere at the time of their observations. We begin by using the airmass, m, to determine the atmospheric transmission, $\varepsilon_{Atm} = e^{-\tau m}$ where τ is the optical depth of the atmosphere. The optical depth is a constant of the atmosphere, but the airmass depends on the altitude, θ, above the horizon as shown in Figure 6. The relationship between the airmass and altitude is

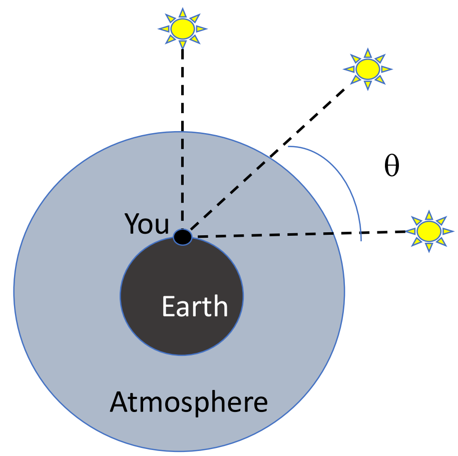

Figure 6: A sketch of the dependence of airmass on the altitude of an observation.

$$m = \frac{1}{\sin(\theta)} \tag{4}$$

At an altitude of 90 degrees, the airmass is 1 atmosphere. It increases in units of atmospheres as the altitude decreases. By recording the altitude when the measurements are taken, we can calculate the airmass.

The measured irradiance is then related to the TOA irradiance by the earth's atmospheric transmission: $I_{meas} = (I_{TOA}^{meas})e^{-\tau m}$. It is convenient to linearlize this relation to make a **Langley Plot** by taking the natural logarithm,

$$\ln(I_{meas}) = \ln(I_{TOA}^{meas}) - \tau m \tag{5}$$

Figure 7 shows a plot with airmass on the horizontal-axis and $\ln(I_{meas})$ on the vertical-axis. Each wavelength shows a linear relationship that has slope of τ, the optical depth, and a y-intercept of $\ln(I_{TOA}^{meas})$.

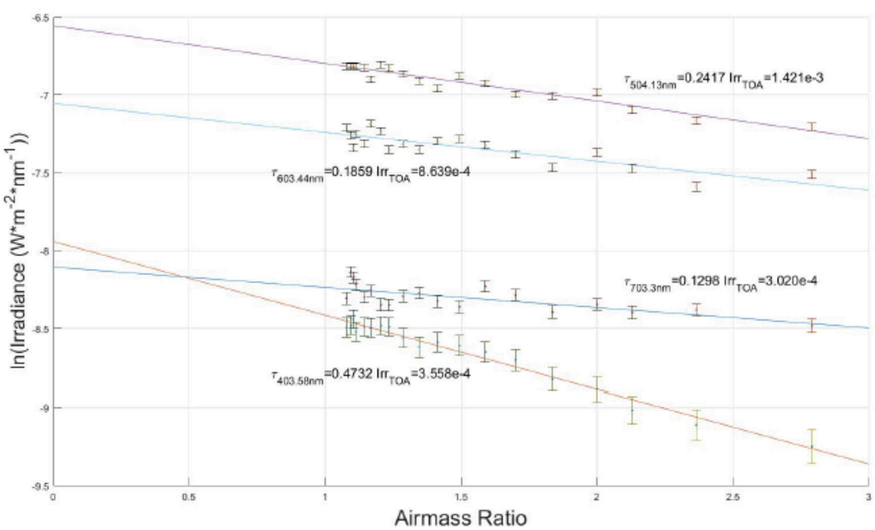

Figure 7: A Langley plot created for the atmosphere in San Luis Obispo on 8/17/2016. There were extensive fires burning in California, so it is especially red due to smoke in the atmosphere.

The factor I_{TOA}^{meas} is the measured irradiance above earth's atmosphere. It is free of atmospheric absorptions, but still needs to be corrected for ε_{Det}. For a particular time of day, i.e. at one altitude, the transparency of the atmosphere is determined as a function of the wavelength, $T_{Atm}(\lambda) = \varepsilon_{Atm}(\lambda) = e^{-\tau(\lambda)m}$. This characterization of the atmosphere is interesting in its own right, but the solar spectrum is eventually what we are after.

The y-intercept is related to the solar spectrum by the detector efficiency.

$$I_{TOA}^{meas} = I_{TOA-SS}\varepsilon_{Det} \tag{6}$$

We turn this around and solve for the detector efficiency using the standard solar spectrum I_{TOA-SS} shown in Figure 8. Since the detector does not change, this factor is the same for all measurements, $\varepsilon_{Det} = I_{TOA-SS}/I_{TOA}^{meas}$. The model labeled AM0 is the standard solar spectrum at the top of the atmosphere, TOA-SS.

As you can see, the Langley Plot provides us with a measurement of the atmospheric transparency and the Standard Solar Spectrum at the top of the atmosphere (AM0) allows us to measure of our detector efficiency. We will use these to measure the top of the atmosphere irradiance, $I_{TOA-BB} = I_{TOA}^{meas}/\varepsilon_{Det}$ and compare it to the theoretical top of the atmosphere irradiance given by combining Equations 1 and 2. The free parameter in the theoretical prediction is the temperature of the sun. A fit to our data will then provide us with a measurement of the sun's temperature.

Quantum mechanics is responsible for both the blackbody spectrum and the quantized energy levels that lead to electron transitions within atoms and molecules. Without these physical features the sun's composition and temperature would remain a mystery. Quantum phenomena are spectacularly useful for remote sensing!

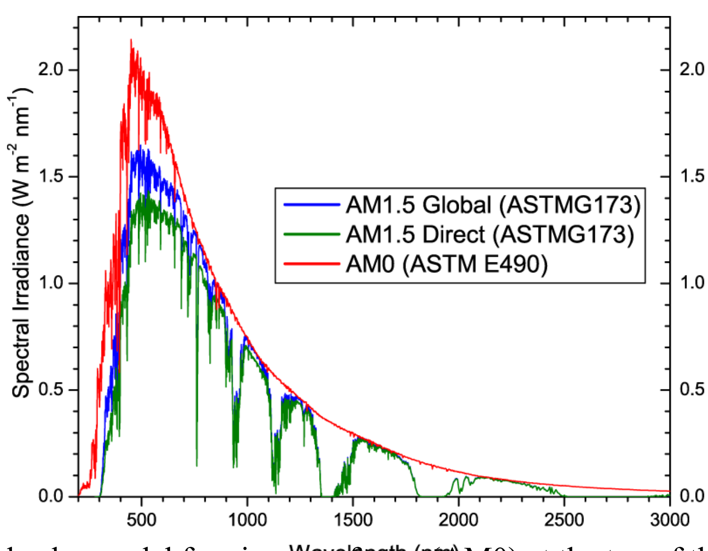

Figure 8: The standard solar model for airmass of zero (AM0) at the top of the atmosphere as well as an airmass of 1.5 (AM1.5) for flat detectors (Global) as well as solar concentrators (Direct) which admit sunlight from more than one direction via a mirror.

Procedure:

Setup the spectrometer on a clear day in a location where you will be able to see the full transit of the sun from sunrise to noon, or from noon to sunset. Thin wispy clouds will adversely affect the experiment so pick a VERY clear day if possible.

Never look at the sun for any reason, or try to measure its altitude. Looking directly at the sun is dangerous and can cause retinal damage. Instead use the calculator found here: http://aa.usno.navy.mil/data/docs/AltAz.php to calculate the sun's altitude based on the time of day. Use (Form B) with the coordinates for San Luis Obispo of 35.27 N (latitude), 120.66 W (longitude) and -8 hours from universal time (UT).

Before you start, determine the time of day when the sun is highest in the sky. A measurement within an hour or two of this time of day will be very useful. As the sun approaches the horizon, you'll need measurements every fifteen minutes or so because the airmass changes dramatically as the sun approaches the horizon. You should quit when the sun is within about 10 degrees of the horizon because the approximation in Equation 4 begins to break down. The approximation in Equation 4 implies that the airmass is infinite when θ is zero, but it's obvious that the airmass is never truly infinite.

Setup a strategy to measure the solar the solar spectrum at about 15 times between its highest and lowest elevation and take the data. You may need to share data with an earlier/later lab section on the same day to create a meaningful Langley Plot.

1. Record the time of day, airmass, and spectrum according to the strategy you have decided upon. You should adjust the exposure time so that the spectrometer collects lots of counts, but doesn't saturate at the highest altitude when the sun is brightest. To improve statistics, you can take as many exposures as you think is reasonable, (1 to 100). Create a directory for the stored files and organize them for the later analysis.

2. Take a "dark spectrum" at least 2 or 3 times during the day. Temporarily block the light entering the pinhole and record the spectrum. If you change the exposure time for any reason, you'll need a dark spectrum with the same exposure time to analyze the data.

3. Between measurements, start to analyze the data. The photon counts observed in your spectrum need to be turned into physics units of irradiance.

$$I_{meas} = \frac{\left(N_{signal} - N_{dark}\right)\times(hc/\lambda)}{(\Delta t\ \Delta\lambda\ A)} \tag{7}$$

   Here the factor hc/λ factor converts the counts $N_{solar} = N_{signal} - N_{dark}$ to units of energy. The Δt is the exposure time used when the data were collected. The $\Delta\lambda$ is the range of wavelengths that are collected in each pixel of the CCD. It's the difference between successive wavelengths recorded in the data files. You can use an average value for this since it changes slightly between the shorter and longer wavelengths. Any errors introduced by this approximation will be removed by the calibration using the standard solar spectrum.

The aperture of the detector , A, is a combination of the size of the first lens, the pinhole, the fiber optic, and the entrance slit to the spectrometer. Our estimated value is $A = \pi r_{eq}^2$ where $r_{eq} = 5.2365\ \mu$m.

You will also need to calculate the uncertainty for each irradiance, δI_{meas}. You can assume that the counting errors dominate and that there are no uncertainties in the wavelengths, exposure times, or aperture.

4. If large sunspots are visible, try taking a spectrum of the sunspot. Avoid the sunspot for your normal measurements because it will be difficult to align for repeated measurements. If there are sunspots, you'll notice that they don't move very much during the day because the solar day is about 25 days at the equator and 34 days at the poles. The differential rotation of the gas becomes interesting for magnetic lines punching through the surface. Magnetic connections often have to stretch as time marches forward. If you want to see the sunspots move, you'll have to return and take a look in a few days. The sun's weather report is updated on this website: http://spaceweather.com.

Analysis:

1. Convert your signal and dark counts, to irradiance using Equation 7. Plot I_{meas} vs. λ for each time of day. Does the I_{meas} appear to decrease as the airmass increases? Make sure you calculate the error bars for each data point.

2. Choose 6 wavelengths that range from blue to red and make a Langley Plot according to Equation 5. Fit each line to determine the optical depth, τ, and $\mathrm{y-intercept}, \ln(I_{TOA}^{meas})$. The wavelengths with the most photons will have the highest magnitude, but you should notice that the largest slopes occur for the bluer wavelengths.

3. When the Langley plot looks correct, fit for τ and $\ln(I_{TOA}^{meas})$ **for every wavelength in your data files.** There are too many to plot, but you shou
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4. Use your measured optical depth, $\tau(\lambda)$ to make a plot of the atmospheric transmission $T_{Atm}(\lambda) = \varepsilon_{Atm}(\lambda) = e^{-\tau(\lambda)m}$. Select a particular airmass, this corresponds to a particular time of day. Do you see the effect of Thompson scattering? It preferentially scatterers blue light over red light? The wiggles are due to absorption by various molecules. The strongest are the absorptions near 680 nm and 760 nm due to CO_2 as well as the wide absorption bands just above 700 nm and above 800 nm due to H_2O. A significant difference between atomic lines and molecular lines is the

number of transitions that can occur at visible wavelengths sometimes resulting in wider absorption features. Your report should include a description of the physical source of the features found in your plot.

5. Measure the detector efficiency $\varepsilon_{Det} = I_{TOA}^{meas}/I_{TOA-SS}$ using your fitted y intercepts. This efficiency depends on the wavelength of light, but is constant throughout the day since the detector doesn't change. Use the AMO0 data providedyou're your instructor. The wavelengths in the AM0 data will not necessarily match those collectred by the Ocean Optics spectrometer so you will have to interpolate to calculate ε_{Det}. Plot $\varepsilon_{Det}(\lambda)$.

   You may notice that this efficiency is very small. Luckily the sun is so bright that we have plenty of photons to waste. The shape of this plot is primarily due to the response of the CCD and the optics. The CCD stops working for very red photons that carry very little energy. For very blue photons, the efficiency is cut off by the optics which tend to be opaque to blue or UV photons. Some of the optical fibers that we use in QLab have a strong absorption line at 780 nm that are due hydroxide used during the manufacturing process. Does your spectrum show evidence of hydroxide molecules in your fiber optic cable?

6. Use the Detector efficiency to measure the solar spectrum at the top of the atmosphere, $I_{TOA-BB} = I_{TOA}^{meas}/\varepsilon_{Det}$. Make a plot of $I_{TOA-BB}(\lambda)$. There are too many points to plot the error bars. Instead, just connect the dots with a line.

7. In the plot you just made, you should notice that some of the absorption features are larger than the statistical jitter in the plot. Estimate the jitter at long wavelengths where there are fewer absorption features and then record the location of each spectral absorption line that is two or more times larger than the jitter. Label each absorption as weak, medium, or strong. Use Appendix A to identify the chemical transition related to each absorption feature.

   Notice that most of the transitions are due to atoms rather than molecules. Although there are some molecules in the coolest parts of the Sun's atmosphere, for the most part the sun is too hot for molecular bonds to form. The opposite is true for the absorption features in earth's atmospheric transmission where most of the absorption features are due to molecular transitions of water and carbon dioxide.

8. Determine the temperature of the sun. Fit the $I_{TOA-SS}(\lambda)$ data **above 500 nm** to the theoretical prediction for $I_{TOA-BB}(\lambda)$ given in

Equations 1 and 2. Leave the temperature as a free parameter. There are too many absorption features below 550 nm, so the black-body feature doesn't dominate the spectral shape.

Write it up:

The main results of this lab are:

1. Langley Plot
2. Atmospheric Transmission Plot
3. Detector Efficiency Plot
4. Plot of the Solar Spectrum.
5. Identification of spectral absorption lines in the earth's and the sun's atmospheres.
6. Measured temperature of the sun.

Additional Questions:

1. What are the units of blackbody radiation? Verify that Eqn. 1 has units of irradiance, $W/(m^2nm)$.

2. Why is the sky blue? Use your measurement of the atmospheric transmission in your explanation. Sketch a small earth that is illuminated uniformly by sunlight coming from a very distant sun. If you stand on the earth and look at an angle away from the sun, what should you observe?

3. Why are the Balmer absorption lines not observed in Earth's atmospheric transmission curve? There is certainly plenty of hydrogen in the atmosphere to absorb photons.

4. Calculate the diameter of the final image from the 2-lens solar telescope. Use the diameter of the sun, and f1=17.5 cm and f2=2.5 cm.

5. If sun spots were visible on the day you took your measurements, did the spectral absorption lines broaden? What is the source of this broadening?

6. What is the source of counts in a dark spectrum? These counts are fundamental to using a CCD detector. You'll have to do some research to understand the sources of background in a CCD.

7. Why are the spectral features in the sun mainly due to atoms rather than molecules? A few molecular lines are visible. Where must these molecules be located so that they do not dissociate in the extreme heat?

8. What quantum transitions are involved in the absorption lines that you found in your spectrum? Look up each electron transition in the NIST database and record the quantum numbers for the electron's initial and final state.

Appendix 1: Spectral Line Analysis for the Sun

Table 1: Atomic transitions that are prominent in the Solar Spectrum. Taken from the NIST database located at https://www.nist.gov/pml/atomic-spectra-database. Neutral atoms identified are hydrogen, calcium, sodium, iron and magnesium. Ionized calcium and iron are also identified. Carbyde is the only molecule that is easily identified in the Solar Spectrum.

Wavelength	Relative Intensity	Atom/Molecule
358 nm	medium	3 Fe I lines
374.5 nm	medium	5 strong Fe I lines
383 nm	medium & wide	Fe I + Hε
393.5 nm	strong	Ca II
397 nm	strong	Ca II
405	weak & wide	Fe I
410 nm	weak	Hδ
430.5 nm	strong	CH
434 nm	weak	Hγ
438 nm	medium	Fe I
486.1 nm	medium	Hβ
517.5 nm	medium & wide	3 Mg I lines
527.0 nm	weak	Fe II
540.5 nm	weak	Fe I + Ca I
589 nm	very weak & wide	Na I doublet
656.3 nm	very weak	Hα.

When spectra are collected on film, they are not usually corrected for either ε_{Atm} or ε_{Film}. Notice the red terrestrial O_2 line. This makes them difficult to use to measure the temperature of the sun. Still, the chemical line identifications are helpful.