Lab 9: Astronomical Spectroscopy II

Purpose

Now that we know what spectroscopy is, let's look at an application within the Sun. The Sun is composed mainly of hydrogen and helium, but astronomers have identified nearly all the chemical elements found on Earth in the atmosphere of the Sun. Helium itself was discovered on the Sun in 1869, 27 years before it was isolated on Earth; the name *helium* was in fact derived from the Greek work for the Sun, *helios*. How is it possible to perform chemical analysis on a body that is 150 million miles away? The answer is that the light from the Sun is analyzed by a spectroscope, an instrument that splits light into its constituent colors or wavelengths.

Introduction

Fraunhofer Lines

The use of spectroscopy began with Issac Newton around 1666. Newton admitted a sunbeam into a darkened room through a round hole. When he passed the beam through a glass prism, the white light was split into a rainbow-like spectrum. Because he used a round hole, his spectrum had low resolution and he saw no details in it. Many years later, in 1802, Williams Wollaston used a narrow slit to define the beam. He noticed four dark lines running across the colored bands. Unfortunately, Wollaston though that the lines were merely boundaries between different colors, and he attached no importance to them. Shortly therafter, in 1814, the noted Munich optician Joseph Fraunhofer not only saw the lines, but made a careful map of 576 of them, assigning letter designations to a dozen of the most conspicuous of them.

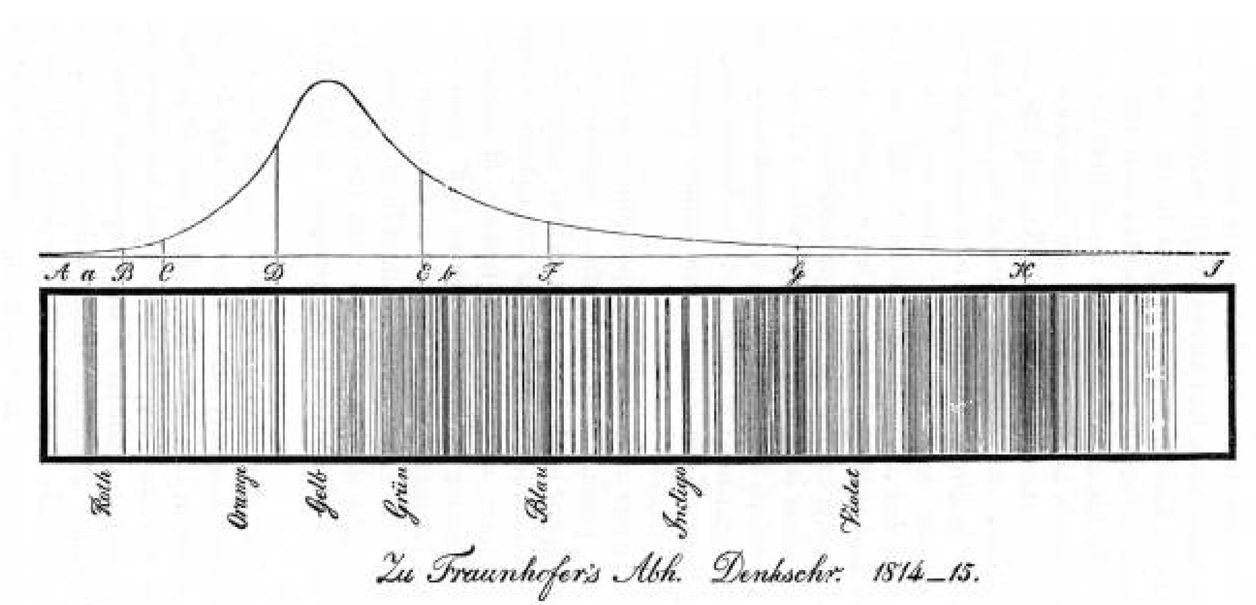


Figure 9.1: Fraunhofer's historic sketch of the solar dark absorption lines, 1814. The curve above is his estimate of the response of the human eye to the various colors.

Thus Fraunhofer achieved the immortality that Wollaston had side-stepped, since the dark lines in the solar spectrum have been known ever since as the *Fraunhofer lines*. Figure 9.1 reproduces one of Fraunhofer's maps, with his letter designation above the lines. Notice that the longer red wavelengths are at the left and the shorter, violet wavelengths are to the right.

The explanation of the dark lines was given in 1859 by Gustav Kirchoff of Heidelberg, Germany. Kirchoff showed that dark lines are produced when an absorbing gas lies between the spectroscope and the source of a continuous spectrum. The continuous spectrum, an unbroken band of rainbow colors, can be produced by an incandescent solid or liquid, or even a gas – at high enough pressure. Kirchoff further demonstrated that the dark absorption lines are characteristic of the chemical elements in the intervening gas. He showed that Fraunhofer "D" line coincides with the wavelength with the yellow emission line of sodium in the lab; ergo, the atmosphere of the Sun must contain the metal sodium. The laboratory spectrum of iron is extremely complex, and Kirchoff succeeded in identifying no less than 60 of Fraunhofer's solar lines with iron. He was similarly able to show the presence of some half-dozen other terrestrial substances in the Sun. It is fair to say that this work in the middle of the 1800's marked the birth of modern astrophysics.

Blackbody Radiation

As you've seen in "Astronomical Spectroscopy I", there are two different types of radiation: absorption and emission. All objects absorb and emit radiation to varying degrees. What governs how much an object absorbs and emits?

For absorption, we define an object's albedo as the fraction of light it reflects. Albedos range from 0 to 1, where an albedo of 0 means that 0% or none of the incident light is reflected, and an albedo of 1 means that 100% or all of incident light is reflected. You probably have intuition about this very effect. If you've ever tried to read a book outside on a nice, sunny day, you've probably noticed that the pages are very bright to look at without sunglasses. Yet, looking at the grass and ground around you, it appears less bright. This is because white paper has a very high albedo (0.7), it reflects most of the incident light, while grass and soil have low albedos (0.25 and 0.17, respectively).

When an object emits light only due to its internal heat and absorbs 100% of the incident light on it (i.e. an albedo of 0), we call that object a perfect blackbody (often referred to as simply a blackbody). "Perfect" indeed implies an idealized construct. There are no such objects in nature. However, some are very close so that referring to them as blackbodies is quite useful. In fact, any opaque object glowing because of its internal heat can be well-described by a blackbody: you, your pet, the Earth, stars, this page, etc.

Figure 9.2 shows the spectrum of a blackbody, the brightness as it continuously varies with wavelength. Notice that the blackbody spectrum peaks in brightness at a certain wavelength. The position of this peak depends only on the temperature of the object. The relationship between the peak emission and temperature is known as Wien's displacement law:

$$\lambda_{\max} = \frac{b}{T}$$

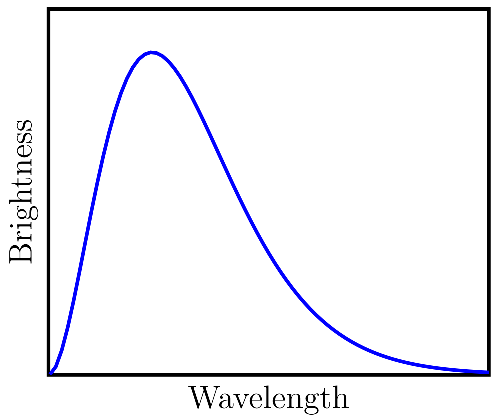


Figure 9.2: Blackbody spectrum sketch

where b is just a constant of proportionality. Because temperature is inversely proportional to the peak wavelength, hotter objects have blackbodies with shorter peak wavelengths. In other words, hotter objects are "bluer".

Since blackbody radiation effectively tells us about the temperature of an object based only on its color, it is particularly useful when applied to stars. For example, the surface of the Sun has a temperature of approximately 5800 K. The peak emission of this blackbody occurs around the green part of the spectrum at a wavelength of around 500 nm.

Interestingly, the curve sketched above the spectrum in Figure 9.1 is Fraunhofer's approximation for the human eye's responsiveness to the different colors. This resembles the blackbody of the Sun through our atmosphere because we have evolved to use this available light, albeit imperfectly.

Light from the Sun

Figure 9.3 shows the basic structure of the Sun. The light energy that we see is generated in the core by fusion reactions, when hydrogen is combined into helium stably under intense pressure. The light then very slowly makes its way out by first scattering or bouncing its way through the radiative zone before being carried through the convection zone in hot rising blobs of plasma (ionized gas) to the photosphere. Since the photosphere of the Sun is the point at which it transitions from opaque and transparent, this is the surface of the blackbody we see.

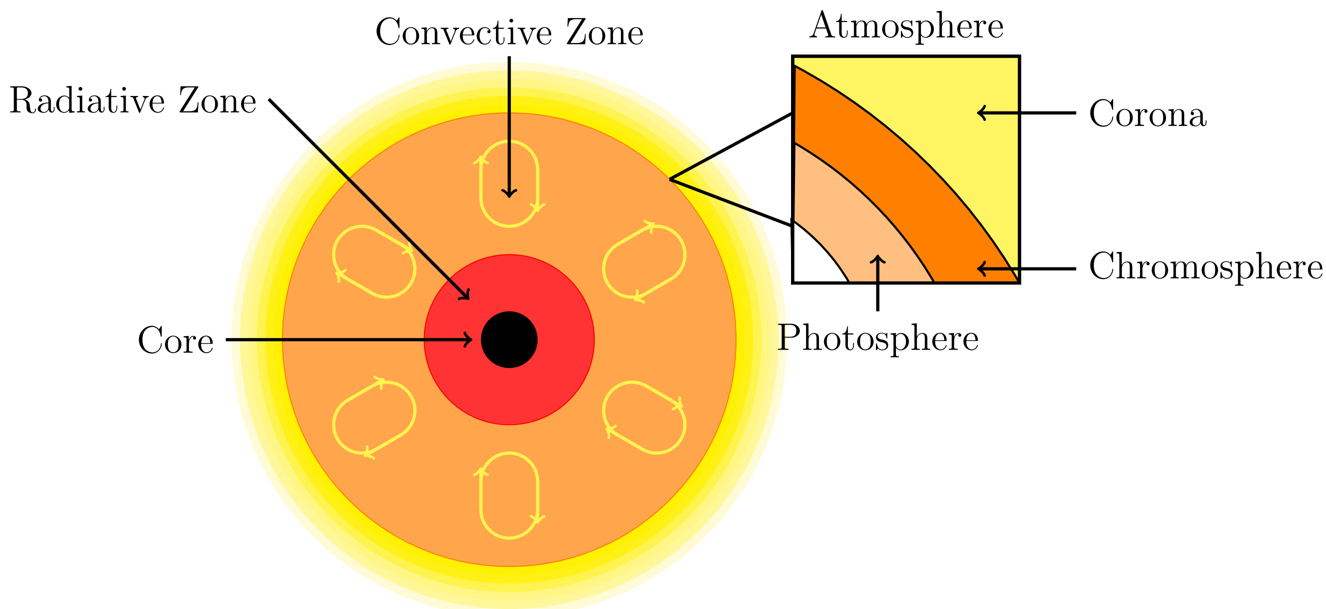


Figure 9.3: Model of the Sun (not to scale)

The Sun's blackbody spectrum must then travel through its atmosphere, which has two layers, the chromosphere and the corona. The corona, the outermost layer, so tenuously extends far out into space that it is rarely noticed (e.g., during a solar eclipse or by a special solar telescope). However, like the atmosphere of the Earth, the chromosphere absorbs some of this light, forming the absorption lines of the Fraunhofer spectrum.

In the same manner as you did for "Astronomical Spectroscopy I", we can use these absorption lines to determine the chemical composition of the Sun!

Laboratory Procedure

Identifying Fraunhofer Lines

Using the reference table below, you will be able to match the wavelength of the absorption lines in the solar spectrum.

Using the lab software:

- Simply press `Generate Spectrum` to see an example of a mock spectrum of the Sun. You will be able to identify a few absorption lines and identify the chemical elements that produce these lines.
- You can click-and-drag over a specific region to zoom in and double-click to zoom out

Write down the wavelengths of each of the lines that you are able to identify. Using the information in Table 9.1, write down the Fraunhofer identification of those lines and the elements that produce those lines.

Wavelength (nm)	**Element or molecule**	**Comment**
393	Ca	Fraunhofer's K Line
397	Ca	Fraunhofer's H Line
410	Hδ	
423	Ca	
431	Fe	Fraunhofer's G Line
434	Hγ	
438	Fe	
486	Hβ	Fraunhofer's F Line
517	Mg	A triplet line
527	Fe	Fraunhofer's E Line
590	Na	Fraunhofer's D Line
656	Hα	Fraunhofer's C Line
686	O_2	Fraunhofer's B Line

Table 9.1: A listing of the more conspicuous Fraunhofer lines, together with the chemical elements or molecules from which they arise

Blackbody Radiation

In this experiment, we will determine the blackbody spectrum by matching curves of different temperatures, a simplified approach to the way real astronomers can determine such temperatures.

Using the lab software:

- Input the desired wavelength into the box at the top of the page. Press `Plot` and a blackbody radiation curve corresponding to that peak wavelength will appear in the plot.
- Use the slider to adjust the green curve to find the temperature that best fits the blackbody emission that you just generated.
- Rinse and repeat for all the desired wavelengths.

Absorption Spectra

As you learned from the "Astronomical Spectroscopy I" experiment, photons can be absorbed by an electron in an atom only if they have the right energy to make the electron jump from its original level of energy to one of the discrete higher levels.

In this experiment you will be sending photons of different energies (given in electron volts or eV) through a gas. Depending on their energies, the photons can pass through the gas or can be absorbed by the atoms in the gas.

Remember that the energy of a photon E_{photon} is related to the wavelength λ. For each value of energy of a photon there is an associated wavelength. The exact relationship is:

$$E_{\text{photon}} = \frac{hc}{\lambda}$$

h is 4.136×10^{-15} eV s, c is the speed of light 3×10^8 m/s.

Using the lab software:

- Your instructor will assign you a mystery gas, use the menu to select which one the simulation uses.
- Use the slider to set the photon energy to 1.6 eV.
- Input the number of photons to send through the gas (we recommend you use 15-20). Keep the number of photons constant for the rest of the experiment. Click on `Start!`. Once the simulation ends for the 1.6 eV energy, record in the provided table the energy, color, wavelength and number of photons detected.
- Increase the energy of the photons by 0.1 eV to 1.7 eV and repeat the simulation. Continue with the process increasing the energy in steps of 0.1 eV until you complete the table.

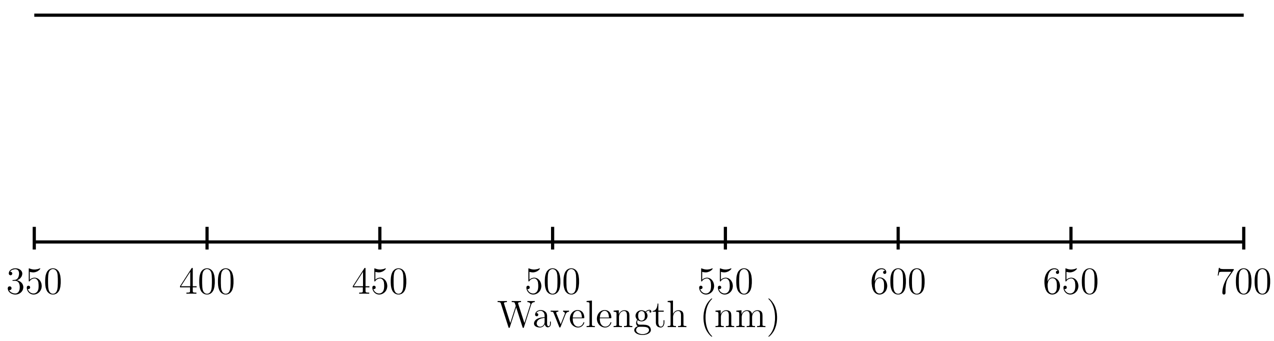
Astronomical Spectroscopy II Worksheet

Name: ______________________________ **Date:** ________________ **Section #:** ________

This worksheet should be filled out as you work through the experiments. Your instructor will either collect it or ask you to upload it to Canvas. Please read the accompanying lab and instructions carefully. Show your calculations and write in complete sentences when appropriate.

Identifying Fraunhofer Lines

1. Use the blank spectrum outline below to draw in the Fraunhofer lines that you can identify, being careful to place them at the appropriate wavelengths. Write the wavelengths on the drawing. Finally, make sure you take note of which line configuration you're using



Graph 9.1

2. Table 9.1 has a listing of of the more prominent Fraunhofer lines, with their chemical identification. Using the table, identify each of the lines that you draw, writing their chemical symbol.

3. Where on the Sun does the continuous spectrum arise? Why?

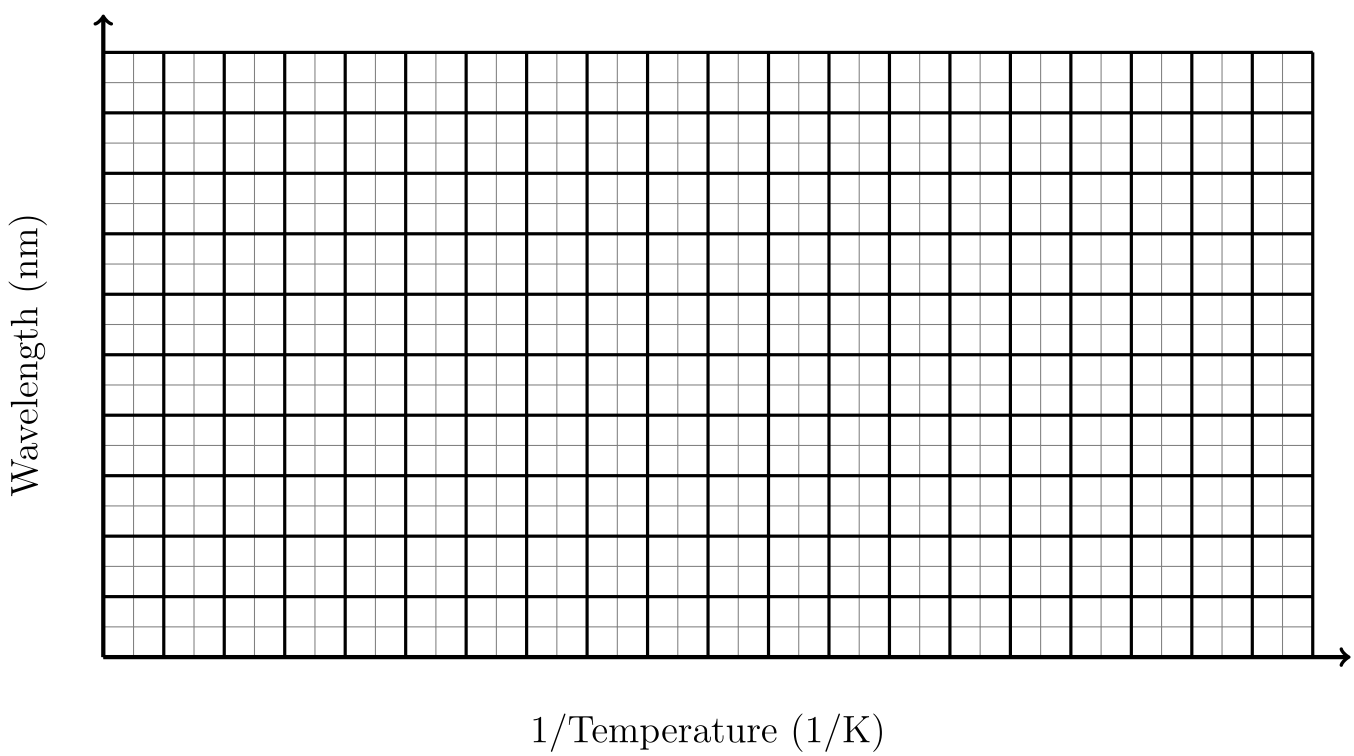
4. Where on the Sun do the Fraunhofer lines arise? Why?

Blackbody Radiation

For this next experiment, we will reconstruct Wien's Law

Data Table 9.1

Wavelength (nm)	**Temperature (K)**	**1/Temperature (1/K)**
300		
350		
400		
450		
500		
550		
600		
650		
700		



Graph 9.2

5. Draw a best-fit line for the data points. What is the slope, using rise over run ($\Delta y/\Delta x$), of this best-fit line?

6. Ask your instructor for the actual value of b from Wien's Law. Calculate the percent error of b to ascertain the accuracy of the best-fit line. What is a potential source of error?

7. Numerically solve for the peak wavelength of the Sun (given that temperate of the photosphere of the Sun is 5,800 K) using the true form of Wien's Law.

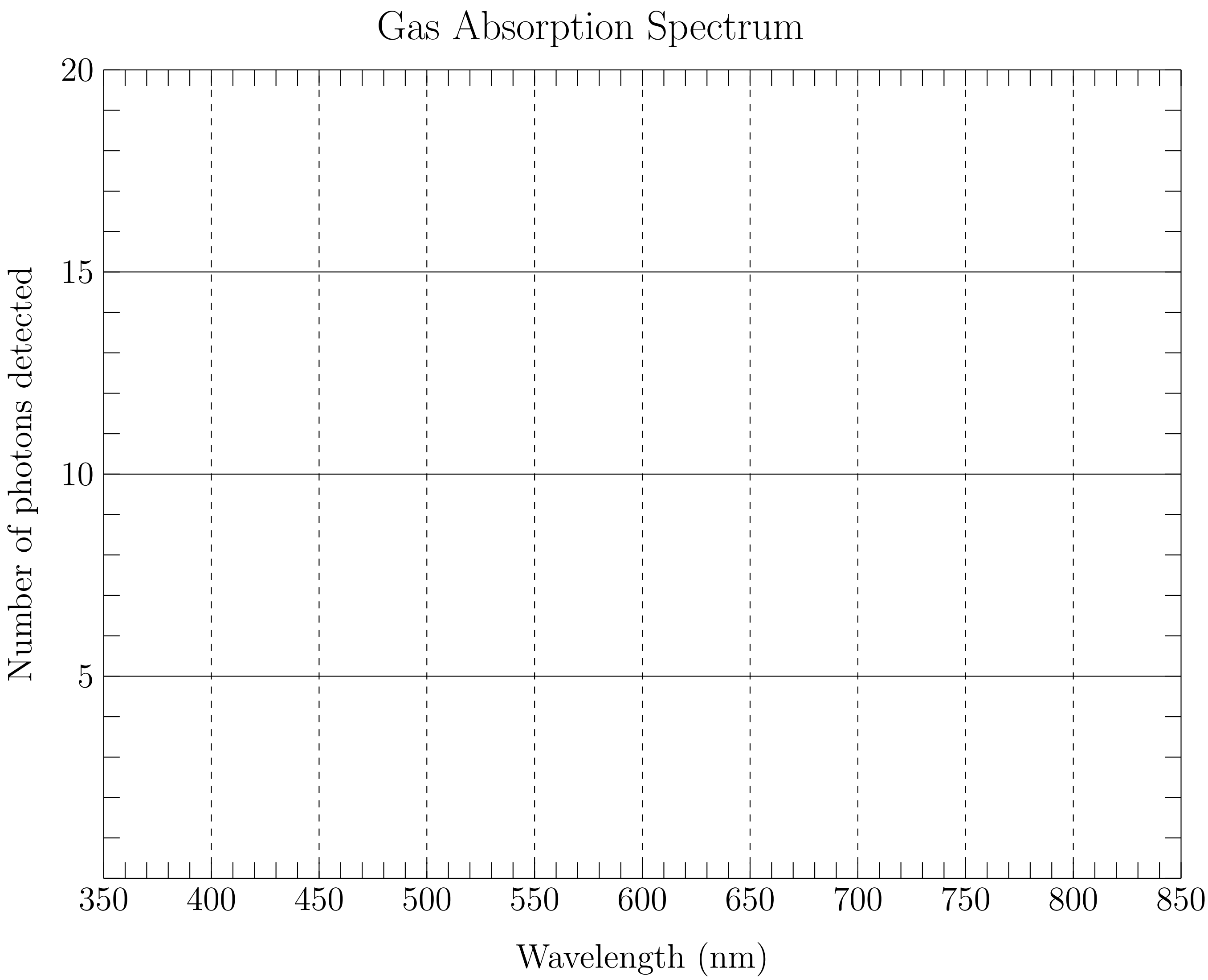
Absorption Spectra

For this next part, we'll be examining the absorption lines that are produced by a cool gas being backlit. Select whichever element you like, but make sure the denote which element you used.

Mystery Gas Used: ____________

Data Table 9.2

Energy (eV)	Wavelength (nm)	Color	Photons Detected
1.6			
1.7			
1.8			
1.9			
2.0			
2.1			
2.2			
2.3			
2.4			
2.5			
2.6			
2.7			
2.8			
2.9			
3.0			
3.1			
3.2			
3.3			
3.4			
3.5			



Graph 9.3

8. Look at the spectra for the mystery gases. What is your mystery gas?

Applications of Astronomical Spectral Analysis

Guidelines for Writing the Report

In this report you will summarize the results from two experiments dealing with spectroscopy: "Astronomical Spectroscopy I" and "Astronomical Spectroscopy II". An important part of this report is applying what you learned from these two experiments and also making use of concepts we learned from other experiments.

You must submit your own work. You can collaborate and exchange ideas with your lab partners, but do NOT copy and paste, your work must be entirely your own. Your submissions will be checked by Turnitin.

In "Astronomical Spectroscopy I", the key concepts you learned about were:

- Learned about the basic principles of spectroscopy, including Kirchoff's Laws, and applications of spectroscopy in astronomy, like identifying elements based on their emission lines.

In "Astronomical Spectroscopy II", the key concepts you learned about were:

- Applied the concept of spectral line identification to identifying absorption lines in the Sun's spectrum, which correspond to chemical elements in the Sun.
- Used blackbody curves to reconstruct Wien's Law, the relationship between the temperature of a body and the wavelength that it emits.
- Learned how photons interact with matter, i.e. that photons of different energies are absorbed by a gas of a particular element, which explains why certain emission lines occur uniquely for each element.

Your report should contain all of the following sections, in this order, with **headers**

1.	Abstract	(5 points)
2.	Introduction	(10 points)
3.	Discussion of Physical Concepts	(10 points)
4.	Methods and Purpose	(20 points)
5.	Data/Results	(10 points)
6.	Discussion	(20 points)
7.	Applications – Design an experiment	(10 points)
8.	Conclusions	(10 points)
9.	Original Data Sheets attached	(5 points)
Total		100 points

Since this report compiles different labs, read through this lab guide carefully. If you're unsure of the requirements of this report, please ask your instructor for clarification as soon as possible.

How to Address Each Section:

Abstract (5 points)

An abstract is just a brief overview/summary of the work. This section should be a very brief overview of the what we're doing and what we achieved. In general, this section should be ∼150 words, but you won't be held to exactly that number. Be succinct and get your point across.

Use numbers as a method of discussing results in the abstract very sparingly. Instead, opt for a more generalized discussion of the results. For example, instead of listing data points describe the trend they follow (linear, exponential, etc..)..

Introduction (10 points)

Give an introduction into the history of spectroscopy and its relevance in modern astronomy. Discuss how each experiment performed showed the importance of spectroscopy in astronomy research.

Focus on the big picture of spectroscopy - what are some cool astronomy problems that can be solved using spectroscopy? Then introduce the reader to the basics of spectroscopy. Leave the specifics to the summary of physical concepts section.

Discussion of Physical Concepts (10 points)

Discuss the concepts introduced and lab and explored within the experiments. These concepts only require one equation this time, but be sure to explain the concepts in the context of what we learned about in class.

- What are the three Kirchoff's Laws? Give some examples of objects that would have spectra classified by each law.
- What is blackbody radiation? How is it related to a continuous spectrum? What is Wien's Law (equation)? How does Wien's Law describe a blackbody?
- What is Bohr's model of the hydrogen atom? How is it related to emission and absorption lines?

Methods and Purpose (20 points)

Explain the methods your group used during the experiments. This should not be a paraphrase of the lab manual procedures. Explain the purpose of each experiment - what did the experiment reveal about spectroscopy? Think about why you did each experiment (not just that you had to do them because the manual said so).

- What instruments were used in each lab (i.e. prism/spectrometer/computer, types of lamp and filters, method of wavelength/color identification)?
- What kinds of spectra did you view and what kind of information did you record about the various spectra?
- What were the main takeaways from each of the computer experiments? What are they supposed to represent physically?

Data/Results (10 points)

Type/computer generate all tables and plots with the data collected during class. Make sure you are using the appropriate plot type (scatter) for the given data and that your data points are actually represented on the plot. Also be make sure that your tables are labeled with the correct units.

Describe the results that you found. What is your figure/table showing? What is the relationship between the two variables (i.e., linear, exponential, etc)? If there is a quantitative trend (i.e., best fit line or theoretical relation) describe it here. Finally, connect your results back to the bigger picture. Do not interpret the results, leave that for the later sections, just clearly state what you found (in full sentences).

Tables

1. (Spectroscopy I) Table of hydrogen lines observed with the spectrograph (Question **??** from the Spectroscopy I worksheet). Include names (i.e. Hα), measured wavelength of the emission line (nm), actual wavelength of the line (nm), and percent error comparing measured with actual wavelength.
2. (Spectroscopy II) From Question 2 in the Spectroscopy II worksheet, create a table of the of absorption lines in the spectrum you observed. Include the measured wavelengths of the absorption lines, Fraunhofer denominations of the lines (if there is one), the chemical element producing the lines and the wavelengths of the lines. Make sure to state which line configuration you used.
3. (Spectroscopy II) Data Table 9.2 of energies, wavelengths, colors, and number of detected photons for the absorption spectra. Also make sure to mention which mystery gas you used.

Plots

1. (Spectroscopy II) Graph 9.2 – wavelength versus the inverse of temperature for Wien's Laws
2. (Spectroscopy II) Graph 9.3 – plot the # of photons detected vs. photon energy or wavelength.

Discussion (20 points)

Error Analysis (10 points):

- How accurate are your wavelength measurements? Discuss the percent error of your calculations.
- How accurate is your measured constant in Wien's Law?
- What are possible sources of error in these experiments? Remember to consider the tools and techniques used for the experiments. Errors are not math mistakes/rounding precision, nor is it (typically) valid to suggest the rulers/lab equipment are manufactured incorrectly.
- How would the errors you identify impact the results of the experiment?

Questions (10 points total):

1. (4 points) Explain, in terms of Kirchoff's Laws, how the Sun has absorption lines on top of a continuous spectra. Consider how each component of the spectra (continuous and absorption lines) are produced by the Sun.
2. (2 points) What is the difference between the dispersion of light by a prism and the dispersion of light by a diffraction grating? What color is dispersed the most/least by each method?
3. (2 points) Why does each element (like hydrogen, sodium, neon, etc.) have a unique spectra, different from any other element?
4. (2 points) The normal human eye is most sensitive to light with wavelengths around 555 nm. Why?

Applications – Design an experiment (10 points)

With our understanding of telescopes, CCD cameras, and spectroscopy in hand, we are now equipped to do real science. In this section, we will design an experiment to determine the chemical composition of a star with an apparent magnitude of +14. Describe the procedure by which you will accomplish this, justifying the tools and methods used. Use the following points to guide your thinking, but be sure to extend your thinking beyond these points.

- Considering the brightness of this star - can we see it with our eyes?
  - What is the minimum size aperture we need to view this star and collect its light?
- What is a method to identify the chemical composition of a star from its light?
  - What tool(s) can we use to achieve this?
- How can you identify the various features of a spectrum and the elements responsible for those features? Is there some sort of calibration you can do with our detector prior to the experiment?
- What are some potential problems you can run into with your experiment design?

Conclusions (10 points)

Summarize the basic principles of spectroscopy and why spectroscopy is important in astronomy. Discuss how the experiments you conducted gave you an understanding of spectroscopy and how the basic activities done during class can be expanded into actual research being done.

Attach Data Sheets at the End (5 points)

Attach the measurement you made from the lab manual. This can either be in a separate pdf file or at the end of this pdf.