Spectra

Introduction

Much of what astronomers have learned about the solar system has been determined through observations of electromagnetic radiation – light. High density objects emit thermal, or blackbody radiation, and light is emitted over a wide range of wavelengths. Different elements emit and absorb light at different wavelengths; these are referred to as emission or absorption lines. This allows astronomers to determine the composition of various objects in the universe. In addition, the fact that light is also emitted/absorbed at a specific wavelength allows astronauts to determine the velocities of objects, through the use of the Doppler shift. The purpose of this lab is to (a) study the properties of light emitted by various lightbulbs, (b) understand how transmission filters work (c) examine the emission lines in hydrogen and verify that the observed wavelengths agree with the theory and (d) use your observations of emission lines from an unknown gas to identify the gas.

Spectral Line Theory

Electrons orbiting a nucleus have an electric potential energy. The energy associated with a single electron is quite small, and is usually measured in units of electron volts or eV for short. An electron in an atom can only have particular energies. That is, the energy of an electron in an atom can only take on certain discrete (or quantized) values. The possible energy levels of the electron in hydrogen are shown below.

\[
\begin{align*}
\text{ionization level} & \quad 13.606 \text{ eV} \\
\text{Level 4} & \quad 12.749 \text{ eV} \\
\text{Level 3} & \quad 12.088 \text{ eV} \\
\text{Level 2} & \quad 10.199 \text{ eV} \\
\text{(ground state)} & \quad 0.000 \text{ eV}
\end{align*}
\]

Figure 1: Energy levels for the electron in a hydrogen atom.
The lowest possible energy that an electron can have in an atom is called the ground state and energies of the other allowed energy levels are given with respect to the ground state (i.e., level 2 in the hydrogen atom has an energy 10.2 eV higher than the ground state). When an electron moves from a high energy state to a lower energy state, the energy goes into emitting a photon of light. As the electron energy levels are quantized, so to is the energy of the emitted photon. Similarly, if a photon with the correct energy hits an atom, it will be absorbed by the electron, causing the electron to jump to an higher energy level. However, if the photon does not have exactly the correct energy, then it cannot be absorbed by the electron and will pass through the atom. This leads to absorption lines in spectra.

The energy \( E \) of a photon is given by the formula

\[
E = \frac{hc}{\lambda}
\]

where \( \lambda \) is the wavelength of the photon, \( h \) is Planck’s constant and \( c \) is the speed of light. Thus, when an electron in an hydrogen atom goes from energy level 3 to level 2, it emits a photon of light with an energy of \( 12.088 \text{ eV} - 10.199 \text{ eV} = 1.889 \text{ eV} \). Using equation (1), this implies that the photon has a wavelength of 656.3 nm, which to our eyes appears red. This line is referred to as the H\( \alpha \) line.

Hydrogen is the simplest possible atom, with only one proton. As you might guess, as you change the number of protons, you change the electric potential energy of the electrons surrounding the nucleus and so the allowed energy levels change. This leads to a change in the wavelength of light which is emitted or absorbed as electrons go from one energy level to another. Thus, each element has a unique set of emission/absorption lines in their spectra. Observations of these lines allows us to determine what elements are present in an object.

**References**

You should review sections 2.3 and 2.4 in your textbook (‘Investigating Astronomy’) before coming to the lab.

**Apparatus**

The equipment used in this laboratory consists of a tungsten light source, lightbulbs, a gas discharge tube, and a digital spectrometer. A computer is used to record and view the data. The digital spectrometer is shown in in Figure 2 and a schematic illustration of how it works is shown in Figure 3.

In the gas discharge tube (Figure 4), an electric current is passed through the glass tube. Electrons absorb some of this energy and jump to a higher energy level. Photons are emitted when these electrons fall back to a lower energy level. During operation, the gas discharge tubes become hot. **Do not touch the glass tubes with your bare hands. Wear the provided gloves when changing glass tubes.**
Figure 2: The digital spectrometer. The blue cable contains an optical cable which directs the light to the digital spectrometer located in the blue box. The data is then sent to a computer using the white cable. **The blue optical cable is very fragile and can easily break. Be careful handling the cable and DO NOT BEND IT EXCESSIVELY.**

Figure 3: Schematic illustration of the digital spectrometer. Light from the optical cable (not shown) enters the spectrometer through the 50 µm slit at the top, bounces off a mirror and then hits two diffraction gratings where it is split into different colors. The colored light then hits a CCD array which digitally records the intensity of light of different colors. This information is sent to the computer and displayed on the screen.
You will also examine the spectra of a common incandescent light bulb, two compact fluorescent bulbs and a halogen (tungsten) lamp, all of which are commonly used. The incandescent lamp is contained in a blue cylinder, (Figure 5). Both the incandescent lamp and the halogen lamp use tungsten filaments.

**Procedure**

In order for light to enter the spectroscope, you need to uncap the fiber optical cable. Be careful not to touch the end of the cable since dirt and finger/skin oil will affect your measurements. To have light enter the spectrograph, the fiber cable will need to be very near to the light source.

To see the output of the spectrograph, a computer runs a software package called Quantum. This will be running when the lab starts. The TA will show you how to use the software. The print symbol on the top right hand side of the top icon bar allows you to print the screen at any time and this does not interfere with continuous data collection.

1. Turn on the incandescent light bulb in the blue tube by connecting the power cord to its back end. Carefully remove the optical cable from its stand and insert the optical cable into the end of the lamp and examine the spectrum of the light bulb. Incandescent light bulbs emit light because a tungsten filament in the bulb is heated and emits light like a blackbody.

   You can adjust the observed spectrums plotted intensity by adjusting the integration time (try 30 ms). You can also adjust the quality of the plotted spectrum (i.e., stop it from changing
so much) by changing the number of scans (try 5). Both these values can be changed by entering numbers in the on-screen boxes for integration time and number of scans.

To color the plot so as to make longer wavelengths appear red and shorter wavelengths blue, click on the icon at the top of the screen, second icon from the rightmost one. (If you hover the cursor over it, it should say color.)

Use the camera icon at the top of the screen to take a snapshot of the spectra this will draw a line for the current spectra which you can then compare to the spectra of the other light bulbs.

2. Remove the optical cable from the tube, clamp it gently in the stand, and position it close toward the halogen lamp. If it not already in a light socket, it is a clear light bulb in the cardboard box. Halogen lamps get very hot! So be careful if you need to unscrew it.

Examine the spectra and compare it to the incandescent light bulb. Record a written description of the spectra on your data sheet, discussing the similarities and differences between the two spectra. Halogen lamps also emit light because a tungsten filament is heated and emits like a black body.

**Question 1:** Based upon the properties of the spectra, what can you conclude about the relative temperatures of the two tungsten filaments in the halogen and incandescent light bulb? Explain your reasoning.

3. Insert the red liquid filled tube into the tungsten lamp and examine the resultant transmission spectra. Record on your data sheet a description of the transmission spectrum. This red tube acts in a similar manner to filters astronomers use when they observe stars and planets.

**Q2:** By referring to the observed properties of the transmission spectra and using your knowledge of the emission from blackbodies, describe what astronomers would see if they observed Mars (reddish-orange in color) and Neptune (light blue) through red and blue filters.

4. Examine the spectra of the two compact fluorescent light (CFL) bulbs. Note that it can take a few minutes for the light output to stabilize from a CFL, so turn on the CFL and wait a few minutes before observing their spectra. Record a written description of the CFL spectra, commenting on how it differs from the spectra emitted by a standard incandescent bulb.

**Q3:** How do the spectra of the two CFL bulbs differ from each other? The CFLs were purchased in a standard hardware store, and one CFL is labeled as having a color temperature of 5000K and the other is a 2700K bulb. The color temperature of a light source is the temperature of a black body that has the same color of the light source. Which spectra belongs to the 5000K color temperature bulb? Explain your reasoning.

**Q4:** What is the peak wavelength of emission of a 5000K and 2700K blackbody? Given the observed properties of the CFL spectra, do you think it is reasonable to label these CFLs as having color temperatures of 5000K and 2700K?

5. Examine the spectrum of the Hydrogen emission lamp. You should easily see a red and green line. The red line corresponds to an electron dropping from energy level 3 to energy level 2, and is called Hα. The green line corresponds to the 4–2 transition and is called Hβ.
By changing the scale on the graph and integrating for longer periods, you should see one or two violet lines.

6. Measure the wavelength of each emission line (clicking the mouse reports the wavelength; you can change the scale of the graph to zoom into different regions). Record the wavelengths of each line in a data table, designating each line with its color. Estimate the error in your measurement.

**Q5:** How did you estimate the error in your measurement?

7. Using the observed wavelengths, compute the energy of the photon $E$ for each line.

8. Compute the theoretical wavelengths and energies for the $H\alpha$ and $H\beta$ lines (from figure 1 and equation 1) and compare them to the experimentally measured values. Compute the percent deviation of the experimental values from the theoretical values.

**Q6:** Determine the energy level transition associated with the violet line(s) you observed. Explain your reasoning.

**Q7:** Why do you not see the transitions to the $n = 1$ level?

9. There are discharge tubes containing other gases available in the lab. Pick one of these unknown gases and record the tube number on your data sheet. Measure and record the wavelengths of at least 3 strong lines in the spectrum (in the same manner that you did for hydrogen) and record this data.

The computers in the lab have a java applet running which shows the emission line spectrum for a number of elements. Clicking the mouse in the displayed spectrum will display the wavelength (in nm) at that point. Using the applet and your measurements, identify the unknown gas. Record on your data sheet how you identified the gas.

**Writing up the Lab**

Make sure your names are on your data sheet, and have the TA sign your data sheet before you leave the lab. If you hand in individual lab reports, one of you will hand in the original data sheet, while the other student can hand in a photocopy.

**Lab reports are due one week after you complete the lab.**

Follow all of the guidelines for lab reports which are posted onto Canvas. Aside from your data sheets, you must use complete sentences throughout your report.

Lab reports are to be put into the A1 box which are located to the left of the main stairs when you enter Wilder Lab.
Pre-Lab Questions

You must answer the following questions before you come to lab. **Hand in your answers to the TA at the start of your lab section.**

The answer to all these questions can be found in your textbook and the lab itself. The pre-lab questions will account for 15% of your lab grade. By reading the lab and thinking about it in advance of performing the lab, you will find that the lab makes much more sense when you start collecting data.

1. What are spectra?
2. How should you handle the glass discharge tubes and the optical cable?
3. Using the information provided in the **Theory** section of this lab and equation (1), calculate the value of $h$ (Planck’s constant). Look up the value of Planck’s constant and verify that you did the calculation correctly. Remember to show your work, and keep significant figures in mind.
4. What do you expect to learn from this lab?