ASTR 101

Exploring the Night Sky

Lab 2: Spectra of Gases and Solids

Date of lab: ______________________

Report due date & time: ______________________

1 Objective

This lab exercise focusses on the generation and measurement of atomic spectral lines, and their applications in astronomy.

This lab exercise corresponds to the course material presented in Chapter 4 of the textbook, and is intended to help you understand the nature of light and the spectra of elements which make up stars and other astronomical objects.

2 Introduction

Due to the quantum nature of light, it behaves simultaneously like a wave (defined by quantities such as wavelength, frequency and speed), and like a stream of massless particles, or packets of energy – called *photons*. For the sake of this lab exercise, we will only be focussing on the wavelike nature of light.

The wavelength of a wave is the distance between consecutive "peaks" or "crests". The wavelength of visible light is short, and is usually measured in nanometres ($1\,\mathrm{nm} = 10^{-9}\,\mathrm{m}$) or angstroms ($1\,\text{Å} = 10^{-10}\,\mathrm{m}$). The wavelength of light determines its colour, as perceived by the eye. Red light has a wavelength of around 6500 Å, green light of about 5000 Å, and blue light of about 4500 Å. The human eye responds to wavelengths in the range of about 4000-7000 Å. A given wavelength of light corresponds to a particular energy for the photons; higher energies have shorter (bluer) wavelengths.

A spectrum (plural *spectra*) is the measurement of the relative intensity of light at different wavelengths (or energy). Broadly, there are three types of spectral features:

- Continuum: A spectrum with smoothly varying intensity across a continuous mix of wavelengths (as opposed to large excesses or deficits of intensity at particular wavelengths) is a *continuum spectrum*. In Physics, a continuum spectrum from an ideal source is also referred as a *blackbody spectrum*. An object that is a blackbody – stars are nearly perfect blackbodies – has a continuum spectrum with a broad peak in intensity. The overall intensity of the source increases sharply with increasing temperature (Stefan-Boltzmann law). Also, with increasing temperature, the wavelength where the intensity of the spectrum is highest moves to shorter wavelengths (Wien's law). Hotter blackbodies are always bluer, and for two otherwise similar blackbodies, the hotter one will be brighter.

- Absorption line: An atom is made up of a nucleus surrounded by electrons. Each electron occupies an energy state, and to be in a particular state the electron must have the exact amount of energy corresponding to that state. Electrons can move from a low energy to a high energy state, but to do so must gain the difference in energy between the two states. The missing energy can come from a photon of the exact energy (and so exact wavelength) corresponding to the energy difference between the two states. Therefore, when light passes through a gas, the electrons in the gas absorb many photons of the same wavelength. This removes radiation of a certain wavelength from the spectrum, so there is a sharp dip in intensity or *absorption* at that particular wavelength. This can appear as a dark bar on a continuum spectrum.

- Emission line: Electrons can also move from a high energy to a low energy state, but must lose some energy by emitting a photon to do so. This can be the source of emission of many photons of the same wavelength, so there is a sharp peak in the intensity at that particular wavelength. This can appear as a bright *emission* line over a faint (or non-existent) continuum. The spectra from the discharge tubes which you will be observing for this lab exercise are emission spectra.

Every type of atom – every element – has a different set of electron states with different energy spacings between them. This means that every element has a *unique and distinct* set of emission/absorption lines. Therefore, by observing which lines are present in light coming from stars or interstellar gas, astronomers determine which elements are present, and thus understand the detailed chemical make-up of these extremely distant objects without ever needing a sample from them! While chemists need samples to do their chemical analysis, astronomers do their chemical analysis just using the light collected by their telescopes!!

Astronomers use the relative strengths of the spectral lines, measured with their *equivalent widths* in the spectrum taken from a mixture of elements to estimate the relative amounts of different elements in that mixture. We thus accurately know the chemical make-up of the Sun, other stars, interstellar medium, distant galaxies, and so on. In addition, *Doppler effect* due to the motion of a gas either toward or away from the observer, causes a uniform shift in the wavelength of all spectral lines from that source; this can be used to measure the speed of the object, e.g., stars, gas, galaxies, etc. This Doppler effect also broadens the spectral lines so that by measuring the width of the spectral lines, we can estimate the internal motion or *turbulence* present in the gases. We can use these same techniques to soon be able to see what elements are in the atmospheres of planets around other stars by observing their absorption lines, and thus perhaps see the first signatures of *life elsewhere in the Universe*! These are only a few applications of spectroscopy – spectrum measurements – in astronomy. *Spectroscopy*, the analysis of the spectra of elements is therefore an essential tool for an astronomer.

One way to observe a spectrum is to split up light from a source by wavelength so that different colours hit a detector at different locations for measurement. In this lab exercise, we will first look at the spectrum directly to get a visual effect. Splitting up light by wavelength can be done in several ways, for instance with water droplets in the air (rainbow), with a glass prism, or with a *grating* which has finely spaced, ruled lines. For this lab, we use such a *diffraction grating*, which is a special film of plastic on which there are 600 parallel lines accurately etched on every millimeter of the film.

3 Equipment

NOTE: All these will be shown in a demo video

- Hand-held diffraction grating, 600 lines/mm
- Simple spectrograph (camera with diffraction grating integrally mounted)
- Incandescent lamp, and fluorescent lamp
- Carousel with gas discharge tubes

4 Procedure

NOTE: The procedure for Parts I and II will also be shown in a demo video. High resolution images of all the spectra given here are also available on Brightspace. Download and use those for doing the lab exercise, and answering the questions for your lab report.

4.1 Part I: Visual observation of different types of spectra

Normally, for this part of the lab, we observe the spectra of different light sources using the handheld diffraction grating. Instead the spectra for different light sources and for different chemical elements have been recorded and are shown in Figures 1 – 4. Your TAs will explain these spectra during the lab class, and outline the lab work you need to complete.

For these visual observations, we have used four different light sources:

1. Incandescent lightbulb with varying input power.
2. Fluorescent lamp.
3. Gas discharge tubes:
4. Sunlight.

Further details of each type, and images are given below.

1. **Incandescent lamp with varying input power**:

   In the incandescent lamp, light is emitted by a tungsten wire heated by electricity to high temperature . The power input to the light bulb can be varied, so the temperature of wire may be increased or decreased. In order to study the spectrum of this light source, the light is passed through a diffraction grating and recorded with a camera in the spectrograph. In the case of the incandescent lamp, since the light source is a heated metal, we observe a *continuum* spectrum. The power input is set to a low value first, and the spectrum is recorded. The power input is then increased to its maximum, and the spectrum is recorded again. The two spectra shown below are for low and high power settings of the lamp. Compare the overall brightness of the two spectra as well as the colors seen in each.

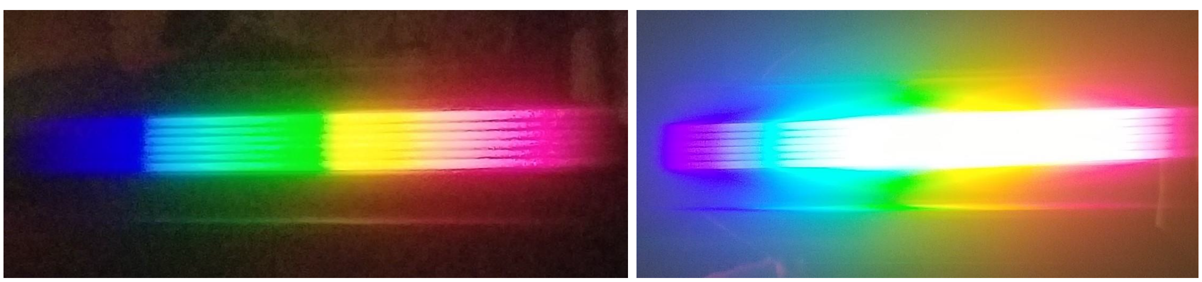

Figure 1: Continuum spectra from the incandescent lamp. Using the handheld diffraction grating, the spectra were photographed using a camera. The spectrum for the low power setting is shown on the left, and for the high power setting, on the right.

2. **Fluorescent lamp**:
   The fluorescent lamp is commonly used for household lighting, and shows an *emission* spectrum superposed on a continuum spectrum. In a fluorescent lamp, the atoms of a gas (common ones are mercury vapour, sodium vapour, and neon) in a glass tube are excited by electrical current. This causes the electrons in the atoms to jump between energy levels and emit light only at certain wavelengths which are typical for that gas. To convert this to useful light (either white or colored), which is pleasing to our eyes, the glass tube is coated with fluorescent coating (the white coating seen inside the glass). In Figure 2, the spectrum of a fluorescent lamp taken with the diffraction grating is shown.

3. **Gas Discharge Tubes**:
   In Figure 3, the emission spectra of six different elements are shown. Each one is produced by a gas

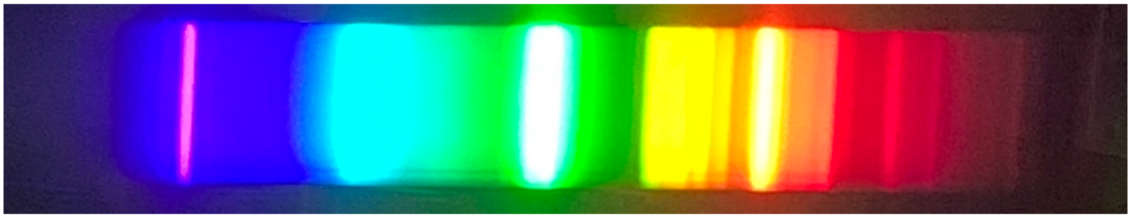

Figure 2: The spectrum from the fluorescent lamp shows a combination of an emission spectrum superposed on a continuum spectrum.

discharge tube mounted on a carousel. The atoms of gas are excited by electricity, similar to the fluorescent lamp. However, these discharge tubes do not have the fluorescent coating, so only the emission spectrum is observed.

4. **Sunlight**:
Sunlight is a good example of an *absorption* spectrum combined with a continuum spectrum. Deep in the core of the Sun, vast amounts of energy are produced by thermonuclear (= *fusion*) reaction. The energy radiates through the outer, cooler layers of gas in the Sun. The extremely high temperature (millions of degrees) in the core produces a continuum spectrum. As this light propagates out through the cooler gas, the gas absorbs light at certain wavelengths depending on the chemical composition of the cooler gases. This creates the absorption lines seen in the spectrum. Since the spectrum of each chemical element is unique, astronomers can estimate the chemical composition of the gas from these absorption lines. In addition, by measuring the depth and width of these lines, scientists can estimate how much of each element is present, the temperature, gravitational force and many other physical properties of the star. A solar spectrum is shown in Figure 4, in which many dark lines, corresponding to the absorption lines produced by many elements, are clearly seen.

Questions

(1) For the incandescent lamp, compare the two spectra corresponding to the low and high power. Explain in your own words the reasons for the differences you notice related to the overall brightness of both spectra, as well as the colors seen in each of them.

(2) In the spectrum of the fluorescent lamp, you can see a continuum spectrum as well as bright, colored lines corresponding to an emission spectrum. Explain in your own words what causes both types of spectra to be seen.

(3) At the following website, an online app is available to generate the spectrum of all the elements.

`http://chemistry.bd.psu.edu/jircitano/periodic4.html`.

Using this app, identify the six elements for which the spectra are shown in Figure 3. To help narrow your search, here is a list of possible elements (along with their proper chemical names as used in the periodic table):

- Argon (Ar)
- Hydrogen (H)
- Helium (He)
- Oxygen (O)
- Mercury (Hg)
- Nitrogen (N)
- Iron (Fe)

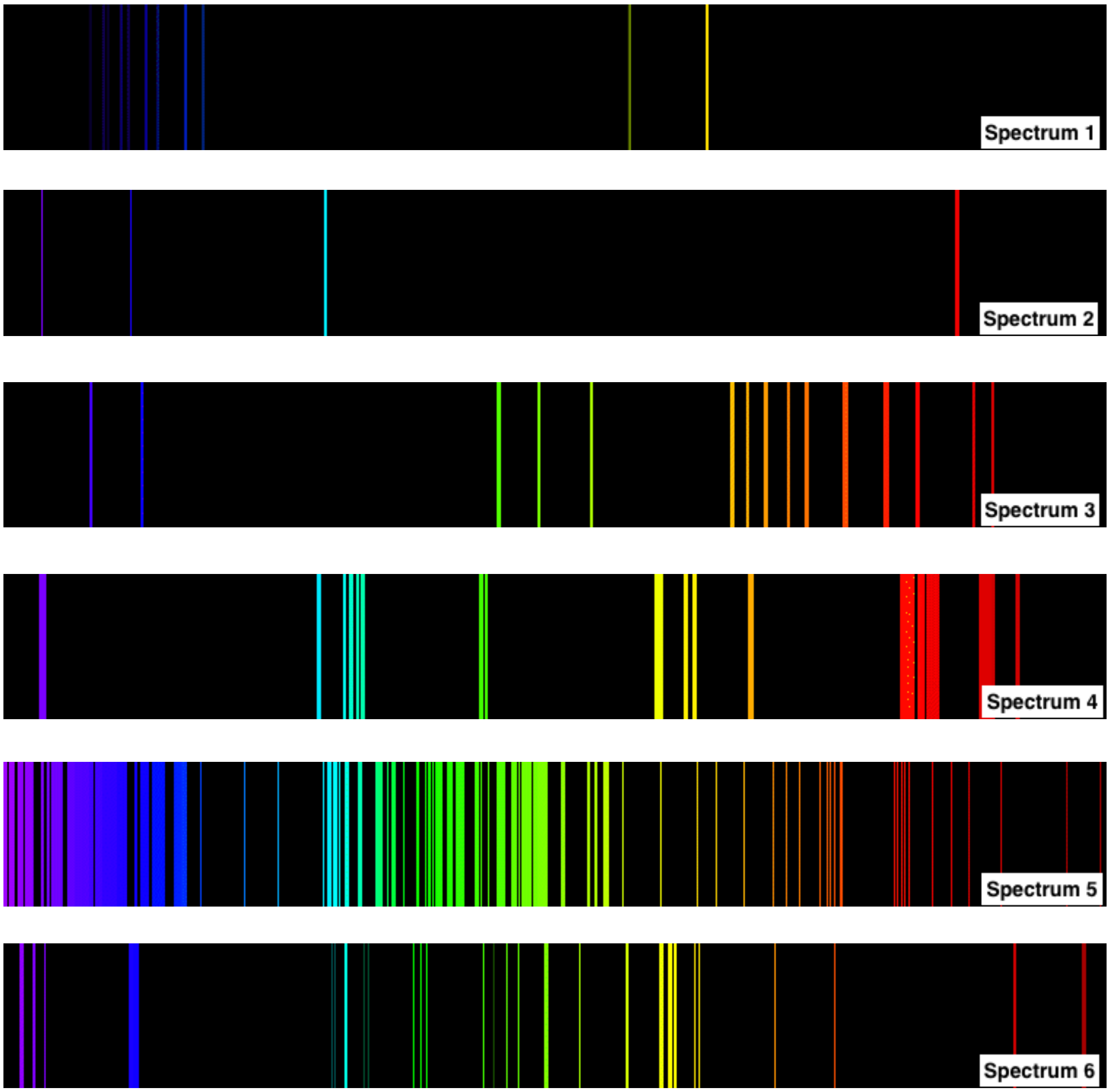

Figure 3: Emission spectra of six different chemical elements, in visible wavelengths. In visible light, blue lines are shorter wavelengths (= higher frequency, higher energy), green is intermediate, and red lines are longer wavelengths and lower energy. Notice the distinct spectral lines in each spectrum, which permits them to be clearly identified by their *spectral fingerprints*. Also refer to the high resolution versions posted on Brightspace to help with identification. (Note: These spectra were taken with a higher resolution spectrograph so that the spectral lines are clearly seen.)

- Uranium (U)
- Neon (Ne)
- Sodium (Na)

In your report, write a brief description of each spectrum (the colors of the spectral lines visible, their numbers, relative brightness, etc.). For each element, mention which spectral lines helped you identify the element (using their colors or positions in the spectrum).

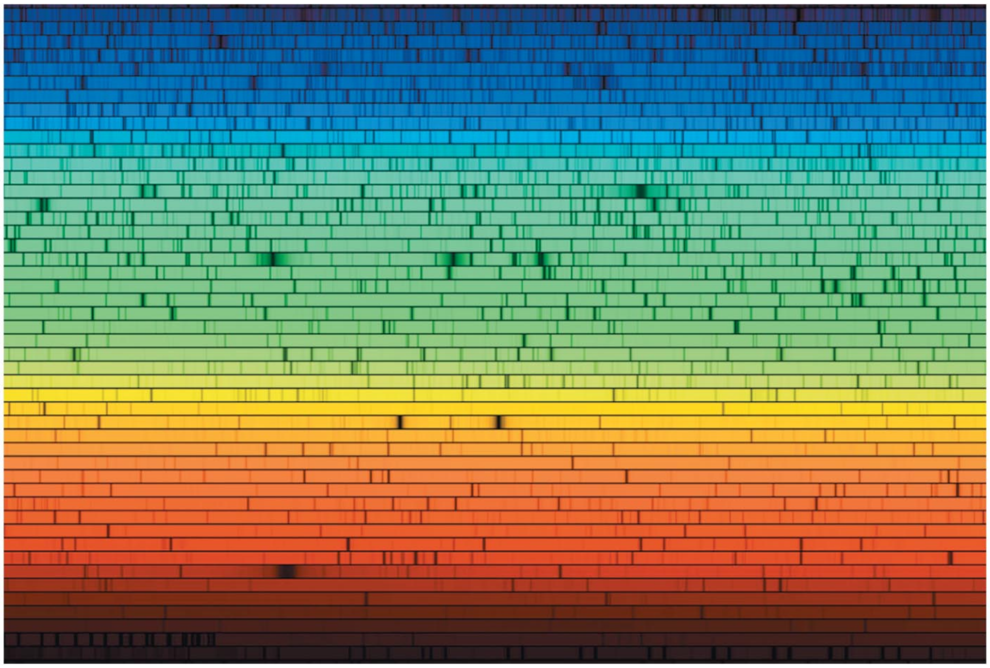

Figure 4: Solar spectrum showing the absorption lines of various chemical elements superposed on a continuum spectrum. Note: This high resolution spectrum is very long, so it has been shown row-by-row, starting with the short wavelength blue on top and proceeding to the long wavelength red in the rows at the bottom.

(4) From all the elements shown on the online app, choose one as your favorite chemical element. Using the online app, find out what its emission spectrum looks like and sketch and describe the spectrum in your report. If you do not have access to proper color pencils, mark the approximate locations of the lines and name their colors.

4.2 Applications of spectroscopy in astronomy

Here are a few questions designed to illustrate the applications of spectroscopy in astronomy. Some additional research is needed in order to answer these questions. For questions related to the blackbody spectra of stars, use the online app available at:
`https://phet.colorado.edu/sims/html/blackbody-spectrum/latest/blackbody-spectrum_en.html`

NOTE: To convert the wavelength shown in μm to Å, multiply by 10000.

Questions

(5) In the Solar spectrum, some of the absorption lines are broader and very clearly seen. With some research, find out the name by which astronomers refer to these lines, and write a brief description of these set of absorption lines.

(6) Name at least **two** chemical elements (=atoms) which cause these absorption lines in the Solar spectrum.

(7) What does the presence of these chemicals in the Sun tell us about its age and formation history?

(8) As discussed earlier, the color of a star is related to the peak wavelength in its spectrum, and indicates its temperature and other properties. Using the online app, find out the color and peak wavelength of the star, *Betelgeuse*, (in the constellation *Orion*), if the surface temperature of the star is 3500°K.

(9) Using some research, find out what type of star *Betelgeuse* is. Does the color your determined match the expected color of the star, based on its type?

(10) Using the online app, find out the color and peak wavelength of the star, *Sirius*, (in the constellation *Canis Major*), if the surface temperature of the star is 10000°K.

(11) What is the spectral type of the star, *Sirius*? Explain whether or not the color you determined matches the expected color based on the star's spectral type?

(12) If the spectrum of a star peaks in the green region of the visual spectrum, using the app, what would you estimate its surface temperature and peak wavelength to be?

(13) How can spectroscopy be used to learn about extrasolar planet atmospheres? What type of spectrum would be observed? What makes this type of observation particularly challenging?

4.3 Part II: Measuring the wavelengths of the helium and hydrogen spectra

In this part of the lab exercise, you will measure the relative positions of the spectral lines in the Helium and Hydrogen spectra, and thus determine their wavelengths. This is how astronomers identify the chemical elements present in stars using their unique '*spectral fingerprints*', and also measure many important physical properties.

Normally, in the lab class, you will use a *spectrograph* (grating + camera) to record the spectra and make these measurements. For the sake of this lab exercise, the spectra have been taken and provided to you. Download the high resolution versions available on Brightspace. Your TA will demonstrate how to make the measurements using GIMP.

NOTE: You will need to download and install GIMP on your computer for this lab exercise. Refer to the installation instructions on Brightspace.

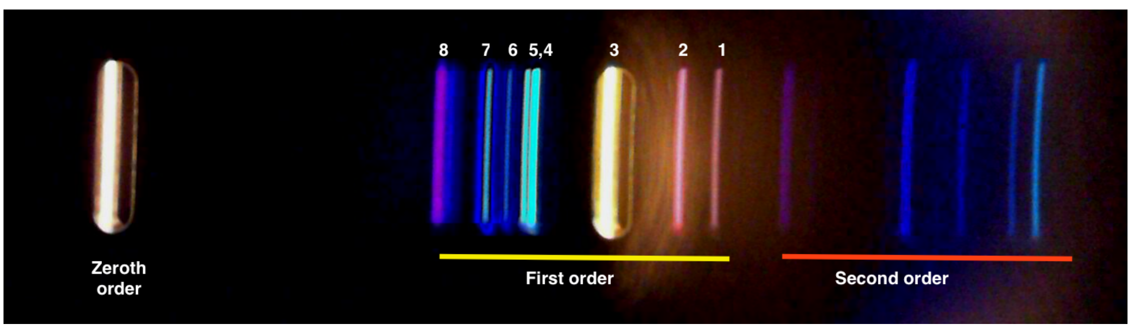

Figure 5: The Helium lamp spectrum with the eight principal spectral lines, listed in Table 1 shown annotated. The lines labelled 5,4 are two closely spaced blue-green lines indicated in Table 1. The zeroth order spectrum (reference point for measurements) and the faint second order spectrum are also shown.

We are given the wavelengths of the eight lines in the Helium spectrum shown in Figure 5. We will use these known wavelengths to calibrate the spectrograph. For this, using GIMP, measure the distance between *zeroth* order spectrum and the position of each of the eight lines in the spectrum. Notice that the red lines have longer wavelengths ($\sim$ 6678 Å) than the violet lines ($\sim$ 3889 Å). In GIMP, these distances are measured in units of *pixels* (= picture elements). Enter these measured distances in Table 1.

Next, plot the wavelengths of the Helium lines against their measured positions. Use the x-axis for the measured pixel positions, and the y-axis for the wavelengths (in Å). Use a proper range and scale of each axis so that all eight points can be clearly seen. You can use either a graph paper, or any software such as *Excel* to do this plot, and fit a straight line through the points. If you are using a graph paper, using a straight edge or a ruler, draw the best fitting straight line through the points representing the positions of the Helium lines you measured. If done properly, the straight line should pass through most of your points, showing that there is a good *linear relationship* between the wavelengths of the lines and their positions, and that you have measured their positions properly. Recheck your measurements if you see any noticeable differences. This relationship, called the *wavelength calibration* is specific to your spectrograph (grating + camera) setup and alignment.

We will next use this wavelength calibration to determine the wavelengths of the hydrogen lines. The hydrogen spectrum was recorded using the same spectrograph set up, so the calibration applies to it. First, open the Hydrogen picture on GIMP. Repeat the same measurement method as you used for the Helium lines. The Hydrogen lines are known by the Greek letters α (alpha, red), β (beta, blue) and γ (gamma, blue/violet), and their relative positions on the observed spectrum are as shown in Figure 6. The H_γ line is the faint, bluish line. Record your measurements in Table 2.

Using your graph, read the wavelength corresponding to the pixel values for the three Hydrogen lines by following their positions up to the calibration line, then reading across to the wavelength. Record your wavelengths in Table 2.

Table 1: Helium spectrum wavelengths and line positions.

Line number	Wave-length (Å)	Line position (pix)	Description
-	–		Zero order image
8	3889		Deep violet
7	4471		Bright blue-violet
6	4713		Faint blue-violet
5	4922		Blue-green
4	5016		Blue-green
3	5875		Yellow
2	6678		Pale red
1	7065		Dark red

Wavelengths and measured line positions of the prominent emission lines in the Helium spectrum. The line numbers match their positions shown in Figure 5. There are two, closely separated blue-green lines, as seen in Figure 5. *The colors given in the last column are only to act as guides, and may not exactly match your interpretation. If in doubt, ask your TA.*

Questions

(14) What are your measured wavelengths of the H_α, H_β and H_γ spectral lines?

(15) Physics data books give the wavelengths of the Hydrogen lines as 6563 Å for H_α, 4861 Å for H_β, and 4340 Å for H_γ. By how many Å do your measurements differ from these standard values? Are the

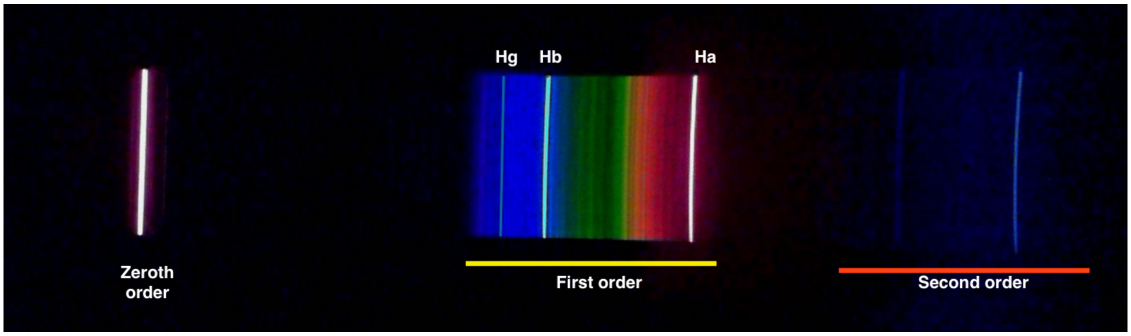

Figure 6: The Hydrogen lamp spectrum with the three principal spectral lines, listed in Table 2 shown annotated. The H_γ line, labelled Hg, is very faint. The zeroth order spectrum (reference point for measurements) and the faint second order spectrum are also shown.

Table 2: Hydrogen emission line measurements.

Balmer line	Line position (px)	Wavelength (Å)	Description
H α			bright red
H β			blue
H γ			faint blue

Measured line positions of the prominent emission lines in the Hydrogen spectrum. Use your wavelength calibration graph to find out the wavelengths of these lines. The colors given in the last column are only to act as guides, and may not exactly match your interpretation.

differences the same for all three lines? Of the three spectral lines, which line is the most discrepant from the standard value?

(16) In the analysis, we have not done a formal estimate of measurement uncertainties and errors in your results. However, in your own words, describe at least **two** sources of measurement uncertainties, and how they will impact your final results. Suggest possible ways by which these uncertainties may be reduced?

5 Suggested Websites

- Blackbody spectrum: `https://phet.colorado.edu/sims/html/blackbody-spectrum/latest/blackbody-spectrum_en.html`
- Spectra of chemical elements: `http://chemistry.bd.psu.edu/jircitano/periodic4.html`.
- Solar spectrum: `http://apod.nasa.gov/apod/ap131002.html`
- Spectra of stellar types: `http://apod.nasa.gov/apod/ap040418.html`