AY105 Lab Experiment #2
Spectroscopy

Purpose

This week, you will work on one of the most important components of optical astronomy -- spectroscopy. The main goal will be building your own spectrograph and using it to resolve the D-lines of neutral sodium (NaI D_1=5895.93 Å, $^2P_{1/2}$-$^2S_{1/2}$; and D_2=5889.96 $^2P_{3/2}$-$^2S_{1/2}$). You will also investigate how spectral resolution depends upon spectrograph design parameters such as grating (or prism) dispersion, slit width, camera lense, etc. Part A makes use of a grating as a dispersive element while Part B uses a prism for dispersion.

Unlike the first week, there are no drawings given to you in this week's lab instructions, nor is the equipment and its setup described in as much detail. You are learning how to figure things out yourselves!

Pre-Lab Work

- Read the entire lab! Figure out what equipments you have on the table. TRY NOT TO TOUCH THE SURFACE OF GRATINGS EVEN WITH GLOVES.
- Review the spectroscopic concepts such as grating ruling and grating blaze angle, "order" of light, etc. (https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=8626)
- Evaluate the equations as instructed in the Background section in order to derive useful relations for lab work and analysis.

Background

Spectroscopy is a very powerful tool in astronomy. By dispersing the light received by a telescope we increase the spectral resolution and thus enable more physical insight into the processes occurring in astronomical sources. Modern spectrographs use a variety of dispersive elements, e.g. the Low Resolution Imaging Spectrometer (LRIS, https://www2.keck.hawaii.edu/inst/lris/) on Keck I uses grating on red side, and grism, a combination of grating and prism, on blue side.

A critical concept for gratings is the grating equation which relates properties of the light (wavelength, λ, and "order", m) to properties of the grating including the distance between grooves or slits, a, and the optical setup which defines several angles. It is given by

$$\frac{m\lambda}{a} = (\sin\alpha \pm \sin\beta)$$

where α and β are the angles between the grating normal and the incoming rays and the outgoing diffracted rays. Note that the plus-sign indicates a reflective grating and a minus-sign indicates a transmissive grating. You will need to solve this equation for $\sin\beta$, as a function of λ, m, a, and α. Now take the partial derivative of $\sin\beta$ with respect to λ, and show that the substitution from grating equation and elimination of α leads to the following dispersive power (i.e., the angular change in the direction of outgoing rays with a change in wavelength $\Delta\lambda/\lambda$) of a diffraction grating:

$$\lambda\frac{\partial\beta}{\partial\lambda} = 2\tan\beta_c\cos^2\theta + \sin 2\theta,$$

where β_c is the value of β at the center of the screen.

The trigonometric identities

$$\sin(A+B) = \sin A\cos B + \cos A + \sin B,$$
$$\sin A\cos B = \tfrac{1}{2}\sin(A+B) + \tfrac{1}{2}\sin(A-B),$$

may be helpful in deriving this expression.

Returning to Equation , substitute $\alpha - 2\theta = \beta_c$, for β and solve for α in terms of the other variables. The trigonometric identity

$$\sin A + \sin B = 2\sin\tfrac{A+B}{2}\cos\tfrac{A-B}{2},$$

may help you simplify your solution analytically.

For prism-based spectrographs, the angle of deviation can be expressed as,

$$D = i - A + \arcsin(n\cdot\sin(A - \arcsin(\tfrac{\sin i}{n}))),$$

where A is the internal angle of the prism ($60°$ in this case), i is the angle of the incident light, and n is the refractive index of the prism. The light path is shown in Fig. 1. For light at a certain wavelength λ, show that, when light ray produces the minimum deviation angle,

$$n_\lambda = \frac{\sin(\frac{A+D_\lambda}{2})}{\sin(\frac{A}{2})}.$$

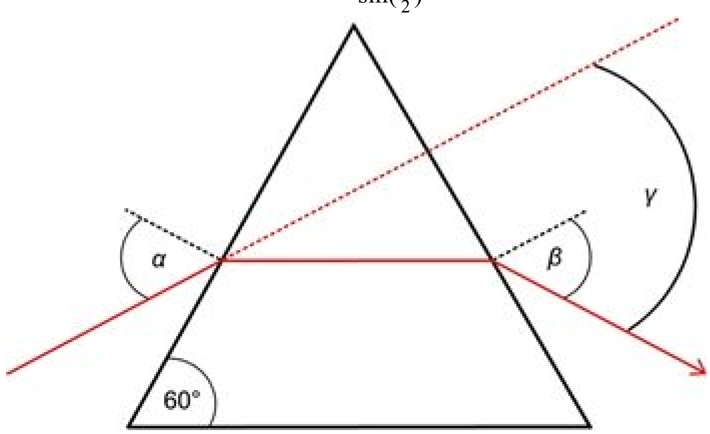

Figure 1: the relationship between the angle of minimum deviation and the light entering the prism.

You can also work on those derivations post-lab if they do not work out for you right away.

Equipment

We will mostly be using the ThorLabs Spectrometer Educational Kit, which includes the following equipments:

- Imaging Optics and Associated Mounting Hardware
- Variable Slit
- 1200 Lines/mm Diffraction Grating
- 600 Lines/mm Diffraction Grating
- Equilateral Dispersing Prism
- Viewing Screen
- Laser Safety Screen

We will also be using:

- Sodium Arc Lamp
- Iris
- ThorLab Visible Achromatic Lens Kit

Equipment list for the ThorLabs Spectrometer Educational Kit:

Item #	Description	Qty.
LEDMF	LED Mount	1
LEDWE-15b	White LED, Pkg. of 5	1
ACL2520U	Condenser Lens	2
FMP1 (FMP1/M)	Ø1" Optic Mount	2
LB1471	Focusing Lens	1
LMR1 (LMR1/M)	Ø1" Lens Mount	2
VA100 (VA100/M)	Variable Slit	1
LB1676	Collimating Lens	1
GR25-1205	1200 lines/mm Diffraction Grating	1
GR25-0605	600 lines/mm Diffraction Grating	1
CH1A	Diffraction Grating Mount	2
PS858	Equilateral Dispersing Prism	1
KM100PM (KM100PM/M)	Adjustable Prism Mount	1
PM3/M	Clamping Arm for Prism Mount	1
EDU-VS1 (EDU-VS1/M)	Viewing Screen	1

MB1824 (MB4560/M)	Optical Breadboard	1
RDF1	Breadboard Feet	4
TR3 (TR75/M)	3" (75 mm) Long Optical Post	9
PH3 (PH75/M)	3" (75 mm) Long Post Holder	9
TR2 (TR50/M)	2" (50 mm) Long Optical Post	1
PH2 (PH50/M)	2" (50 mm) Long Post Holder	1
BA1 (BA1/M)	Post Holder Base, 1" x 3" x 3/8" (25 mm x 75 mm x 10 mm)	6
BA2 (BA2/M)	Post Holder Base, 2" x 3" x 3/8" (50 mm x 75 m x 10 mm)	4
TPS5	Laser Safety Screen, 12" x 12" (305 mm x 305 mm)	1

Lab activities

Your main goal for this lab is to understand the factors that contribute to the resolution of a spectrograph.

Part I: Grating Spectrograph

Using the equipments on the optical table, setup with the Na arc lamp as the light source (you can choose to start with the LED, which has a bright "continuum" but does not have any lines). Your goal is to use one of the gratings (between 600 lines/mm, and 1200 lines/mm) to form an image on the white screen. Some of the equipments may not be necessary. You also need to choose your lenses wisely (see the note below).

Make sure about the following issues:

1) The Na arc lamp needs some time to warm up.
2) Use the iris to filter out the scattered light created by the light source, but keep as much useful light as possible. Do not hesitate to use the black screen for additional straylight control.
3) Use a lense with a proper focal length as the collimator. Gather enough light with the collimator, but do not introduce too many optical aberrations.
4) Form an image of the light source onto the slit. Be careful when adjusting the slit width. Do not force the slit jaws together.
5) Choose a proper camera lense to form images on the screen. The light beam shall fill out as much of the grating surface as possible. The resultion is ultimately determined by the total number of lines illuminated by the beam.
6) You may want to set up the grating on a rotational stage (same as last week) to measure its angle.
7) Use the techniques you learned in Lab 1 to align the equipments while setting up.
8) You shall see the NaD doublet on your screen. If not, rotate the grating and adjust the focus.

Sketch the configuration so far in your notebook. and record the collimating mirror focal length, grating grooves/mm and blaze angle θ_B. Mark on your sketch the grating blaze direction. Given this, where should the screen be located? What blaze wavelength, λ_B, do you derive for your grating from the grating equation evaluated in first-order Littrow configuration ($m = 1$; $\alpha = \beta = \theta_B$)? Is this reasonable? In which order would you expect the NaD lines to be brightest with this grating?

Useful formula: the lens equation

To help you choose the right lens for the job, find its optimal location with respect to the object to be imaged (e.g. the Na lamp of LED onto the slit, and the slit onto the screen), as well as the image location itself, the lens formula and corresponding magnification M might come in handy.

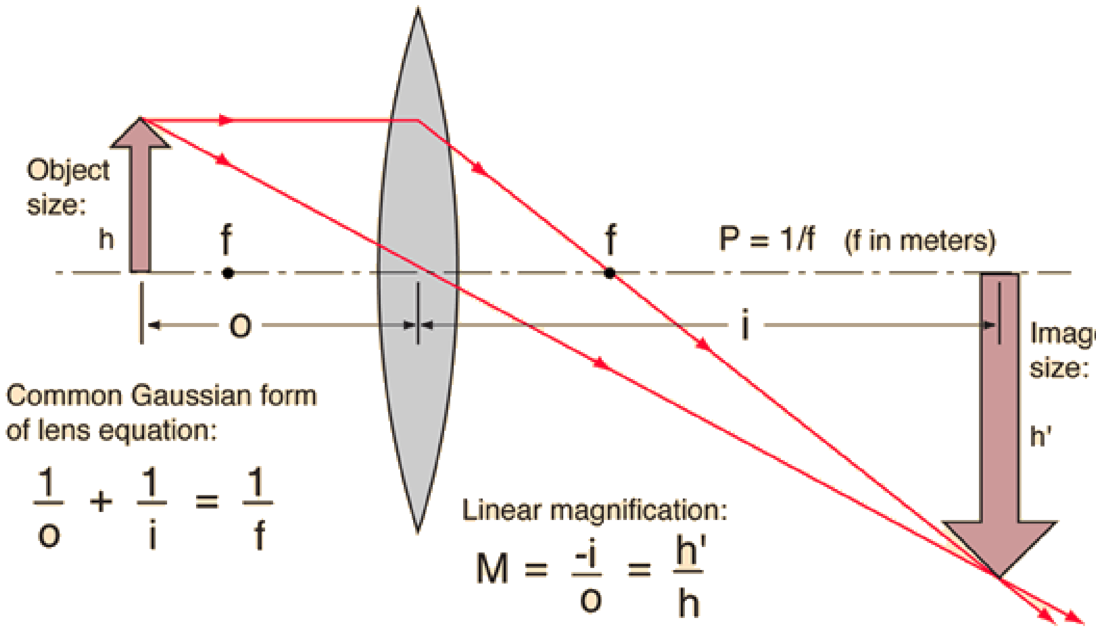

Figure 2: Lens Formula

Part I Measurements: Determine the zero point of the rotational stage when the grating is normal to the incident beam. Move back to the best configuration where you can see the NaD lines clearly. Identify the 0th and 1st order of the dispersion light. Measure the α and β angles and calculate the wavelength of the doublet.

Adjust the slit width, and determine the point when the doublet is distinguishable. Change the camera lens or the grating (control your variables), repeat the measurement of the slit width.

(Just for fun: Adjust the camera lens so that the light illuminating the grating is collimated, i.e. image at infinity and object at focus. Use your eye to observe the emission spectrum of NaI directly. You can even take a picture of the spectrum with you cell phone camera! Identify some of the spectral lines that are too weak to be projected on the screen.)

Part I Discussion: Given the phenomena you see during the experiment, discuss the properties that affects the spectral resolution. Is a narrower slit always better?

Part II: Prism Spectrograph

Use the Na arc lamp as the light source. (Still, if you found it is difficult to align or focus with Na lamp, feel free to use the LED first, and then switch back.) Change the dispersive element to prism. Reconfigure your equipments if necessary. Rotate the prism and find where the angle of minimum deviation for NaD lines is reached.

Part II Measurements: Measure the angle of deviation and calculate the refraction index for NaD lines. How does your measurement compare to Fig. 2.

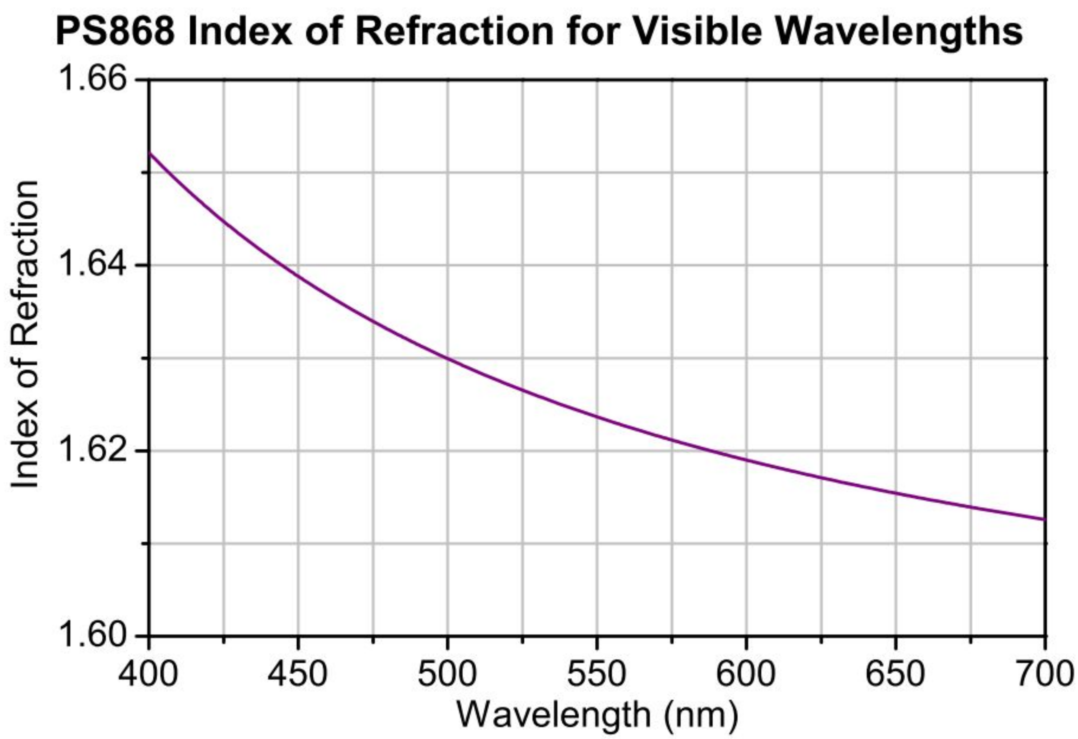

Figure 2: The refraction index of the prism as a function of wavelength.

Cauchy's equation describes n(λ), the refractive index of the prism material as a function of wavelength λ in µm:

$$n^2(\lambda) = A_0 + A_1\lambda^2 + A_2\lambda^{-2} + A_3\lambda^{-4} + A_4\lambda^{-6} + A_5\lambda^{-8},$$

which is valid over optical wavelengths and less so in the infrared. You will have to find the "Constants of the Dispersion Formula" for the particular glass used in the prism (such as borosilicate, fused silica, hard crown, barium crown, corning pyrex, flint, etc.) https://refractiveindex.info/ is a good resource for this. Using that equation to fit the curve in Fig. 2.

Part II Discussion: Derive the spectral resolution ($\lambda\frac{\partial\beta}{\partial\lambda}$) of the prism spectrograph we constructed during the class. How does it compare to the grating spectrographs? Does it match with what you see?