ASTR:4850 - Slitless Spectroscopy

1   Introduction

Spectroscopy is crucial to astronomy. It is the principal diagnostic for determining the temperature, the chemical composition, and the kinematics of stars, nebulae, and galaxies. Spectroscopy is of equal importance to physics. No experimental evidence was of more importance to the emergence of modern physics than the existence of spectral lines of different atoms and molecules. Today, spectroscopy continues to be one of the most important experimental or observational measurement in both astronomy and physics.

In optical astronomy, there are four different classes of spectrographs: slitless, longslit, multislit, and integral-field spectrographs. This course will experiment with optical spectrographs in the first two classes (slitless and longslit). In longslit spectroscopy, a narrow slit placed at the telescope's focal plane is used to prevent light sources outside the slit from entering the spectrograph, which significantly improves the S/N of the source spectra by drastically reducing the sky background. Because of the longslit, the observer has to center the target source precisely on the slit, and most times they cannot obtain spectra from more than two sources at the same time. By removing the slit, slitless spectroscopy resolves these two issues at the cost of (1) elevated sky background emission (which decreases S/N) and (2) spectral overlapping among sources (which limits its use to fields where the source density is low).

In this lab, we will set up a simple slitless spectrograph in two different configurations, and in each configuration, we will measure and analyze the spectra from gas spectrum tubes.

Optical spectroscopy is enabled by a grating, prism, or its combination (*grism*). These dispersion elements make rainbows that we call spectra. As illustrated below, when parallel rays of light is normally incident on a transmission grating, it diffracts and interferes after passing through the evenly spaced grooves/lines of the grating. The condition for constructive diffraction is given by the grating equation:

$$d \sin \theta = n\lambda \tag{1}$$

where d is the spacing between adjacent lines, θ is the diffraction angle, n is an integer, and λ is the wavelength of the light. Usually the grade of a grating is given as the number of

$$d \sin \theta = n\lambda$$
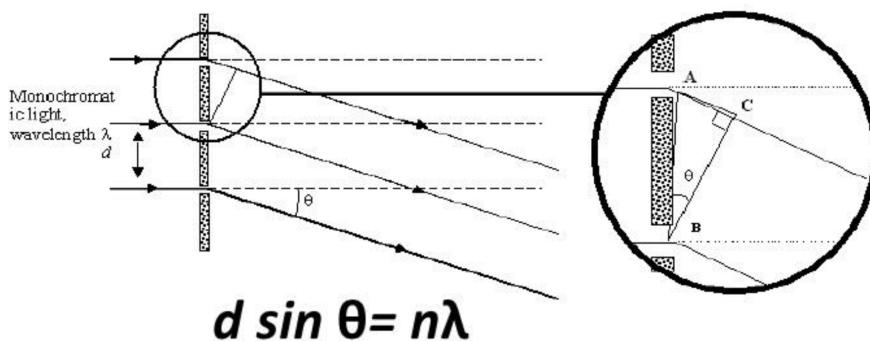
lines per millimeter (N in l/mm) instead of the spacing between adjacent lines (d), but the two quantities are simply related as $d = 1/N$. So the grating equation has another form that is easier to use for astronomers:

$$\sin \theta = n\lambda(\text{Å})N(\text{l/mm}) \times 10^{-7} \tag{2}$$

where the last term 10^{-7} takes out the difference between Å(10^{-10} m) and mm (10^{-3} m).

Example spectra from a diffraction grating is given below. When $n = 0$, there is no dispersion, so the 0th-order spectrum is a direct image of the source (the star at the center in the figure below). Immediately on either side of the 0th-order image are the 1st-order spectra (i.e., $n = \pm 1$; the two rainbows in the figure below); then farther out, the higher order spectra ($n = \pm 2, \pm 3, \ldots$). Because the detector is large enough to record only one of these orders, gratings are constructed to preferentially diffract at a certain angle so that the order at that angle is the brightest spectrum among all orders.

Star   Brighter of the two spectra to the right.

Before moving on, a couple things to note here:

- The dispersion direction is perpendicular to the grating's grooves. Look through your grating and note how the orientation of the dispersed light changes when you rotate the grating.

- The incident parallel rays remain parallel after passing through the grating, so a focuser lens/mirror must be used to form images of the spectra on the CCD detector.

2   Equipment List

The main components of the lab equipment are:

- Grating: Star Analyser SA-100 (1.25-in diameter, 100 lines per mm)

- Focuser: Orion ShortTube 80-A with tripod (80 mm diameter, 400 mm focal length)

- Camera: Orion StarShoot G3 monochrome CCD camera

- Light Source: Gas spectrum tube carousel with optical fiber.
  Warning: gas spectrum tubes have short lifespans, please turn off the power when not taking data. During alignment, the Nitrogen or Air gas tube is the preferred one to use because they last the longest.

Figure 1: Spectrograph Setup 1. *Left*: Spectrum tube aligned with the SA-100 grating. *Middle*: The focuser (Orion refractor) placed at an angle to catch the 1st-order spectrum. *Right*: Example spectrum taken in this setup (note that the spectrum is truncated by the grating, meaning that the grating was placed too far from the focuser).

3   Experiment Setups

In this lab, we will take spectra in two separate experiment setups.

In Setup 1, we will place the grating between the light source and the focuser. The advantage of this setup is that the light incident on the grating is in approximately a parallel beam (i.e., planar wavefronts). This is how most spectrographs are set up at observatories, except that we *neither* amplify the source signal with a telescope *nor* collimate the converging beam of the telescope into a parallel beam with a collimator lens/mirror. The omission of the telescope and the collimator significantly simplified the experiment, but the drawback is that we cannot implement this setup for night sky observations because (1) it's hard to place the grating high above the focuser and (2) starlight is too weak without amplification from a telescope.

In Setup 2, we will place the grating between the focuser and the CCD detector. The advantages of this setup are (1) the focuser now doubles as a telescope that amplifies the signal (thus enabling nighttime observations), and (2) a wider spectral range can be covered by the detector. But the disadvantage is that the light incident on the grating is a f/5.0 converging beam instead of a parallel beam, violating the requirement of the grating equation.

4   Setup 1: Grating in front of focuser

4.1   Dispersion Angle Calculation

Before setting up your experiment, do the following calculations to predict the expected outcome:

- Use Eq. 2 to calculate (1) the angle spanned by the 1st-order spectrum (i.e., $n = 1$) in the optical wavelengths (e.g., 4000 to 8000 Å), and (2) the angle between the center of the 1st-order spectrum (e.g., 6000 Å) and the 0th-order image. The former tells us how wide an angle the rainbow spans, the latter tells us at what angle (with respect to the axis of the grating) we should look for the rainbow.

- Calculate the field of view (FoV) of the CCD camera when mounted on the Orion focuser. Use degrees as the unit for all angle calculations.

- Now compare the angular span of the rainbow with the FoV. Is the CCD large enough to cover the entire optical wavelength range? If not, what fraction of the optical spectrum can be covered?

- Calculate the distance above which the 1.25-in diameter grating will appear smaller than the CCD FoV. This sets the maximum distance between the focuser and the grating. If the grating is placed from the focuser at a distance beyond this limit, the wavelength range of the recorded spectrum will be limited by the size of the grating instead of the size of the CCD detector.

Record the answers on lab notebook, then copy the answers on lab report.

4.2 Optical Alignment

The spectrograph is illustrated in Fig. 1. The suggested alignment procedure follows. First do the coarse alignment:

- Check Grating: The grating should have been installed on its stand. Hold it against a light source to make sure the dispersion direction is horizontal. If not, adjust by carefully rotating the grating.

- Grating-Source Alignment: Place the grating directly facing the carousel. Keep in mind that the focuser needs to be placed from the grating not greater than the maximum distance you calculated in the previous subsection to avoid spectral truncation due to the grating size.

- Make sure the power supply is off while rotating the carousel. Rotate to the Nitrogen or Air lamp and turn it on.

- Find the 1st-order spectrum with your built-in focuser (your eyes). While seeing the spectral rainbow, walk towards and away from the grating, does the size of the rainbow change with distance? Do you notice that the rainbow gets truncated by the grating beyond certain distance?

- Place the Orion focuser along the direction and at about the same height where your eyes see the rainbow.

- Adjust the focuser until you see the rainbow through its eyepiece. I suggest using the eyepiece with the longest focal length, thus the smallest magnification power. If you cannot put the grating into focus, don't worry. The spectrum is at the same distance as the carousel, not at the distance of the grating.

- Adjust the focus until you get a sharp image of the spectrum. At this focus, is the grating holder in or out of focus? Is the carousel in or out of focus? Does your observation confirm the statement I made in the last bullet point?

- Remember to turn off the lamp whenever it is not needed.

Then the fine alignment. Now we will use Neon lamp to choose a specific wavelength range:

- Make sure the power supply is off while rotating the carousel. Rotate to the Neon lamp of the carousel and turn it on. We choose Neon for this setup because its brightest emission lines only span between 5800 Å to 7500 Å.

- Adjust the telescope's pointing and position until the spectrum is at the center of your field of view.

- Remember to turn off the lamp whenever it is not needed.

4.3   Taking Spectra with CCD Camera

Once the spectrograph is aligned, we can take data with the CCD camera:

- Keep the telescope locked in position and do not move carousel and the grating.

- Replace the eyepiece with the CCD camera. Remove the diagonal mirror if necessary.

- Turn on the Neon lamp of the carousel.

- Adjust the focus until the CCD camera is in focus and a sharp image of the spectrum is obtained.

- Adjust the pointing of the telescope until the spectrum is well centered on the CCD.

- Adjust the rotation of the CCD camera until the spectral lines are vertical and the dispersion direction is horizontal.

- Decide on the best exposure time to use.

- For best results, lights in the room should now be switched off.

- Save a few images of the Neon spectrum as FITS files with appropriate names.

- Turn off the lamp

- Take 5+ bias frames.

Show your best image of the spectrum in your lab report.

Figure 2: Spectrograph Setup 2. Top: the Orion camera attached with a Star Analyzer grating on the nosepiece. Bottom: example spectrum of an optical fiber mounted on the Nitrogen gas tube.

5 Setup 2: Grating Behind Focuser

5.1 Dispersion Angle Calculation

In Setup 2, the grating will be placed on the nosepiece of the CCD camera. Once you thread in the grating, measure the distance between the detector and the grating and do the following calculations:

- Strictly speaking, Eq. 2 is no longer applicable because the incident light is now in a converging f/5.0 beam (i.e., spherical wavefronts). But in practice, we can use the dispersion angles calculated using Eq. 2 in §4.1 and the grating-to-detector distance you measured to estimate (1) the distance in pixels spanned by the 1st-order spectrum (i.e., $n = 1$) between 4000 and 8000 Å, and (2) the distance in pixels between the center of the 1st-order spectrum (i.e., 6000 Å) and the 0th-order image.

- Now compare the distances in pixels with the size of the CCD. Is the CCD large enough to cover the entire optical wavelength range?

- Repeat the calculations for a 200 line/mm grating (SA-200).

Record the answers on lab notebook, then copy the answers on lab report.

5.2 Optical Alignment

The spectrograph is illustrated in Fig. 2. Now with the signal amplification of the telescope, we can afford losing most of the light from the spectrum tubes. So we will install an optical fiber in front of the tubes to simulate a star-light source. The alignment procedure is much simpler than the previous setup:

- Install optical fiber adapter on the carousel.

- Install optical fiber, turn on the Nitrogen lamp and make sure you see light coming out of the fiber.

- Secure the output end of the fiber on a horizontal surface and point it at your Orion focuser (now doubled as a telescope) on the other side of the room.

- Point the telescope at the optical fiber's output end, adjust the focus until a sharp image of the fiber is obtained.

- Turn on the Nitrogen lamp.

- Make sure you can see the shining bright spot at the center of the fiber through the telescope eyepiece.

- Adjust the telescope pointing until the bright spot is at the center of your field of view.

- Turn off the lamp.

5.3   Taking Spectra with CCD Camera

Once the spectrograph is aligned, we can take data with the CCD camera:

- Install the other SA-100 grating on the camera's nosepiece.

- Keep the telescope locked in position.

- Replace the eyepiece with the CCD camera. Remove the diagonal mirror if necessary.

- Turn on the Nitrogen lamp of the carousel.

- Adjust the telescope focus until the CCD camera is in focus and a sharp image of the 0th-order direct image and 1st-order spectrum is obtained.

- Take out the camera, adjust the rotation of the grating, retake images until the 1st-order spectrum is aligned horizontally on the CCD image.

- Adjust the pointing of the telescope until the 1st-order spectrum is well centered on the CCD while keeping the 0th-order image in the image.

- Decide on the best exposure time to use.

- For best results, lights in the room should now be switched off.

- Save a few images of the Nitrogen spectrum as FITS files with appropriate names.

- Repeat for Hydrogen, Helium and Neon lamps. Make sure to turn off the power before rotating the lamps.
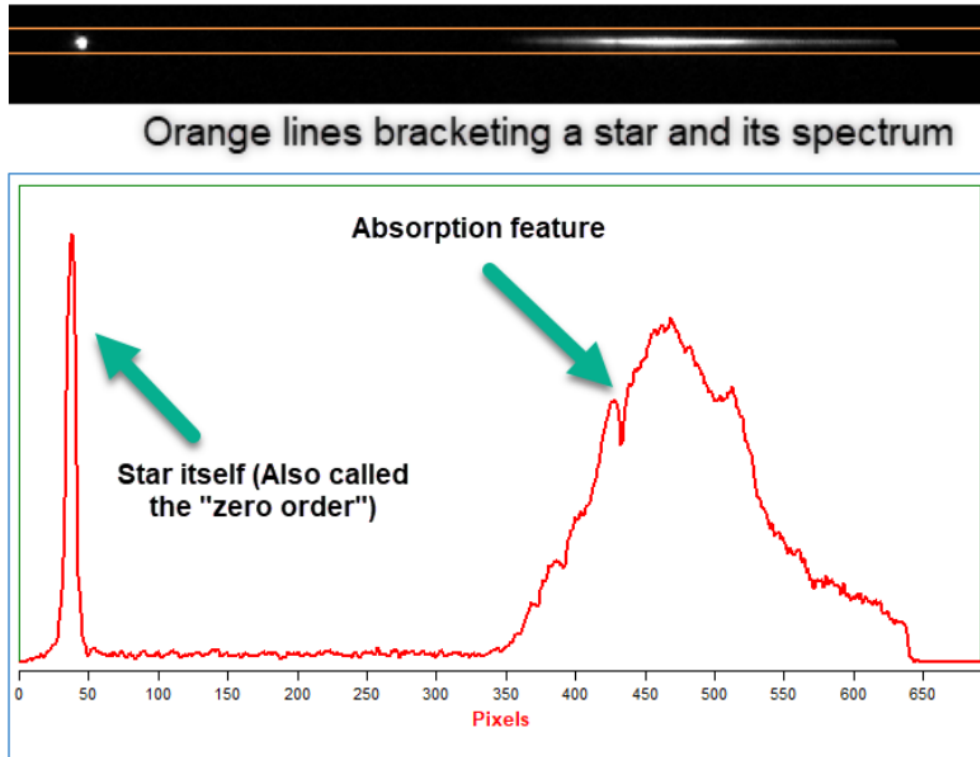
- Turn off the lamp.

Figure 3: Extracting a 1D spectrum from a 2D stellar spectrum. *Top:* rectangular extraction window overlaid on the 2D spectrum. *Bottom:* extracted 1D spectrum: count vs. x pixel coordinates.

- Take 5+ bias frames for subsequent bias subtraction.

Show your best image of the spectrum in your lab report.

6 Spectral Analysis

This python analysis will utilize your lamp spectra taken with the optical fiber and the grating on the camera's nosepiece (Setup 2).

6.1 Spectral Extraction

Your spectra have been recorded by pixels on a regularized 2D (x, y) grid. This FIT file is often called the raw 2D spectrum: count vs. (x, y) pixels. But spectra are usually plotted in 1D as count vs. wavelength. So the first step of spectral analysis is to extract a 1D spectrum (count vs. x) from the 2D spectrum (count vs. (x, y)).

For simplicity, we start with the Hydrogen lamp spectrum taken in Setup 2 because it shows only two prominent lines that are widely spaced and the wavelength coverage is wider in Setup 2 than in Setup 1.

Because most part of the CCD contains no spectral data, we first define the extraction region so that we can exclude most of the noisy pixels that contain no signal from the lamp.

- Load your best spectrum taken with the hydrogen lamp in Setup 2 into DS9. Adjust the contrast levels to make the lines visible.

- In the image, identify the 0th-order image and the 1st-order spectrum. It should look similar to the example in Fig. 2, but with fewer lines in the 1st-order spectrum.

- If you have taken the data following the instructions, the 0th-order and the 1st-order should roughly line up horizontally in the CCD frame.

- Draw a horizontal rectangular region that bracket the 0th-order image and the 1st-order spectrum like the one shown in Fig. 3. This is the extraction region of your spectrum.

- Record the center y-position (y_0) of the extraction region and its height (h).

Next, write a python code to load the raw FITS data, subtract the master bias, and at each x position sum up the counts of pixels within the extraction region (i.e., from $y = y_0 - h/2$ to $y = y_0 + h/2$). Plot the extracted raw spectrum as count vs. x-position as in the bottom panel of Fig. 3. The following example code might be useful to get started:

```
1  ####################
2  # Spectral Extraction
3  ####################
4  # import needed extensions
5  import matplotlib.pyplot as plt # plotting package
6  import astropy.io.fits as pyfits
7  from numpy import *
8
9  # load bias-subtracted arc lamp image
10 arcfile = pyfits.open('Hydro_Setup2_bsub.fits')
11 arcimg = arcfile[0].data
12
13 # define extraction region
14 y0 = 300 # y center of extraction region
15 dy = 10 # half width of the aperture
16 (ny, nx) = shape(arcimg) # dimensions of spectral image
17
18 # find a 1-d spectrum by summing across the aperture
19 arc = zeros(nx)
20 for i in range(nx):
21     arc[i] = sum(arcimg[(y0-dy):(y0+dy+1), i])
22 # array of x positions
23 x = 1+arange(nx)
24
25 # plot raw spectrum (count vs. x-position)
26 plt.figure(2)
27 plt.xlabel('X Position (Pixel)')
28 plt.title('Raw spectrum')
29 plt.ylabel('Sum Counts (ADU)')
30 plt.plot(x, arc, '-b')
```

6.2 Wavelength Calibration

A spectrum is incomplete without wavelength information. In this section we attempt to establish an approximate empirical conversion between pixel coordinates and wavelengths. This procedure is called wavelength calibration. Because we can look up the rest-frame wavelengths of emission lines from common elements, we can obtain the pixel-to-wavelength relation by identifying emission lines in the observed spectrum of a calibration lamp, like the hydrogen gas tube we used in this lab.

First, plot the extracted spectrum of Hydrogen, and measure the x-coordinates of the peaks that correspond to the 0th-order image (let's call it x_0) and the two strongest Hydrogen Balmer lines in the 1st-order spectrum ($x_{H\alpha}$ for Hα at 6562.85 Å and $x_{H\beta}$ for Hβ at 4861.33 Å). Think about which direction does wavelength increase in the 1st-order. That will help you identify which line is which.

Then, set the x-position of the 0th-order image as the origin of the new x' coordinate system (i.e., define $x' = x - x_0$), because the 1st-order spectrum shifts together with the 0th-order image and the x-positions of the 0th-order images from different lamps are unlikely to be the same.

We can now solve for the pixel-to-wavelength relation based on the CCD coordinates and the known wavelengths of the two identified lines (Hα and Hβ). Because we only use two lines, we will approximate the non-linear relation with a linear dispersion relation:

$$\lambda(x') = \lambda_c + D \cdot (x' - x_c) \tag{3}$$

where three constants need to be solved: D is the dispersion in Å/pixel, and λ_c and x'_c are the wavelength and x' coordinate of the reference line. It's easy to solve these constants with the two Hydrogen lines: you can first set λ_c and x_c to the wavelength and the CCD x-coordinate of Hβ, then solve for D using wavelength and the x-coordinate of Hα.

Use this relation to convert x' to λ and plot the wavelength calibrated 1st-order spectrum of Hydrogen (count vs. λ). Overlay the wavelengths of Hα and Hβ in the plot as vertical dotted lines. Show this plot and report your calculated linear dispersion relation in the lab report.

The following example code might be helpful for you to get started:

```
#####################
# Wavelength Calibration
#####################
# 0th order position in pixels
x0 = 50

# extracted spectral data from the previous step
s1 = arc              # counts
p = 1+arange(len(s1)) # pixel numbers
p = p - x0            # convert from x to x' using 0th order position

# calculate centroids for each line
linec = array([   172,     485]) # approximate center of interval (pixel)
linec = linec - x0               # convert from x to x' using 0th order
    position
lined = array([     4,       4]) # width of interval to calculate
    centroid (pixel)
```

```
16  linew = array([4861.33, 6562.85]) # wavelength of lines (Ang)
17  centroid = 0.0*linec
18  for i in range(len(linec)):
19    # index of array elements included in this line (note the +x0 term)
20    k = range(linec[i]-lined[i], linec[i]+lined[i]+1) + x0
21    # calculate centroid (flux-weighted mean)
22    centroid[i] = sum(p[k]*s1[k])/sum(s1[k])
23    # print result
24    print 'guess, range, centroid = ', linec[i], lined[i], centroid[i]
25
26  # solve for constants in wavelength calibration
27  x_c = centroid[0]
28  l_c = linew[0]
29  D = (linew[1]-linew[0])/(centroid[1]-centroid[0])
30  print 'reference pixel = ', x_c
31  print 'reference wavelength (A) = ', l_c
32  print 'dispersion (A/pix) = ', D
33
34  # plot the spectrum: Counts vs. versus wavelength
35  w = l_c + D * (p - x_c) # x' to wavelength
36  plt.figure(3)
37  plt.title('Wavelength-Calibrated Spectrum')
38  plt.xlabel('Wavelength (Ang)')
39  plt.ylabel('Sum Counts (ADU)')
40  plt.plot(w, s1, '-b')
41  plt.show() # display the plot
```

6.3   Check the Accuracy of the Calibration

To obtain more precise wavelength calibration, 20 to 40 lines from multiple gas lamps are usually used (e.g., arc lamps of Thorium, Argon, Neon, and Iron, instead of Hydrogen). But how good is the linear approximation? To answer this question, we need to use spectra of the Helium and the Neon lamps that you took right after the Hydrogen lamp.

The National Institute of Standards and Technology (NIST) provide online tables giving the wavelengths of strong lines of Helium and Neon. Note that the air wavelengths are given in Angstroms (Å). Select lines to plot only in the optical wavelength regime (4000 to 8000 Å).

Our simple testing procedure is:

- extract spectrum from the Helium lamp data;

- measure the x-coordinate of the 0th-order image (note that this x_0 is likely different from the x_0 measured from the hydrogen lamp spectrum because the various components may have shifted, so the x' coordinate needs to be redefined);

- apply your derived wavelength calibration (Eq. 3) to convert the new x'-coordinates to wavelengths;

- plot count vs. wavelength (this is your wavelength calibrated spectrum of Helium);

- overlay the known wavelengths of Helium emission lines on the spectrum as dotted vertical lines;
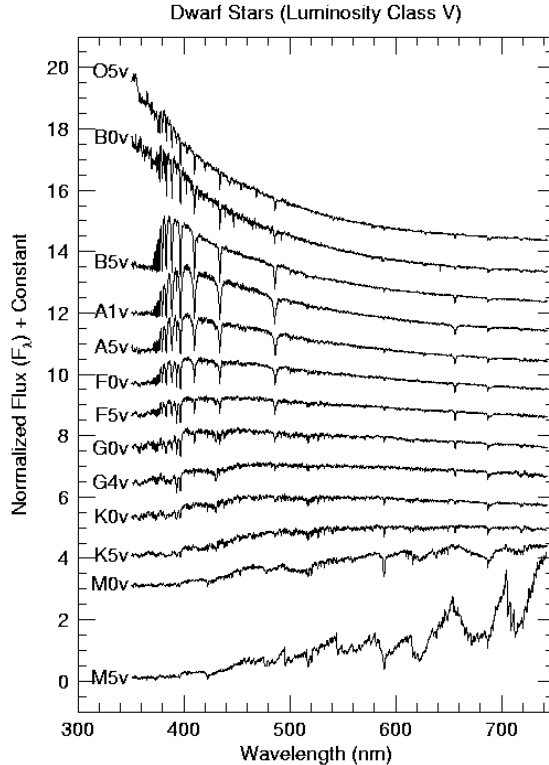
Figure 4: Optical spectra of main-sequence stars from the hottest (O type) to the coolest (M type). Click here to learn more about stellar spectral classification.

- calculate the deviations between the vertical lines and their corresponding peaks in the spectrum (it is sufficient to do this for the only most prominent lines);

- Repeat this for Neon lamp data.

Show these figures and report the mean deviations in Å in your lab report.

7   Take Stellar Spectrum (Bonus Activity)

Completing this roof-top activity during the two week period will earn up to 10 bonus points. On a clear night, set up your spectrograph in Setup 2 on the roof with either the Orion refractor or the Meade LX200GPS, take spectra of a bright star, note essential information in your observing log, extract and wavelength calibrate the spectrum. Look up the star's spectral type (see Figure 4), and compare your spectrum with the spectrum of a star with the same spectral type in the MILES stellar libraries by plotting them with Python. Identify prominent absorption features, and comment on the similarities you observe between your spectrum and the archival spectrum and the likely causes of any significant differences you notice between the two. Figures showing your wavelength calibrated spectrum and the archival spectrum of the comparison star are required.