Spectroscopy in the Laboratory

ASTR 222/522

Introduction

Spectroscopy is crucial to astronomy. It is the principal diagnostic for determining the temperature and chemical composition 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 this lab, we will have the pleasure of measuring and analyzing spectra. We will use the SBIG SGS with ST-7 camera.

Equipment

- SBIG ST-7 camera, with power adapter and USB cable
- Computer running the CCDOps software package and DS9 for image analysis
- SBIG Self-Guiding Spectrograph
- Gas discharge tubes of hydrogen and helium (other elements would be good, too)
- USB flash drive for transferring data files

System Setup

- Remove the top panel of the spectrograph. Looking inside will give you a very clear idea of how the spectrograph works.
- Connect the USB cable from the camera to the laptop. Bring up CCDOps, connect to the camera, and listen for the contented clicking sounds.

Sometimes spectral images are binned along the vertical direction. Typically one integrates a stellar spectrum across the whole width of the stellar image, usually several pixels. When acquiring spectra, CCDOps has an option to do this binning for you. Setting 'Vertical Binning' to a value greater than one simply combines that number of adjacent vertical pixels. To set the vertical binning for dark frames, do Camera/Setup and look at the 'CCD Setup' part of the dialog box. It should be fine to set 'Vertical Binning' to a small whole number to combine vertical sets of pixels and allow shorter exposures times. However, it seems that CCDOps ignores 'Vertical Binning' when taking dark frames, so keep 'Vertical Binning' set to 1. It is important to have a set of dark frames that can be directly subtracted from the spectrum images; the dark frames should have the same vertical binning and exposure time.

- To acquire a spectrum, do DSS/DSS Mode then check the boxes for 'Grab Spectra' and 'Enable DSS', set 'Vertical Binning' to 1, adjust the exposure time, and then click 'OK'.

- The 'Grab Spectra' command does not do dark frames, so you'll need dark frames for all the exposure times that you use for your final set of spectra. Note that the exposures needed for the spectra can be long, so you might want to cool the CCD. Be sure that your spectra and darks are taken at the same temperature and with the same vertical binning.

We are now ready to take data.

Data Taking and Measurements

The main goal of this lab exercise is to calibrate the spectrograph. You will now take spectra of hydrogen, helium, and neon lamps. We will need to have the lights off in the lab for this part.

- Select the Hydrogen tube in and turn it on.
- Acquire a spectrum. Adjust the exposure time so that the brightest pixels have values of at least several 1000 counts but are not saturated. Save the spectrum with a filename containing 'hydrogen'. You should also get into the habit of specifying the object (in this case 'hydrogen lamp') while saving so that it is written to the FITS header.
- Repeat the this procedure for the helium tube and the neon tube. Save the hydrogen and neon spectra.
- Now we'll test the orientation of the dispersion axis. Do this by adjusting the caliper in the red direction by a few nanometers. Take a spectrum and record it as neon-red. Return to the original caliper value and move slightly in the blue direction, and repeat this procedure. Be sure that you can visually tell that the lines shifted. If you can't, move the caliper more and be sure to record the values you use.
- Check that you have a full set of spectra (hydrogen, hydrogen, neon, neon-red, and neon-blue) and that the brightest pixels in the images have a decent signal but are not saturated. Go back and re-acquire any spectra that are bad or dodgy. Now take and save dark frames for every exposure time that you used for your set of final spectra. Be sure that each dark is at the same temperature as the corresponding spectrum.
- When you are finished, shut down the system and copy all the files to the flash drive.

Calibrating the Spectrograph

Now let's identify the various lines in each spectrum.

- Load the three spectra for neon into ds9. You will want to look at all three spectra simultaneously, so after you load the first spectrum, do Frame/New Frame before loading each of the other spectra. Then after all three spectra are loaded, do Frame/Tile Frames and Frame/Frame Parameters/Tile/Rows. You should see your three spectra in three rows.
- You may want to play with the scale settings for each image in ds9 in order to get the lines visible. People often look at spectra using an inverted colormap (Color/Invert Colormap).

- After you are done adjusting your images, do Frame/Match/Frame/Image to make sure that all of the images are lined up in ds9. This allows you to directly compare pixel number between the images.
- Save a plot of the three images (together) and be sure to make a note of which image is which. You now know the orientation of wavelength along the x-axis of the CCD.
- Now load the hydrogen spectrum into ds9. The dominant lines in the hydrogen spectrum should be H-alpha at 656.285 nm and H-beta at 486.133 nm. Write down the image x coordinate of the center (vertically and horizontally) of the H-alpha and H-beta lines. These are your first approximation to the calibration of the spectrograph. Estimate the width of the line (in terms of number of pixels).
- Write down the image y coordinates of the center of the lines for use later. These should be the same or very close to the same. Determine the width of the line image in y.

You will now calibrate your spectrograph using Python and your hydrogen spectrum with its newly identified lines.

In general, there can be a complex relation between pixel number p and diffraction angle θ that depends on the optical properties of the spectrograph. If the diffraction angles are small, $\theta << 1$, then the relation between pixel number p and diffraction angle θ can be approximated as $p = a\theta + b$. We will use a linear relationship. Note that since there are only two strong lines in the hydrogen spectrum, we don't actually have enough information to derive a more complex calibration curve. In astronomical research, much larger line sets, often 20 to 40 lines or more, are used to correct for non-linearities in the pixel number versus wavelength relation.

- Grab the file hydrogen.py from Moodle and load it into your preferred text editor. Edit the lines that read in the spectrum files to match the names of your files. Edit the variable y0 to match the value that you found using ds9 for the (vertical) line center and the variable dy to be half of the width of the line (or a bit smaller).
- Run the program. You should see a 2D image of the spectrum, similar to what you saw in ds9 (you many want to edit the values for vmin and vmax in the plt.imshow command if the lines don't show up well) and a line plot of a 1D spectrum. Adjust y0, dy, vmin, and vmax until you are happy with the plots.
- Now edit the values in the arrays ‘linec’ and ‘lined’ to match the line centroids and half the line widths that you estimated from ds9. Note that these values must be integers. Make sure that the centroids correspond to the right wavelength in the array ‘linew’.
- Run the program again. Inspect the vertical lines overdrawn on the 1D spectrum plot. Each pair of dashed lines marks the interval used to calculate the centroid of a spectral line. The solid line between them marks that centroid. Check your intervals and centroids and adjust them so they look reasonable. The iPython plot windows are interactive, so you can zoom in on your lines. Click on the cross with arrows,

then left click in the plot window to pan and right click to zoom. Clicking on the house will restore the plot to its original settings.

- When everything is good, run the program again save the 1D spectrum (versus pixel number) plot.
- After calculating the centroids, the program does a linear fit to the pixel versus wavelength relation (which is trivial when only using two points). Rather than using just two parameters as needed to specify a line, the program prints out three parameters which are the average pixel number of the lines used in the calibration, the corresponding wavelength, and the slope of the relation. Record these.
- The last part of the program applies the calibration, makes a spectrum plot versus wavelength, and calculates centroids in terms of wavelength given a line list in terms of wavelength. Inspect that plot. Adjust the values of 'lined' in the 'Line centroids in wavelength' part. Save the plot when you are satisfied. Note that with only two points for the calibration, the calculated wavelengths should match the known values exactly. Once you have a calibration, specifying lines of interest in terms of wavelength is much more convenient since the wavelengths are known before hand.

Having now calibrated our spectrograph, we can test the accuracy of the calibration.

- Save a copy of hydrogen.py as spectra.py. Delete the stuff about plotting the spectrum versus pixel number and finding line centroids in pixels (since we will now be working in wavelength). You can also delete the stuff about plotting the difference image if you like (or leave if it you like to double check you have the right spectrum image). Replace the lines where the calibration is calculated with statements that assign your calculated values to centralp, centralw, and slope.
- Run the program and checks that it work on the hydrogen spectrum and finds the appropriate centroids.
- Now look at the helium spectrum. Edit the file name (and dark file if needed) to load the helium spectrum. Find as many lines as you can (you may see more than 5). You might want to change to a log scale on the vertical axis to see weak lines. It is good to pick narrow lines, since the broad features are often combinations of multiple lines and it is harder to accurately calculate the centroid of a broad line.
- You can get an estimate of the wavelength of by moving your cursor over it and recording the x position at the bottom right of the plot window. Find your lines in the Tables at http://physics.nist.gov/PhysRefData/Handbook/Tables/heliumtable2.htm If there are multiple lines close to your estimated wavelength, pick the one with the highest intensity in the table. Edit the values for linew and lined.
- Note that you really need to inspect each line. The centroiding code will always find a centroid, even if there is no line present. Indeed, if you draw an interval on a region with no line, the centroid will be very close the center of the region, so it is easy to get spurious good agreement between input wavelengths and centroids.

- After you have found five or so lines and calculated their centroids, save a plot of your spectrum with all of the centroids overplotted.
- Take your centroids and calculate the difference (centroid - known wavelength) and then the standard deviation of those differences. The standard deviation is a measure of the accuracy of your calibration of the spectrograph. Calculate it in wavelength units and also convert that number into pixels using the slope of your calibration. Record your calculations.