In this lab, you will practice using a spectrograph and reducing 'long-slit' spectroscopy data. We are actually using a fiber-fed spectrograph instead of a long-slit spectrograph, so we have created a 'pseudo-slit' by laying out the fibers in a linear pattern.

Your learning goals for this lab are:

- to obtain spectra of astronomical sources
- to calibrate and reduce spectroscopic data
- to measure spectral lines

The lab includes observation, data analysis, and data reduction.

1 Observations

We observed the following targets:

- Jupiter
- A moon of Jupiter
- The Ring Nebula
- Vega
- At least one binary star system

We also observed calibration lamps. The Neon lamp spectrum should serve as the basis of your calibration.

2 Reduction

Recommendation: Do the full process described here (reduction, trace and extract, wavelength calibrate) for *one* star (of your choice) before doing any of the other stars. Reduce the data by dark-subtracting them.

Dark-subtract each of the different exposure types by matching the exposure times listed in the file names and confirmed in the FITS headers.

Median-combine the images of the same source to reject cosmic rays. However, if there is offset between the images that would result in losing signal, do not combine them.

- **Only median-combine images if they are already aligned.**
- **Do not attempt to median-combine images at different flux levels.**
- **If you can't median-combine in the image, you can median-combine the normalized spectra instead.**
- **Not all of the spectra are "good". If an exposure has weird artifacts, note that and exclude it from further analysis (your note should include an image showing what the problem is)**

For the spectroscopic reduction, follow the process described in the Spectroscopy lectures and on the astropy guides:

- https://learn.astropy.org/tutorials/1-SpectroscopicTraceTutorial.html
- https://learn.astropy.org/tutorials/2-WavelengthCalibration.html
- https://learn.astropy.org/tutorials/3-Trace_Extract_Wavelength-CalibrateSpectrum.html

A modified version of the tracing guide was given in class to account for our slightly more poorly-behaved spectra.

Your aim is to produce wavelength-calibrated one-dimensional spectra for each of the targets.

3 Trace and Extract

Trace and extract spectra from each of the targets that has a continuous spectrum. Use either the combined (median combined) spectrum or the brightest spectrum.

Use the traces from each of these targets to obtain the corresponding extracted spectrum from your combined flat field image (if the sky image is usable as a flat - you'll need to assess this).

- **This process is shown in the Wavelength Calibration notebook. In brief: obtain the trace and trace profile of the star, which give you the (x,y) locations to pull the spectrum from, then use that to extract the spectrum just like we did for the mercury, neon, and krypton lamps.**

Use a trace from one of the stars (probably the brightest) to extract a spectrum from Jupiter.

- **Our extended images consist of 7 distinct spectra, just like the calibration lamps, because this is a fiber-fed spectrograph with 7 independent fibers. There are other ways you can get the individual spectra, but the simplest is just to use the trace of a single assuming that the star's spectrum has the same curvature as the extended source's seven spectra.**

Use the traces from each of these targets to obtain the corresponding extracted spectrum from the wavelength calibration spectra (He, Ne). Assess whether the wavelength solutions will be different for each extracted spectrum: do the lines appear at different pixel positions?

- **Note that there are calibration lamp spectra from the beginning and end of the night. For each spectrum you're extracting, check how much the calibration lamp spectra differed from the beginning to the end of the night: how much did the wavelength solution change? What does that imply for your uncertainty on the wavelength solution?**

4 Wavelength Calibrate

Wavelength calibrate your spectra.
Show your work!
Estimate the uncertainty in your wavelength solution.

- **Uncertainty estimation should follow the wavelength-calibration notebook, but you do not need to prove that the uncertainty is dominated by systematic errors, you can just estimate the standard deviation of the fit residuals.**
- **I hope you can just repeat exactly what I did in the notebook without extensive fine-tuning of parameters. If you find yourself getting lost, spending a lot of time here, ask for help and/or move on! At least do the neon-based wavelength solution identification, since you need that for the next step, though.**

5 Fit and identify spectral lines

Once you have your wavelength-calibrated spectra, you will use Vega as a spectral flat field as decribed in the "Line Profile Measurement" lecture. As part of that process, you will fit line profiles to the hydrogen lines in Vega's spectrum.

Fit the Hβ 4861 angstrom line from any star in which it is detected. Report the velocity of the line and the equivalent width.

- **You need to select the part of the spectrum that contains this line and *normalize* it, most likely by fitting the continuum with a linear model.**
- **You should fit a Gaussian absorption line and use its integral to get the EQW.**
- **You can fit these two together, following the example in the 'measuring line properties' notebook.**

In Jupiter's spectrum, which is the reflected solar spectrum, identify and fit (and measure EQWs of) as many Fraunhofer lines (`https://en.wikipedia.org/wiki/Fraunhofer_lines`) as you can. Make a table of the measured wavelength, width, EQW, and uncertainty on those fitted quantities.

In the twilight spectrum, you may also see these lines. Are they at the same wavelength? Are they the same relative depth?

Compare to your other stellar spectra. Which lines are detected in other stars? Are there lines detected in other stars not seen in the Sun's spectrum? Again, report this in a table.

You should have one table for each target (each star, Jupiter and its moon(s), and the nebula).

6 Measurements

Your measurements should include:

- The measured wavelength coverage, and pixel spacing, from your wavelength calibration solutions. (especially note: if you took multiple calibration spectra, did the wavelength solution change?)
- The Equivalent Width of the hydrogen lines in Vega's spectrum
- The wavelength of any emission lines in the Ring Nebula's spectrum
- The wavelength, and identity, of spectral lines in other targets (you may be limited to Hydrogen lines, but there should be some Fraunhofer lines identifiable too)
- The pixel scale of the slit viewer on the acquisition and guiding system (you will get this from the observations of the binary system)

7 Turn In:

- Your formal writeup
- Your complete work notebook in .ipynb and .pdf form
- Plots of each of the wavelength-calibrated spectra
- Tables of measurements

The writeup rubric is:

1. Introduction (5%): Describe the purpose of the lab & background
2. Procedure (55%): Describe the setup of the hardware and the data taking and reduction process
3. Data Analysis (25%): Report and analyze your measurements
4. Data Packaging and Delivery (10%): Put the data together and turn them in with appropriate metadata
5. Conclusions (5%): Summarize what you learned