Research Methods in Astrophysics

Final Project — Due Tuesday December 20, 2016.

Late submissions will not be graded!

This project will count as either 20/30% of your grade. The other 30/20% will be your score on the midterm exam. I will use which ever is the better grade as the larger percentage. A fraction of the grade will be based on clarity of your write-up.

Determine the mass of a black hole candidate

Below we will determine the mass of a candidate black hole using spectra taken with the SMARTS 1.5-meter telescope and RC spectrograph. I will first provide you with the reduced spectra from several nights to determine velocities and determine the nature of the unknown object. I will then ask you to try reducing one night's worth of data.

Stellar Mass Black Holes: The spectra analyzed below are of a luminous star in the Milky Way with an massive unseen companion, either a black hole, neutron star or white dwarf. Given the following statements, estimate the number of stellar mass black holes predicted to exist in the Milky Way:

- In regions where stars form, 0.5% of stars are sufficiently massive to turn into a black hole.
- In the Milky Way, we see $1x10^9$ M_{sun} low mass stars with masses less than 0.5 M_{sun}.
- In regions where stars are currently forming, 70% of stars have masses less than 0.5 M_{sun} whose lifetimes are longer than the age of the Universe.

We currently have evidence for 20 stellar mass black holes in the Milky Way, all of which were discovered in X-rays. Give two or more reasons why the number of observed black holes is much lower than the number predicted. Explain why finding black holes which do not emit X-rays would be interesting.

Measuring Velocities: Spectra of a candidate black hole binary system is available on the class website. The object was observed several times over the course of a month. The first line of each file is the observation date, the remaining rows are the wavelength (Å) and flux.

a. Using the spectra themselves, determine the spectral resolution, R. Does R change significantly as a function of wavelength?

b. Over-plot the spectra, noting that the overall continuum is different between the five spectra. Determine a single normalization value for each spectra, which you can multiply/divide by, so that the spectra roughly line up over each other.

c. Based on the continuum shape and absorption lines seen in the spectra (and comparing back to the spectra in PS #8), roughly what spectral type is the luminous star? Assuming this is a main sequence star, can you estimate a mass?

d. *Measure velocity by eye:* Chose any one of your spectra as a template which we will use below. The majority of lines in the spectrum come from the Hydrogren Balmer sequence. Identify three absorption lines in the spectrum. State the rest wavelength of these lines and measure by eye their observed centers in each observed spectrum. Averaging your results from the 3 lines, what is the absolute velocity shift for this spectrum?

e. *Measure relative velocities:* Repeat this above procedure to measure velocities for all 5 spectra.

f. **Extra Credit:** *Measure relative velocity by Chi2:* Use 'template fitting' discussed in lecture to determine the relative velocity shift for each spectrum. You can write your own scripts, or use 'canned' scripts you find online. If the latter, explain what the script is doing. Show your chi2 plots and demonstrate that you are getting more accurate velocities than the by-eye method above.

g. Combining your results from *(d)* and *(e/f)*, plot the absolute velocity for the 5 spectra versus time of observation. What is the maximum velocity shift you observe for the system?

h. **Extra Credit:** The velocities you compute are in the Earth-centric frame. Correct your velocities to the heliocentric frame using the time listed in the first line of each spectrum file and available code to calculate this correction. Explain in general how the code is computing this correction. Given the size of this correction, does this affect your final estimation of the compact object mass below? https://gist.github.com/eteq/5000843. Use 'vlt' as the observatory.

i. The observed object is a black hole binary candidate. Based on lecture notes, describe the components of the system and how you would estimate the mass of the black hole. Using the maximum velocity difference measured above and a reasonable estimate for the orbital period of the system (justify your choice), determine the minimum mass of the unseen companion. What is your best guess for the nature of he unseen companion?

Reducing the Data: You will next reduce the spectra from one night above. The goal of the work below is to overplot your extracted 1D spectrum to the spectrum provided above. We will be working with the spectrum 110913.txt

- *Wavelength image:* Read and display the calibration arc lamp file, `nl_comp.fits`. Describe what you are seeing and how this image was obtained. Next, chose 100 rows in the center of the image and collapse these into a 1-dimensional array. Plot pixel number version flux for this array.

- *Identify lines:* We need to identify specific lines in the above array. The plot provided at the end of this problem set shows lines from a He Ar lamp. To get you started on this process, I have identified 3 lines in your spectrum:

line = [991, 624, 227, 822]

pixel = [5015.67, 4471.48, 3888.65, 4764.86]

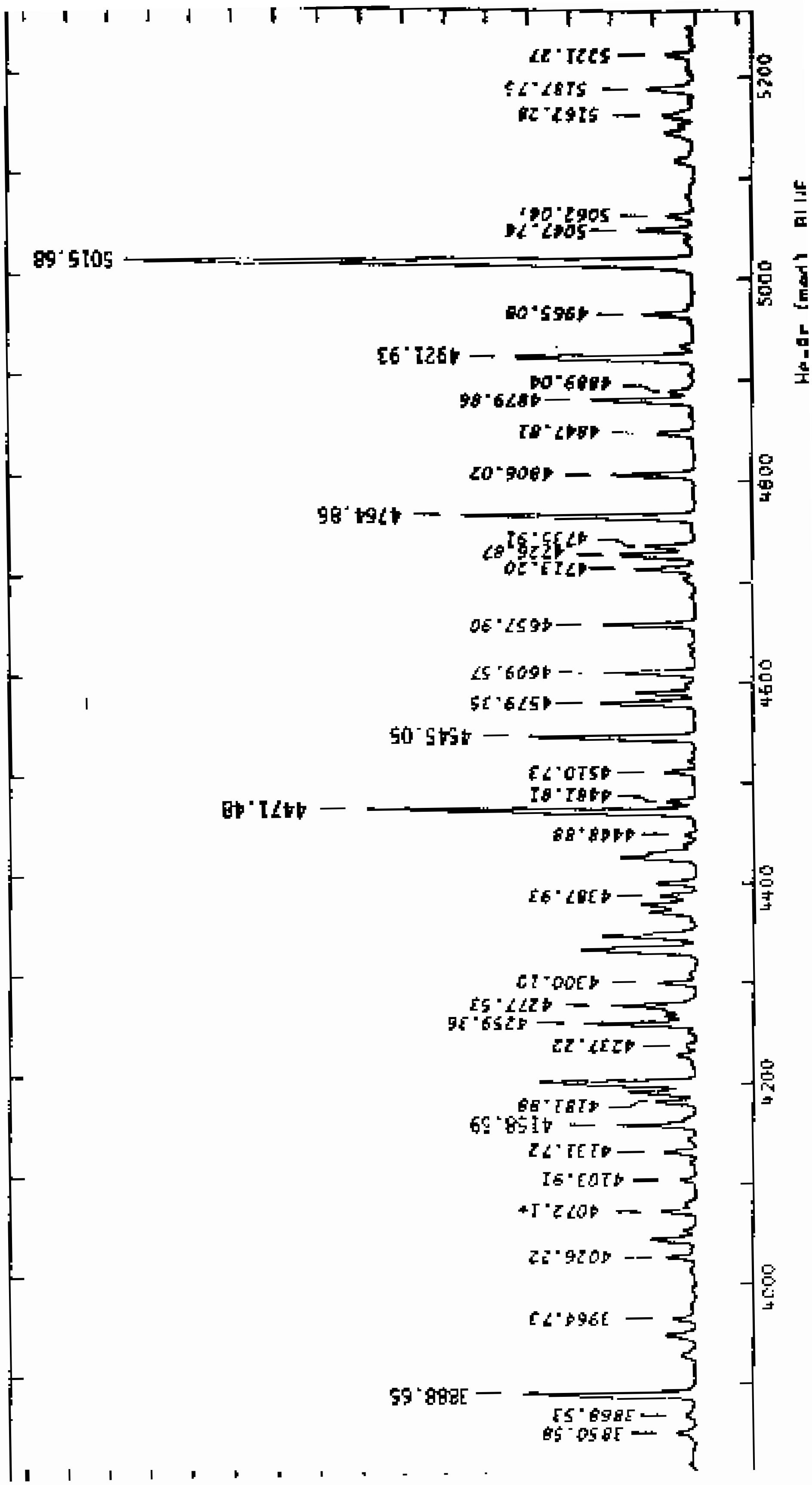
Identify at least an additional 3 lines and overplot the position of these lines in your 1D plot above. **Half Extra Credit:** Identify 10+ lines in the spectrum. We have included a file with line centers on Canvas. **Full Extra Credit:** Better determine the center of each line by fitting a Gaussian curve to the region around each line.

- *Fit the Wavelength Array:* Fit a polynomial to your pixel/wavelength array. We suggest using a polynomial of order 3 or 4 and using the numpy modulue: `np.poly1d`. Write out the final fitted function and demonstrate that it correctly predictions the wavelength of the 3 strongest lines above given their pixel positions.

- *Extract the science spectrum:* Now read and plot your science image (n1_sci.fits). Identify the rows over which the science object is seen an extract the 1-dimensional spectrum. Plot the spectrum first as pixel vs. Flux. Next apply the wavelength solution above and plot your 'final' science spectrum as wavelength vs. Flux.

- *Check your work:* Overplot your final spectrum against the spectrum provided '110913a.txt'. Do these two spectra agree? Explain where any possible differences might be coming from.

Extra Credit: Perform additional data reduction steps including sky subtraction and flat fielding. Show how these steps affect the final spectrum.



He-Ar (mod) BLUE
5200
5000
4800
4600
4400
4200
4000
5221.37
5187.75
5162.28
5062.04
5047.74
5015.68
4965.08
4921.93
4889.04
4879.86
4847.81
4806.02
4764.86
4735.91
4726.87
4713.20
4657.90
4609.57
4579.35
4545.05
4510.73
4481.81
4471.48
4448.88
4387.93
4300.10
4277.53
4259.36
4237.22
4181.88
4158.59
4131.72
4103.91
4072.1+
4026.22
3964.73
3888.65
3868.53
3850.58