Lab #2 "Introduction to Spectroscopy"

Lab report is due at 4pm on Oct 30 (Monday). Submission on Quercus.

Of all objects, the planets are those which appear to us under the least varied aspect. We see how we may determine their forms, their distances, their bulk, and their motions, but we can never know anything of their chemical or mineralogical structure; and, much less, that of organized beings living on their surface...
Auguste Comte, The Positive Philosophy, Book II, Chapter 1 (1842)

1. Overview and Goals

Spectroscopy is a fundamental tool used by all physical sciences. For astrophysicists, spectroscopy is essential for characterizing the physical nature of celestial objects and the universe. Astronomical spectroscopy has been used to measure the chemical composition and physical conditions (temperature, pressure, and magnetic field strength) in planets, stars, and galaxies, as well as their velocities. One of the key aspects of spectroscopy is wavelength calibration. In this lab, you will conduct two types of wavelength calibrations, one with Neon lamp for 1-dimensional spectra and the other with OH telluric sky lines on a 2-D dispersed image, to determine the temperature of a blackbody spectrum and velocity of ionized iron gas from a supernova explosion. In addition to the wavelength calibration, you will attend a campus telescope session to have an experience in obtaining spectra of stars (or planets) and reducing them.

Schedule: This is a four-week lab between October 2 and October 30. There will be no class on October 9 for Thanksgiving. Group-led discussions will take place on October 16 and 23. (More information on Group-led discussion will be given separately.)

2. Key Steps

1. Understand how spectroscopy is done, especially wavelength calibration.
2. Obtain a wavelength solution (= mapping solution between the detector pixels and wavelengths) of Neon spectrum taken with a spectrograph equipped with a 1-dimensional detector (= linear detector) using the known wavelengths of Neon lines.
3. Apply the wavelength solution to determine the temperature of a perfect blackbody spectrum assumed to have been taken with the same spectrograph.
4. Obtain a wavelength solution of OH sky lines for a 2-dimenaional dispersed image in the near infrared.
5. Apply the wavelength solution to obtain the velocity of ionized iron gas by comparing the intrinsic wavelength of [Fe II] 1.644 micron and the measured wavelength.
6. Attend one of the telescope sessions at the campus observatory to obtain spectra of bright astronomical objects (e.g., Vega, Jupiter, etc).
7. Reduce the data of the bright objects that you obtained at the campus telescope to extract their spectra and discuss the nature of the observed objects on the spectra.
8. Write a report on your work. (See the document on lab report writing.)

2.1 Wavelength solution of 1-dimisional Neon spectrum and blackbody temperature

Figure 1 shows a simple laboratory setup for spectroscopy: *the left panel shows the entire setup, while the right panel shows the interior of the spectrograph USB4000*. Photons from the light source (e.g., Neon lamp, blackbody source) are transferred to the entrance of the USB4000 spectrograph by optical fiber. Inside the spectrograph, the entered photons are dispersed by grating (component ⑤) before they are recorded in 1-dimensional detector (component ⑨). The detector has **1024 pixels**. (Note that there are other optical components inside the spectrograph that reflect, collimate, and focus the photons.) The spectrograph is configured to be sensitive to photons roughly in the range of 500–800 nm.

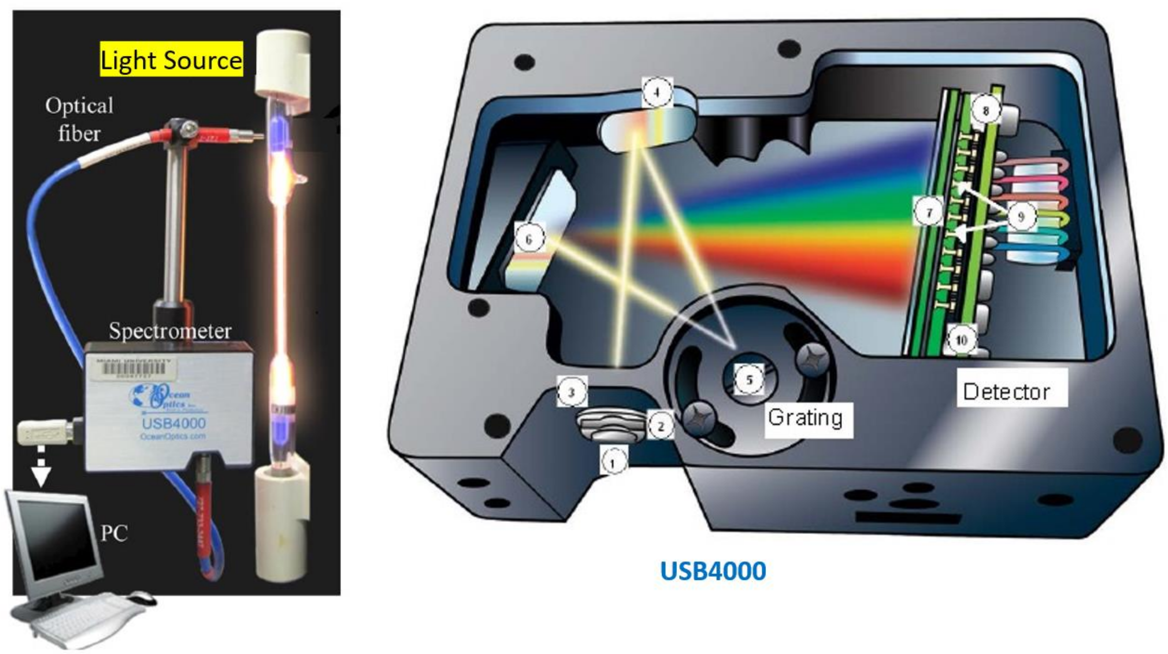

Figure 1. (Left) Experimental setup for laboratory spectroscopy using USB4000 spectrograph. (Right) Internal configuration of the USB4000 spectrograph.

The final goal of this experiment is to determine the temperature of a blackbody source by analyzing its spectrum obtained with the same spectrograph. In the folder linked to the following web page

https://drive.google.com/drive/folders/1rEH9VUJx6dikh-P9YDvAWjA6OfMf1Ejf?usp=sharing

you can download a file named "**Group_?_BB.dat**" which is the spectrum of the blackbody source for your group. If you plot the spectrum, it looks like the following.

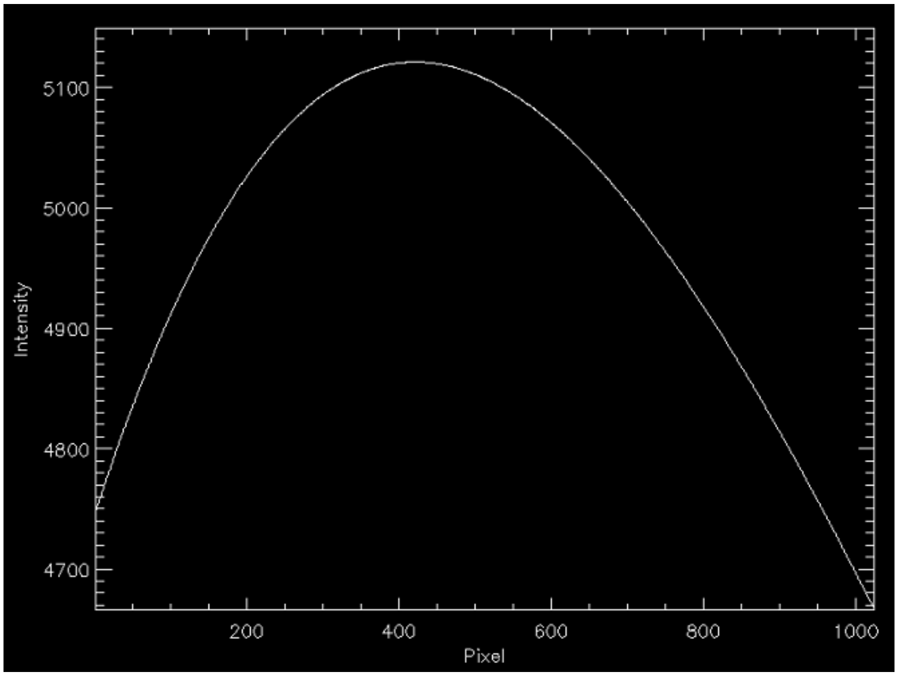

Figure 2. Example spectrum of the blackbody source obtained with the spectrograph.

In order to estimate the temperature of your blackbody source, you need to obtain the wavelength solution since temperature determines the wavelength depednecy of a blackbody spectrum. In the same web page above, you can find a file named "**Ne_calib.dat**," and it is a spectrum of a Neon lamp obtained with the same specrtrograph. Its spectrum looks like the following

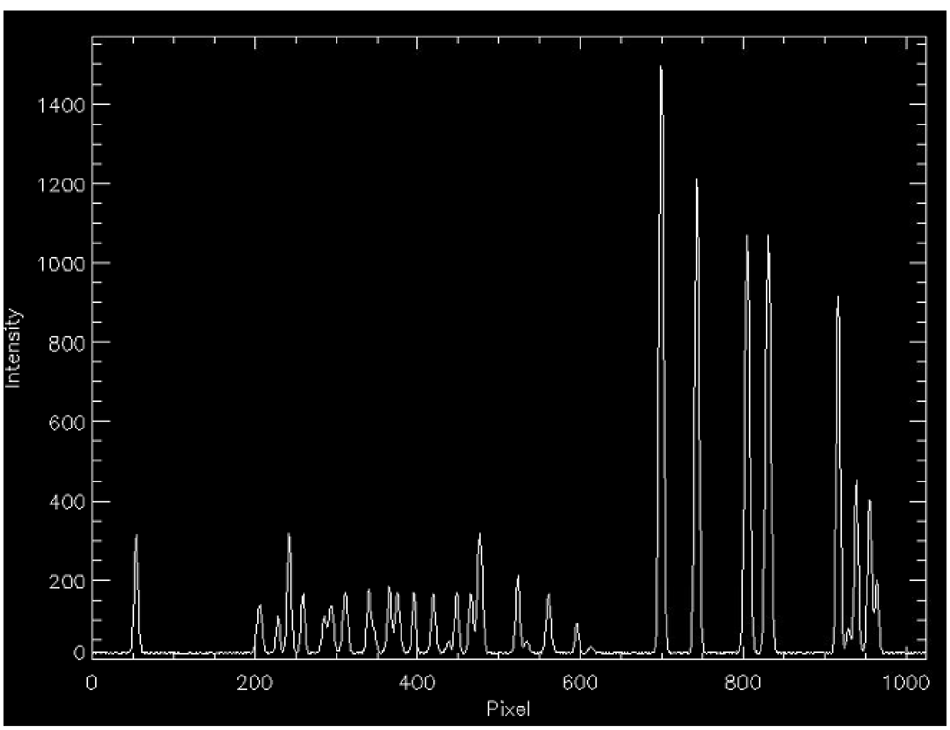

Figure 3. Spectrum of a Neon lamp in "Ne_calib.dat."

Neon has many line transitions in the wavelength range of 500−800 nm as listed in Figure 4,

511.367	640.225
511.650	650.653
540.056	653.288
576.441	659.895
582.015	667.828
585.249	671.704
588.189	692.947
594.483	703.241
597.553	717.394
602.000	724.512
607.433	743.890
609.616	747.244
612.884	748.887
614.306	753.577
616.359	754.404
621.728	837.761
626.649	849.536
630.479	878.375
633.442	1117.752
638.299	1152.275

Figure 4. Wavelengths (in nm) of bright Neon lines. (The source is https://www.oceaninsight.com/globalassets/catalog-blocks-and-images/manuals--instruction-old-logo/wavelength-calibration-products-v1.0_updated.pdf)

and the relative strengths of these lines are shown in Figure 5.

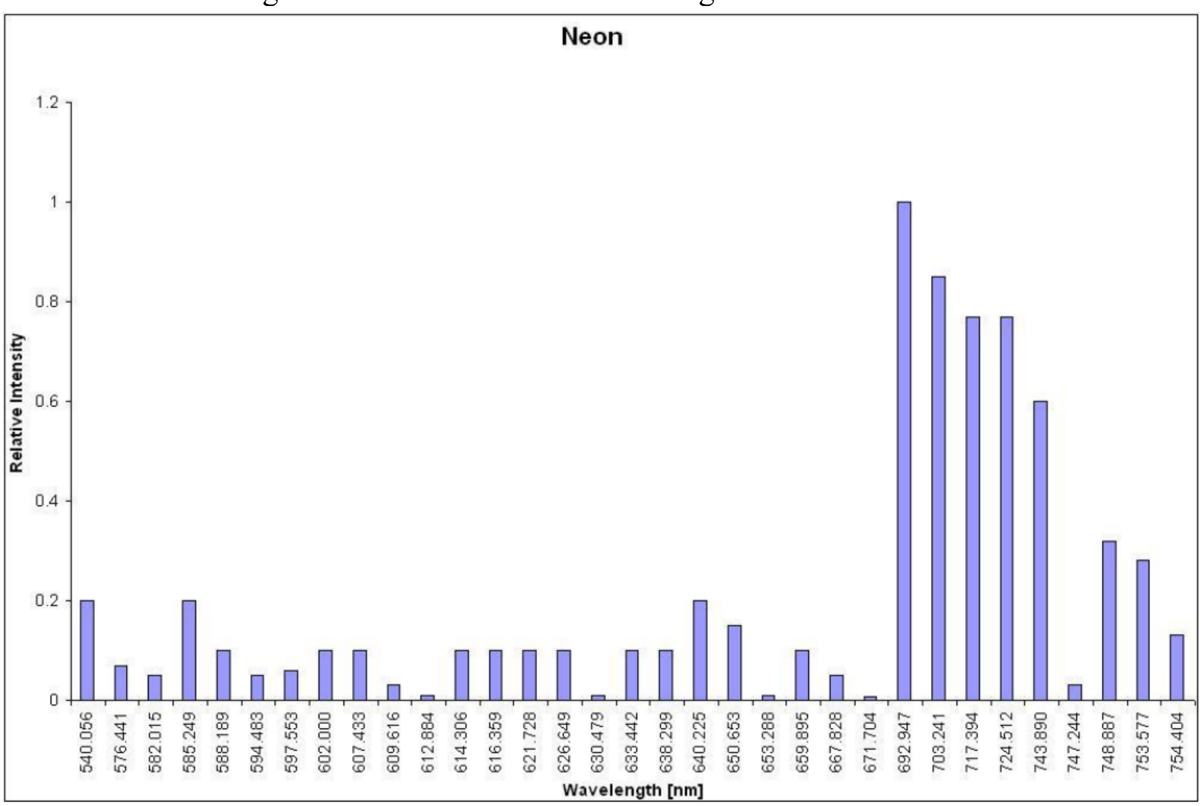

Figure 5. Relative intensities of the Neon lines above. This plot is from the same source as Figure 4.

Now you can obtain the wavelength solution of the spectrum in Figure 3 and determine the temperature of your blackbody. You need to follow the following steps for this.

1. Identify the wavelengths of the Neon lines in Figure 3 as many as possible using the information in Figure 4 and 5. Some nearby lines may overlap.
2. Determine the *centroids* (i.e., pixel positions) of the lines. (There could be many different ways to do it.)
3. Obtain a linear least square fitting between the pixel positions of the Neon lines that you identified and their wavelengths. How good is the fitting? The linear fitting is the wavelength solution.
4. Apply the wavelength solution that you obtained in step 3 above to your blackbody spectrum. Now you know the wavelengths of the blackbody spectrum. What is the temperature of your blackbody?

2.2 Wavelength solution of 2-dimisional dispersed image using OH sky lines to estimate the velocity of ionized iron gas

As we learned in the class, one convenient way to obtain a wavelength solution in the near-infrared waveband is to use the OH sky telluric emission lines. So, let's apply this method to real data. In the same web page above, you can download a file named "**Near-Infrared.fits**" which is a real data file of a 2-dimensional dispersed image of ionized iron gas (= Fe II) from a supernova explosion saved in the FITS (= Flexible Image Transport System) file format. (The FITS format is the standard data format in astronomy.) The file looks like the following if you use a FITS viewer program like DS9 available at https://sites.google.com/cfa.harvard.edu/saoimageds9. (*Note that adjusting scale and changing contrast is important to see images in DS9. You can try ZScale and move mouse on the image with the right button pressed to adjust contrast.*)

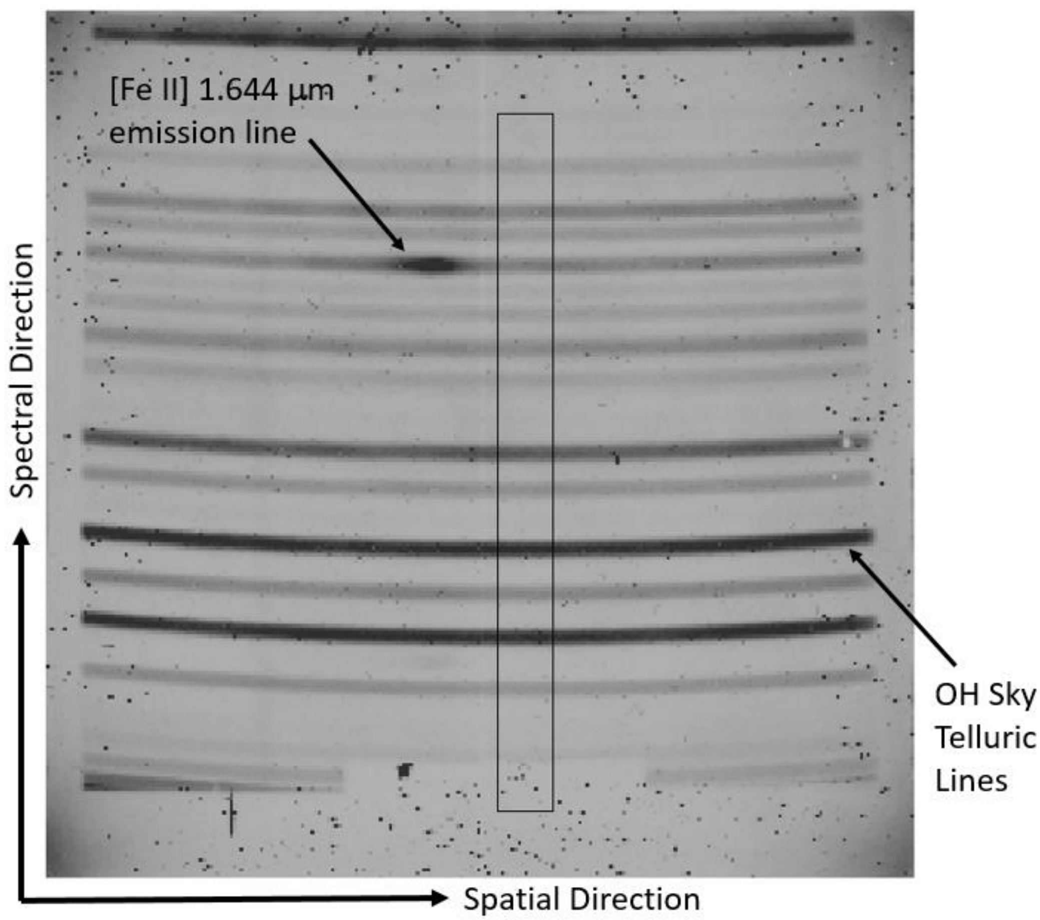

Figure 6. Dispersed image of ionized iron gas from a supernova explosion.

You can see that it is dominated by the OH sky lines, but there exists clear [Fe II] 1.644 micron emission almost overlapping with one of the OH lines. Figure 7 is a spectrum of the OH lines in Figure 6 created by using the area in the rectangle Figure 6 by taking the median value of each row in the rectangle.

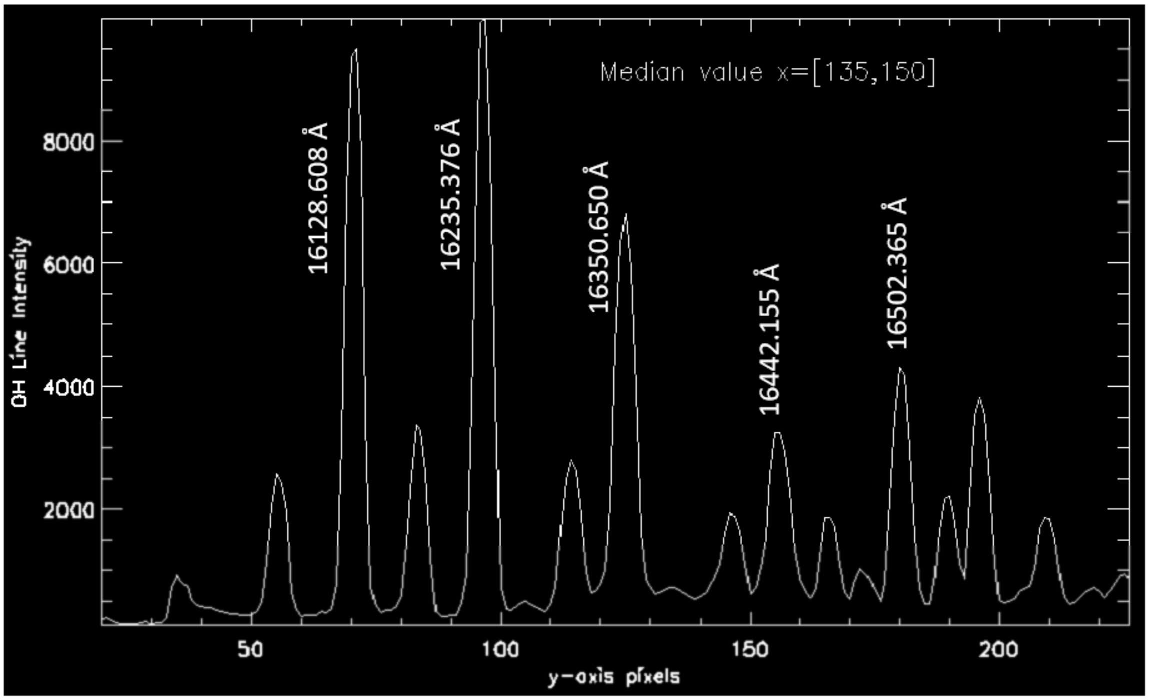

Figure 7. Spectrum of the OH telluric sky lines in Figure 6. Five bright lines are identified with their wavelengths.

Five bright OH sky lines are easily identifiable using the relative intensities of the known OH lines in Figure 8.

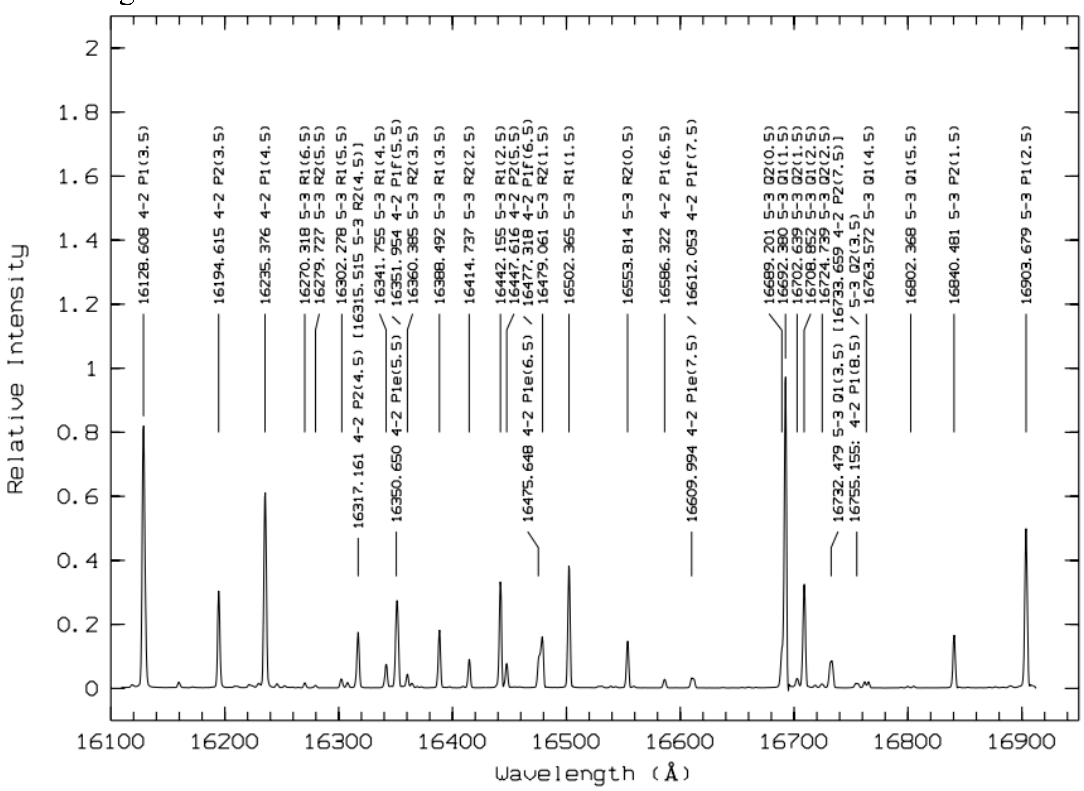

Figure 8. Relative intensities of known the OH telluric sky lines in the wavelength range of 1.610-1.690 micron from the paper of Rousselot et al. 2000. (Note that this paper is linked in the class web page.)

Now you can calculate the velocity of the iron gas in Figure 6 using the observed wavelength of the [Fe II] 1.644 micron line. You need to follow the following steps for this:

1. In addition to the five already identified OH lines, identify as many more OH lines as possible from a region near the [Fe II] emission (e.g., the rectangular box) in Figure 6.
2. Determine the central positions (in terms of y-axis pixel numbers) of the identified lines, and then conduct polynomial fitting of the central positions to the wavelengths. This gives a wavelength solution, which is mapping between the pixel positions and wavelengths. You can choose the degree of the polynomial fit between 1 (= linear least fit) and 3.
3. How good is your wavelength solution, or what is the uncertainty of your wavelength solution?
4. Determine the central position of the [Fe II] emission in Figure 6 in y-axis, and then apply the wavelength solution that you already obtained above using OH sky lines to estimate the wavelength of [Fe II] emission in Figure 6. The intrinsic wavelength of the [Fe II] 1.644 μm line emission is 1.6439981 μm. What's the velocity of the gas emitting the [Fe II] emission in Figure 6?

3. Nighttime Observing with the Campus Telescope

We will conduct real astronomical observations to obtain spectra of bright objects (e.g., Vega, Jupiter, Albireo, Scheat, etc) using a spectrograph on the campus telescope located on the 16th floor of the McLennan Physics tower. Michael Williams (williams@astro.utoronto.ca), who is in charge of the lab equipment and telescope operation, will be there to set up the telescope and spectrograph and help you collect your data. We will use *Shelyak Alpy* spectrograph for the observations. The spectrograph information is available from this link:

https://www.shelyak.com/produit/alpy-600/?lang=en

We will extract spectra of the observed objects after applying the standard data reduction process, including subtraction of dark (bias), flat-fielding, and wavelength calibration. **A guideline of how to conduct the data reduction process will be given during lecture hours. Also, the details of the logistical issues of the nighttime observing session will be posted and explained later on the class homepage and during lecture hours.**