Step 3: Finding the velocity of each galaxy

The velocity is relatively easy for us to measure using the Doppler effect. An object in motion (in this case, being carried along by the expansion of space itself) will have its radiation (light) shifted in wavelength. For velocities much smaller than the speed of light, we can use the regular Doppler formula:

$$\frac{(\lambda - \lambda_o)}{\lambda_o} = \frac{v}{c}$$

λ **measured wavelength**
λ_o rest (laboratory) wavelength
v velocity
c speed of light

The quantity on the left side of this equation is usually called the **redshift**, and is denoted by the letter **z**.

The formula for redshift should remind you of the process where you calculated your percentage error: [(your value) - (true value)] / (true value). Thus, we can view the redshift as a "percentage" wavelength shift.

For this lab, all wavelengths will be measured in Angstroms (Å), and we will approximate the speed of light at 300,000 km/sec. Thus, we can determine the velocity of a galaxy from its spectrum: we simply measure the (shifted) wavelength of a known absorption line and solve the equation **v = c z**.

For Example: *A certain absorption line that is found at 5000Å in the lab (rest wavelength) is found at 5050Å when analyzing the spectrum of a particular galaxy. We first calculate z: redshift = [(measured wavelength) - (rest wavelength)] / (rest wavelength)*

$$z = \frac{\lambda - \lambda_o}{\lambda_o}$$

We find that z = 50/5000 = 0.001 (=v/c) *and so conclude that this galaxy is receding with a velocity of 3000 km/sec* **(v = z*c).**

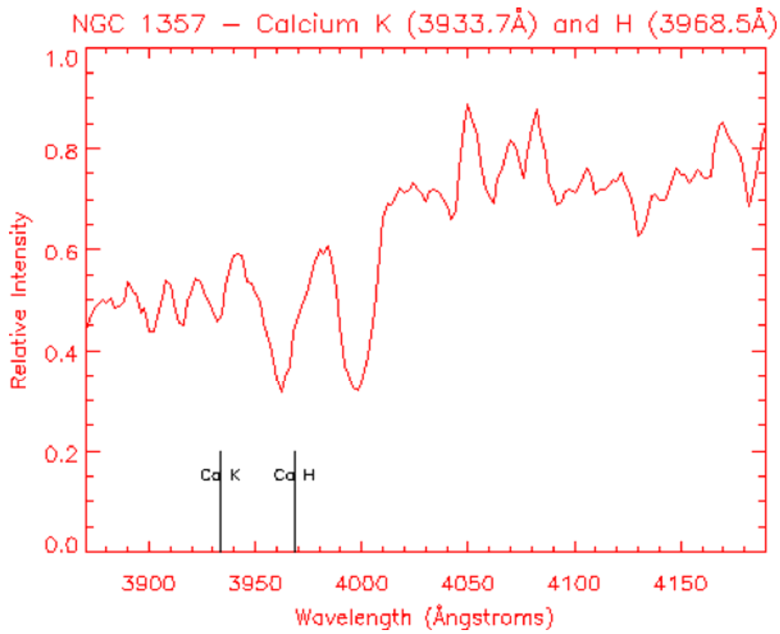
Measuring the Spectral Lines

- The **velocity** of the galaxy is determined by measuring the redshift of spectral lines in the **spectrum** of the galaxy. The full optical spectrum of the galaxy is shown at the top of the web page containing the spectrum of the galaxy being measured (see link below). Below it are enlarged portions of the same spectrum, in the vicinity of some common galaxy spectral features: the hydrogen transitions hydrogen-alpha (656.28 nm), hydrogen-beta (486.13 nm), hydrogen-delta (410.17 nm) as well as the "K and H" lines of ionized calcium (393.37 and 396.85 nm). The enlarged portions of the same spectrum are **"clickable"** and will return a wavelength value corresponding to where you "clicked." Take a brief look at the spectrum for NGC1357 and the analysis of the spectrum. You should try to use similar logic when measuring the rest of your selected galaxies.

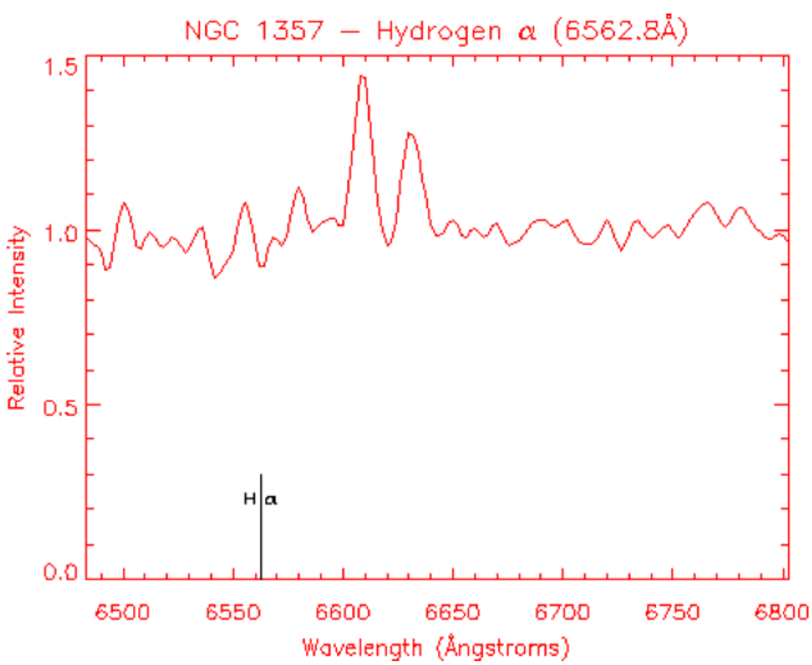
- You are now ready to do your measurements, but before you do, take a look at a sample analysis.

THE HUBBLE LAW

Analysis of NGC1357

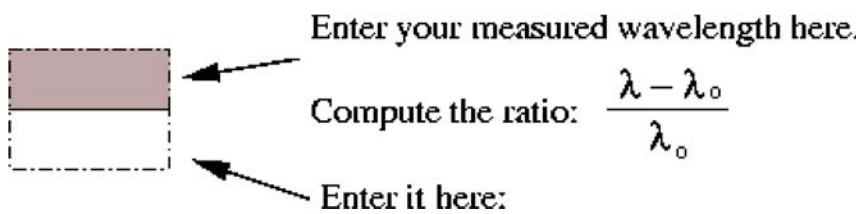


The absorption lines due to ionized calcium will be among the strongest ("deepest") of all the lines. It's a good initial step with any of the spectra to find these two lines. The black lines at the bottom of the figure (Ca K and Ca H) show the location of the **rest** wavelengths. These rest wavelengths are also spelled out at the top of the figure. As you can easily see, the measured wavelengths are going to show a sizeable shift toward redder wavelengths. On the working spectra, you will be clicking at the **bottom** of each of these strong wavelengths. For this galaxy, the measured wavelength of the Ca K line was 3962.0 Angstroms (carry at least 5 significant digits); and for the Ca H, 3997.2 Angstroms. The differences between measured and rest wavelengths are (3962.0 - 3933.7) 28.3 Angstroms and (3997.2 - 3968.5) 28.7 Angstroms. The redshifts are 28.3/3933.7 = 0.0071, and 28.7/3968.5 = 0.0072.



As you can see in this figure, there are two strong emission lines that are greater than 30 Angstroms away from the rest wavelength of hydrogen-alpha, shown by the black vertical line at the bottom. Pick the strong emission line that is to the left (blue-ward) of the other strong emission line, even if the other one has more intensity. (The strong emission line on the right is usually due to oxygen.) We expect the wavelength shift for this hydrogen line to be slightly greater than that of the calcium lines (for reasons that you need not worry about). The measured wavelength was 6608.6 Angstroms, giving a shift of (6608.6 - 6562.8) 45.8 Angstroms. The redshift is 45.8/6562.8 = 0.0070. You should recognize immediately that although the wavelength shift was greater, the redshift (*z*) is nearly exactly the same. (As it should be if we are measuring the correct line; after all, it's the same galaxy!)

1. Make sure you have a copy of the Data Table, either from downloading or from the course pak.
2. Note that for each galaxy there are two lines of data under each "spectral lines" column. The first line contains the measured wavelength. The second line contains the calculated redshift.



3. Start with NGC 1357 to see if you can duplicate or come close to the values discussed under the analysis. Note how the data table has been filled in for NGC 1357, and make sure you understand what numbers go where and what calculations are being done.
4. Move on to the next galaxy, NGC 1832. Note that this galaxy, too, has been measured for you. Again, see if your measurements mimic these.
5. Use the velocities of these galaxies as part of what is needed to calculate the Hubble constant. At this stage you should try to weed out all but about 12-15 galaxies (including those already done).
6. Now move on to the next galaxy that you have selected. Starting with the calcium lines, measure the wavelength of the **same but shifted** line by clicking at the middle of the spectral line (i.e. at the "greatest depth" of absorption or the "peak" of emission) in the spectrum of the galaxy. Write this wavelength in the box below the appropriate line designation in your data table. (Note: It is due to the peculiarities of each galaxy that some spectral lines are absent, or show up in **emission** instead of **absorption**.)
7. Do this for the rest of your selected galaxies, trying to measure the shifts of the 3 lines discussed in the analysis for NGC 1357. For each of your galaxies, you will measure, calculate redshifts, average redshifts, derive a velocity (remember: $v = z * c$). These are the **"y"** values for your graph. Then you will be ready to find the **"x"** values -- the corresponding distances.
8. For the galaxies **not used** simply cross out the row next to the galaxy number.

Here is the "intercept" page (reached on-line, of course) that will link you to the real data for the 27 galaxies.