Astronomy Lab
The Doppler Effect & Age of the Universe

OBJECTIVES:
Explain why the changes in frequency and wavelength occur in the Doppler Effect.
Use spectra to calculate red shift.
Calculate velocity using the Doppler Effect.
Perform simple calculations using the correct number of significant figures.
Use dimensional analysis to convert from one set of units to another (for example km/s to mi/s).
Use real supernova data to create a Hubble Diagram.
Calculate Hubble’s constant.
Measure the age of the universe.
Practice good record keeping.

BEFORE YOU COME TO LAB:
• Review previous exercises: "Significant Figures", "Dimensional Analysis". If you have not already done so, work the last set of problems in your lab notebook.
• Review your notes and the text on the Doppler Effect (Go to the lecture calendar and find the powerpoint slideshow if you missed this lecture).
• Read this write up.
• At the top of a right hand page, enter the title “Doppler Effect and Age of the Universe” (Table of Contents too).
• You can cut and tape in the Objectives above into your lab notebook. Then write “PREPARATION” and answer these questions below in your lab notebook.

PREPARATION:
1. What is the Doppler Effect?

2. What is a supernova?

3. How old is the universe in billions of years?

PROCEDURE:
Background on the Doppler Effect and Supernovae
Type Ia (one-A) supernovae can be used as standard candles to calculate distance. They are the best way to measure cosmic distances up to and beyond 1000 megaparsecs (Mpc). Type Ia supernova are thought to form from the explosion of a white dwarf that has gained too much mass from a companion red giant nearby.
Astronomers measure the spectra of Type Ia supernovae when light from the object passes through a prism to split the light into its different wavelengths (spectrum). The spectra can then be investigated in detail to discover useful information about the light source, such as chemical composition, Doppler shift, and velocity.

The Doppler Effect occurs from a shift (or change) in the wavelength and frequency due to relative motion between the source and the observer. We experience the Doppler Effect when an ambulance drives past with the siren going. As the ambulance (source) approaches you (observer), the sound wave is compressed (squished together) and the sound is higher frequency and pitch (shorter wavelength). The opposite happens when the ambulance drives away from you and this results in a lower frequency and pitch (longer wavelength).

The same Doppler Effect observed from the sound waves coming from the ambulance can be observed with light. When an object giving off light in the universe moves toward Earth, the light waves are pushed closer together and when an object moves away from Earth, the light waves are stretched out. When the light waves are stretched out, the spectra from the light source is shifted toward the red end of the spectrum and called a red shift and the light source is moving away from the observer. If the light source is moving toward the observer, then the spectra is shifted toward the blue end of the spectrum and called a blue shift.

**Gathering Frequencies From the Supernovae Spectra.**
The shifted frequency is known as the observed frequency and can be compared to the frequency at rest for a light source not moving. If both the rest and observed frequency are known, then the red shift can be calculated. For this lab we are using spectra information from Type Ia supernovae from [https://wiserep.weizmann.ac.il/search](https://wiserep.weizmann.ac.il/search). The observed wavelength is taken from the
spectrum with peaks shown where lines would be in the absorption spectra from the supernova. An example spectrum from the first supernova is shown next. The vertical lines are used as the rest wavelengths to compare to the observed wavelengths found from the middle of the spectrum peaks.

![Supernova Spectrum](image)

**Calculate the Red Shift, \( z \), in Column 4.**

The rest and shifted (observed) wavelength, \( \lambda \), information has already been collected for you in the next table. You need to calculate the red shift, \( z \), for each of the supernovae using the formula below. The wavelength units are Angstroms (Å) which is \( 10^{-10} \) m. Use the correct number of significant figures for all your calculations.

\[
z = \frac{\text{observed wavelength}}{\text{rest wavelength}} - 1
\]

<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Supernova Name</strong></td>
<td><strong>Observed Wavelength (Å)</strong></td>
<td><strong>Rest Wavelength (Å)</strong></td>
<td><strong>Red Shift, ( z = (\lambda_{\text{obs}}/\lambda_{\text{rest}}) - 1 )</strong></td>
</tr>
<tr>
<td>SN 2018jky</td>
<td>5958</td>
<td>5872</td>
<td></td>
</tr>
<tr>
<td>SN 2018byw</td>
<td>5744</td>
<td>5576</td>
<td></td>
</tr>
<tr>
<td>SN 2017cbv</td>
<td>5691</td>
<td>5669</td>
<td></td>
</tr>
<tr>
<td>SN 2016fjp</td>
<td>5563</td>
<td>5170</td>
<td></td>
</tr>
</tbody>
</table>
Calculate the Velocity, \( v \), in km/s in Column 5, and mi/s in Column 6.

Next the velocity, \( v \), of each supernova can be calculated using the red shift and the speed of light.

\[
\text{velocity} = \text{redshift} \times \text{speed of light}
\]

The speed of light, \( c \), is approximately 299,792 km/s.

Note: This equation only works for redshift smaller than \( z = 1.0 \)

For the table below, you can rewrite Column 4 Red Shift in this table to make it easier to calculate the velocity in km/s (Column 5) and in mi/s (Column 6). You will need to do Dimensional Analysis when changing the velocity from km/s to mi/s. When you find the velocity in mi/s, show your work below the table in your lab notebook for at least one calculation so you can remember what you did and this makes any mistakes easier to see. Use \( 1 \text{ mi} = 1.609 \text{ km} \).

<table>
<thead>
<tr>
<th>Supernova Name</th>
<th>Red Shift, ( z=(\lambda_{\text{obs}}/\lambda_{\text{rest}})-1 )</th>
<th>Velocity, ( v=z^*c ) (km/s)</th>
<th>Velocity, ( v ) (mi/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 2018jky</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SN 2018byw</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>SN 2017cbv</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SN 2016fjp</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Graph the Distance and Velocity Data. Calculate Hubble’s Constant, Column 8.

The distance, \( d \), to each of the supernova has already been calculated for you in the next table using the apparent magnitude of each supernova as compared to the standard magnitude of Type Ia supernovae (magnitude of -19.6). The apparent magnitude data for the supernovae was gathered from: https://sne.space/. Take the time to rewrite Column 6, velocity, \( v \) (mi/s) in the next table. You will need the distance and velocity data together to plot them in your next steps.

Use the data from Columns 7 and 6 in the next table to create a graph known as Hubble’s Diagram. Plot or graph Column 7, distance, \( d \), on the x-axis (horizontal) and Column 6, velocity, \( v \) (mi/s), on the y-axis (vertical) for each of the supernovae on the graph provided or recreate the graph in your notebook. Wait to calculate Column 8 until after you have graphed Columns 7 and 6.
<table>
<thead>
<tr>
<th>Supernova Name</th>
<th>Distance, d (Mly=million light years)</th>
<th>Velocity, v (mi/s)</th>
<th>Hubble’s Constant, H=v/d (mi/s/Mly)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN 2018jky</td>
<td>312</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SN 2018byw</td>
<td>535</td>
<td></td>
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</tr>
<tr>
<td>SN 2017cbv</td>
<td>54.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SN 2016fjp</td>
<td>1360</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Hubble's Diagram**

Hubble's Law $v=Hd$
This plot of velocity vs. distance is known as Hubble’s Diagram from which we get Hubble’s Law:

\[
\text{velocity} = \text{Hubble’s constant } \times \text{ distance} \\
\text{v} = H \times d
\]

**Draw a Best-Fit Line Through Your Graphed Data.**
Now look at your Hubble’s Diagram and use a ruler to draw a straight line through the data as a best-fit to your data. This straight line needs to go through the origin or the point (0, 0) on the graph. The line you draw will not connect all of your points for each supernovae but instead will be a line that is best fit in between each of the points.

**Calculate Column 8 and Your Average Hubble’s Constant.**
Use the distance (millions of light years) data in Column 7 and the velocity (mi/s) data in Column 6 to calculate column 8, Hubble’s Constant, H. You can find Hubble’s Constant, H, using the formula below.

\[
H = \frac{v}{d}
\]

After you have each of the Hubble’s Constant values, average them using the common average formula below.

\[
H_{\text{average}} = \frac{(H_1 + H_2 + H_3 + H_4)}{4}
\]

**Calculate the Age of the Universe.**
1. Step 1. Calculate the average Hubble’s Constant from the 4 supernovae data using the average formula above. This \( H_{\text{average}} \) is also the slope of the line in your graphed data. This is your answer to question 1 on the next page.
2. Step 2. Use your calculator to take \( 1/H_{\text{average}} \). You can use the \( 1/x \) button on your calculator to do this.
3. Step 3. Multiply your answer by \( 5.879 \times 10^{18} \) mi/Mly, which is the number of kilometers in the distance of a million light years. You can use your mobile phone as a scientific calculator if you turn the calculator app sideways (horizontal) then the EE button is visible. You can enter this in your calculator as follows: \( 5.879 \) then EE button and then \( 18 \) and then =.
4. Step 4. Divide your answer by \( 3.1536 \times 10^{16} \) s/Byr, which is the number of seconds in a billion years.
5. Step 5. Now you have the age of the universe in billions of years (Byr). Label your answer and include units. You can write this down as your answer to question 1 coming next.
QUESTIONS:
1. What is your average H, Hubble’s constant? (include units)

2. What is your calculated age of the universe? (include units)

3. How does your calculated age of the universe compare to the actual age of the universe you wrote down at the beginning of this lab write-up? (larger or smaller) Your calculation is wrong because it does NOT include inflation or the rapid expansion of an early, tiny universe.

4. What would happen to the calculated age of the universe if the Hubble constant were:
   a. larger than you found?
   b. smaller than you found?

5. Refer to your redshift values in Column 4. What does it mean that all your red shift values are positive?

6. What would it mean if your redshift were negative?

7. Why does the best-fit line to your data need to go through the origin of your graph? Think about what this "origin" corresponds to in the Universe.

8. Ideally your plot should be a straight line, but it probably isn't. Consider and write down a few of the possible sources of error. These error sources may lead to calculating a different age of the universe than what scientists actually estimate currently. (Inflation theory is the main reason your age of the universe is calculated incorrectly here).