The Doppler Effect

With Applications to Astronomy

The Doppler effect is a phenomenon of waves, observed when either the source of the wave, or the observer, is moving with respect to the other. This causes the frequency of the wave to appear to increase or decrease, based on the direction, and how fast the source and observer are moving away from or toward each other. You have heard, for example, a car horn that passes by seems to go up in pitch as it approaches, and go down in pitch as it moves away. The Doppler effect is also observed with light emitted from galaxies and other luminous objects in space, receding from Earth's point of view, throughout our expanding universe. In this experiment, we will explore the Doppler effect with sound, and then extend these principles to astronomy in the context of light.

Watch the video explaining The Doppler Effect experiment; https://youtu.be/2pdtsnUbVE4

What you will need:

- Smartphone with the PhyPhox app installed (https://phyphox.org/)
- Tablet or laptop with internet (tone generator app or website, keyboard, etc.)[1]
- Calculator

[1]Here's a good on-line tone generator; https://www.szynalski.com/tone-generator/

Procedure

Set-up:

With an online tone generator, you will be able to select the frequency you would like to try for your experiment. Choose a frequency within the range of between 800 Hz and about 1200 Hz (the optimum range for phone microphones). If you want to verify the exact frequency from the tone generator, the **Audio Autocorrelation** function in the Audio section of Phyphox will help you determine the exact frequency of your audio source. Your audio source must be a true and stable pitch, matched to the PhyPhox app.

Open the Phyphox app, and under Acoustics, find **Doppler Effect**. You will be presented with four parameters, the most important of which is the **base frequency**. While the speed of sound varies with medium and temperature, the default setting of 340 m/s (the speed of sound in air at room temperature) will be suitable for most indoor environments.

Once you have identified the exact frequency you want to try for your experiment, enter that value as the **base frequency**. For the purposes of our experimental calculations, we will define the base frequency as the **source frequency**.

Doing the Experiment

Once you have decided on the frequency you want to use to conduct your experiment (source frequency, f_s), calculate the corresponding wavelength (source wavelength, λ_s), using the equation below.

Beginning with the familiar equation relating wavelength and frequency to the speed of light,

$$c = \upsilon\lambda$$

substitute C_s for the speed of sound (340 m/s), and find the **source wavelength** (λ_s) for your chosen frequency, f_s.

Show your calculation and answer with the correct units.

$$\lambda_b = \frac{C_s}{f_b} =$$

answer ____________

With this, you can begin the experiment. You will be collecting data related to sound. Any talking, shuffling, traffic, fan running, fidgeting with the phone, or other outside sounds will be picked by the microphone and distort your data. **Quiet is key**!

1. Set up your laptop (or other audio source) as close as you can to where you will sit or stand, still allowing enough space for you to circle your phone (running Phyphox) overhead. You will simply swing your phone overhead (microphone facing outward), with your arm outstretched.

2. When you are ready to begin collecting data, start the audio source, and press the play button at the top of the screen on the Doppler effect experiment.

3. Circle the phone overhead, doing your best to maintain a **constant radius** and a **constant speed**. These are crucially important parameters!

   Try for 15-20 rotations, at a rate of about two seconds per rotation. Your data will reflect the **frequencies observed** by your phone while it is in motion.

4. Stop data collection with the pause button, and pause the sound source.

1. Go to the **Results** tab, and click on the frequency graph. Your graph should consist of a series of repeating ups and downs. Drag/expand the view to fill the screen for a full view of 4-5 cycles, similar to the graph below.

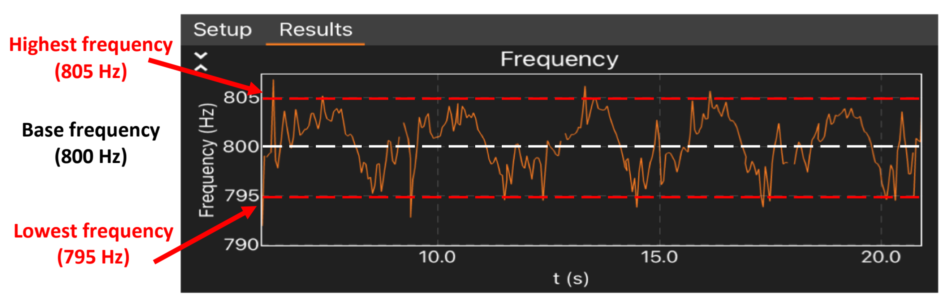


Figure 1. Sample data using a base frequency of 800 Hz.

Make a drawing of your own graph, showing the overall shape of the data, and labeled axes. Show the values of the highest and lowest frequencies, and the base frequency. Use arrows to indicate,

(a) where on the graph you think your phone is **moving away** from the audio source, and

(b) where you think your phone is **moving toward** the audio source.

From the frame of reference of your phone, it would appear as if the frequency is changing with time, but from your reference frame, this would not be the case. This is the Doppler effect; *an apparent change in frequency (or wavelength) of a wave resulting from the relative motion between the source of the wave and the observer* (in this case, your phone). The speed of sound for both the moving observer (your phone) and a stationary outside observer (you) is the same, constant under the same conditions of air and temperature.

Using the highest and lowest **frequencies** recorded by your phone during your experiment, calculate corresponding wavelengths. Show and label your calculations and answers below. You will actually use these wavelengths to calculate the velocity of the phone at these points along its path.

Wavelength of the highest observed frequency,

$$\lambda_{high\ frequency} = \frac{c_s}{f_{high}} =$$ answer ____________

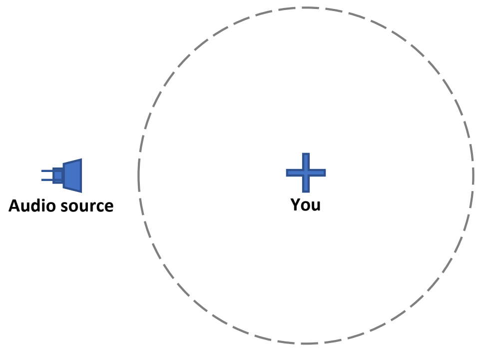
Wavelength of the lowest observed frequency

$$\lambda_{low\ frequency} = \frac{c_s}{f_{low}} =$$ answer ____________

Review of Concepts

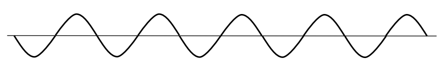
1. You and your phone (the observer), are in different reference frames, with respect to time. Were you able to hear these changes in pitch of the sound? Explain whether you think you should be able to hear the same changes in pitch recorded by your phone and why.

2. The diagram below is a top down view of the path of motion of your mobile phone relative to the audio source.
    a. Draw an arrow to show the direction in which the phone is moving on the path.
    b. Label the position(s) on the circular path (using H, L and E) where the frequency you measured was the ***highest frequency*** (H), the ***lowest frequency*** (L), and the ***frequency equal*** to the base frequency (E).



    c. Which position would represent the longest wavelength? (circle one) H L E
    d. Which position would represent the shortest wavelength? (circle one) H L E

3. The shape of the wave for a source frequency in a Doppler experiment is shown below.



In the following table, draw what you think the shape of the wave will be (compared to the above wave) with the motion of the observer. Also indicate if you think the *frequency* will increase or decrease, compared to the original frequency.

Movement of observer	Shape of the wave	Observed frequency will (circle one)
Toward the audio source		increase / decrease
Away from the audio source		increase / decrease

4. Describe the frequency or pitch of the sound ***you heard*** from the audio source as you swung the phone around overhead during the experiment.

5. Describe any points in the path of motion of the phone where the frequency recorded by your phone was equal to the base frequency, and explain why this might occur.

6. Using the two wavelengths you already calculated above for the highest and lowest frequencies, and the wavelength of the source frequency, you can actually calculate the velocity of your phone (1) moving away from the sound source, and (2) moving toward the sound source, using the equation below. Show both calculations and label your answers to include the correct units, using the following equation.

$$v_{phone} = c_s \frac{\lambda_{observed} - \lambda_{source}}{\lambda_{source}}$$

7. One of the two calculations above will give you a positive answer; the other, negative. What do these signs tell you about the direction of motion of the phone, relative to the audio source? (Hint – Consider the relationship between the sign and where the wavelength occurs in the orbital path diagram.)

8. Think of an everyday example of something that relies of the Doppler effect to work.

9. Describe how you think your results would be affected if, instead of the phone in motion, the phone was fixed in position and the audio source circled around the phone?

Applications to Astronomy

Light reaching us from distant galaxies and other luminous objects in space bears a common message – the universe is expanding. How do we know? The answer comes from what astronomers refer to as a consequence of the Doppler effect called ***redshift***.

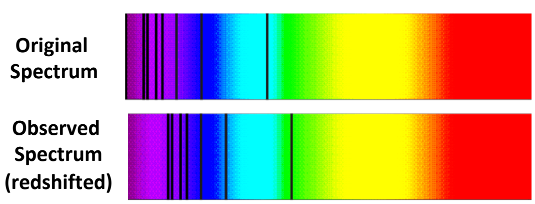
Light, like sound, is also a wave and, in a similar way, light waves can also appear to be either compressed or expanded, relative to the motion of the source and/or observer. Light waves reaching Earth from distant galaxies *almost* always appears to be a longer wavelength (redder) than they really are, appearing slightly closer the red end of the visible spectrum, or ***redshifted***.

The idea of an expanding universe was proposed by Edwin Hubble in 1929. Hubble built his theory from observations by Indiana native V.M. Slipher, who noted in 1914 the redshift the spectra of stars in distant galaxies indicating they were moving much faster than stars in our own galaxy (the Milky Way). Slipher calculated the velocities of these galaxies using the Doppler shift.

The Doppler effect with regard to light provided the first concrete evidence that the universe is expanding. The wavelengths of known sources of light from distant luminous objects across the cosmos appeared typically have wavelengths slightly longer than they should. Analogous to sound, the longer apparent wavelengths from these sources imply that they must be moving away. The further away the objects are, the greater the redshift; the faster they are moving.

The spectrum of light, emitted from a galaxy or a star, nebula, supernova and other luminous objects, exhibits distinct black lines absent of color. The missing wavelengths in these absorption spectra are tell-tale signatures of the chemical elements of which the object and its environment is composed. In an **absorption spectrum,** specific wavelengths of light are **absorbed** by the gases in and surrounding the object, and therefore appear to be dark bands out of a continuous, rainbow spectrum.

Figure 2 compares the absorption spectrum of our sun (not moving away from us here on Earth), and the spectrum of a galaxy outside our local group. The **spectral lines** in the lower figure are shifted toward longer wavelengths in the spectrum from where they are expected, implying that the source is in motion.



http://voyages.sdss.org/preflight/light/redshift

The top figure shows the spectral lines in the absorption spectrum of our sun.

Notice that the spectral lines of the galaxy in the lower figre are shifted toward the red (longer wavelength) end of the spectrum, indicating that the galaxy is moving away.

Redshift

The spectra of all galaxies outside our local group exhibit spectral lines at a longer (redder) wavelength than expected. Redshift (z) can be calculated using a ratio, similar to the way you used the wavelength ratios with sound, here using the shift in wavelength, where λ_s represents the **source wavelength** when the sources is not moving, and λ_o the **observed wavelength**.

$$Redshift\ (z) = \frac{\lambda_o - \lambda_s}{\lambda_s}$$

As an example, if the source wavelength of a spectral line is known to be $393.3\ x\ 10^{-9}\ m$, and that line in a receding galaxy is found to be 401.8 x 10^{-9} m, the red shift of that galaxy would be:

$$z = \frac{\lambda_o - \lambda_b}{\lambda_b} = \frac{401.8\ x\ 10^{-9} m\ -\ 393.3\ x\ 10^{-9}\ m}{393.3\ x\ 10^{-9}\ m} = 0.0216$$

Velocity

While different in context, the same equations apply to light that we used for sound. With this in mind, we can calculate the motions (radial velocities) of the galaxies and other objects, using the shifts in wavelengths of the light we measure. Hubble also discovered that the further away an object was, the more redshifted its spectrum, implying the faster it was receding, potentially exhibiting velocities that can approach the speed of light. To be consistent with convention, we'll use the speed of light, $c = 3.00 * 10^5\ kms^{-1}$.

$$v = c * z = c\,\frac{\lambda_o - \lambda_s}{\lambda_s}$$

Taking the redshift from the previous calculation, we can now calculate the speed at which the galaxy in our example would be moving away, relative to Earth:

$$v = c * z = 3\ x\ 10^5\ km\ s^{-1} * 0.01216 = 6480\ \text{km} * s^{-1}$$

Distance and Hubble's Law

One of the most significant revelations from Hubble's data in the late 1920s was his discovery of a relationship between the speed of recession of galaxies (how fast they are moving away) and the distance they are from Earth. This is summarized in Hubble's Law, $\boldsymbol{v} = \boldsymbol{H_0}\ \mathbf{d}$, or $\boldsymbol{H_0} = \frac{\boldsymbol{v}}{\boldsymbol{d}}$, where

v = velocity of a galaxy (in km/s)

H_0 = Hubble constant (measured in km/s/mega-parsec)

d = distance to the galaxy (in mega-parsecs, Mpc; 1 Mpc = 3.3 x 10^6 light years)

Applying the quantities from the previous calculations,

$$Distance = \frac{c * z}{H} = \frac{3\ x\ 10^5\ km\ s^{-1} * 0.0216}{70.8\ km\ s^{-1} Mpc^{-1}} = 91.5\ Mpc = 3\ x\ 10^8\ light\ years$$

Now, try your hand, using your knowledge of the Doppler effect and redshift, to answer the questions that follow.

Review of Concepts

1. A spectral line from a red giant has a base wavelength of 589 nm. When observed from Earth, however, astronomers find the spectral line is slightly redshifted to 591 nm. How fast, and in what direction is the star moving relative to Earth?

2. A star that produces yellow light at a frequency of 581.2 nm is observed to be moving through the night sky. When astronomers view the absorption spectrum of the star, they see a spectral band at the same wavelength, 581.2 nm. How could it be that a star might be moving with respect to Earth, while still producing light of a frequency that appears the same relative to both Earth and its position in the sky?

3. If the wavelength of 65nm is emitted by one component of a double star is shifted by 0.05 nm compared with that of its companion, what would be the velocity of the companion?

4. All galaxies outside the Local Group exhibit redshift. Within the Local Group, however, some galaxies exhibit a spectral shift in the opposite direction, a ***blueshift***. The Andromeda Galaxy (M31) is such an example. What do you think this might tell you about the trajectory of M31 relative to our own Milky Way Galaxy?

5. Spiral galaxy NGC 1232, found in the constellation Eridanus, has a velocity of 1603 km/s relative to Earth. Using a value for the Hubble constant of 70.8 $km\ s^{-1} Mpc^{-1}$, calculate the distance, in light years, that the galaxy is from Earth.

Additional resources:
https://www.teachastronomy.com/textbook/The-Expanding-Universe/Relating-Redshift-and-Distance/
http://astro.wku.edu/astr106/Hubble_intro.html

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