

Determining the Motion of Galaxies Using Doppler Redshift

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Overview

The Doppler effect of sound is a method used to determine the relative speeds of an object emitting a sound and an observer. Depending on whether the source and/or observer are moving towards or away from each other, the frequency of the wave will change. This in turn creates a change in pitch perceived by the observer. The relative speeds can easily be calculated using the following formula:

$$f' = f \left(\frac{v \pm v_o}{v \pm v_s} \right),$$

where f' represents the shifted frequency, f represents the frequency of the source, v is the speed of sound, v_o is the speed of the observer, and v_s is the speed of the source. v_o is added if moving towards and subtracted if moving away from the source. v_s is added if moving away and subtracted if moving towards the observer.

The figures below help to demonstrate the perceived change in frequency. The source is located at the center of the smallest circle. The picture shows waves expanding as they move outwards away from the source, so the earliest emitted waves create the biggest circles. If both the source and observer were stationary, the waves appear to pass at equal periods of time, as seen in figure IA. However, if the source is moving, the frequency appears to change. Figure IB shows what would happen if the source moves towards the right. Although the waves are emitted at a constant frequency, they seem closer together on the right side and farther spaced on the left. So if an observer were located to the right of the source, the observer would detect waves passing more frequently than the actual frequency emitted by the source. Conversely, an observer to the left of the source would detect waves passing less frequently.



Figure IA. Emission of waves from stationary source.



Figure IB. Emission of waves from source moving to the right.

Light waves act in a similar manner. If the source is moving away from the observer, the light appears to have an increased wavelength or shifts closer to the red end of the light spectrum. As wavelength increases, the frequency decreases. Conversely, if the light is moving towards the observer, the light appears to have a smaller wavelength or shifts closer to the blue end of the light spectrum, and the frequency increases. These changes in wavelength are named redshift and blueshift, respectively.

Scientists have conducted research that has shown that light from distant galaxies is always redshifted. Therefore, all galaxies are moving away from our own. This must mean that our universe is expanding. Also, the speed of the galaxy is directly proportional to its distance, as described by Hubble's law. So, galaxies that are the farthest away from Earth are moving away from us the fastest.

Rationale

"My students are robots," is a statement I have made many times over the past few years. What do I mean by calling them robots? I started my teaching at a charter school that emphasized the "I do, We do, You do" model. I would teach them how to solve a certain type of problem; we would practice solving the same type of problem a few times; and then students would solve more problems in the same manner. If students were able to replicate the method I showed them to solve the problems, they would succeed. They were never asked to think for themselves or explain an answer. Students were programmed to answer the questions a certain way and would often forget what they learned after an assessment.

However, I want more for my students. I want them to be critical thinkers equipped with the skills necessary to solve real problems. I want them to question theories and laws taught in class; they should want to prove it for themselves through discovery and research, rather than just accepting the concepts taught as fact. Because of this desire to push my students to higher-order thinking, I have begun to incorporate more inquiry

activities and discussions as I encourage my students to make observations, gather and analyze data, and think for themselves.

I will be challenging my students in a few ways throughout this unit. I will begin the unit with a lecture and activities on the Doppler effect. They will be asked to apply what they learn about the Doppler effect in order to make predictions about redshifts. We will have a class discussion comparing the two phenomena. At the end of the unit they will conduct their own research similar to that of a physicist or astronomer. They will obtain real data and analyze what they collected in order to study the movement of distant galaxies. I believe these activities will encourage my students to think deeply and apply what they learn. They will also gain a better understanding of authentic science research through this experience.

Objectives

This unit is designed to be taught to a group of 11th graders enrolled in an introductory physics course. It will be an addition to the unit on waves already being taught in the course.

The objectives of the unit are the following:

- Describe and calculate the properties of a wave
- Explain the Doppler effect
- Calculate the speed of a source and/or observer using the Doppler effect
- Explain redshift
- Compare the Doppler effect of sound to the Doppler effect of light
- Utilize real data to determine the movement of distant galaxies
- Understand how scientists collect and analyze data in order to make predictions about natural phenomena

Strategies

We will begin the unit with an introduction on waves and their properties. Students should be able to differentiate between longitudinal and transverse waves. They should also be able to label and calculate various qualities of a transverse wave, such as the following: crest, trough, amplitude, wavelength, frequency, period, and speed. Students will then explore the Doppler effect of sound. They will have both lecture and exploratory labs inside and out of class. This will then be followed by its relation to the Doppler effect of light. This will all lead to a culminating activity related to the motion of galaxies.

Students will explore the Doppler effect of sound with an inquiry-based activity using smart phone applications. One of the most important activities will be a discussion on how the Doppler effect of sound and light are related. Students will be challenged to

predict occurrences based on what they know about the Doppler effect. Finally, students will choose a galaxy and calculate its distance from Earth using real data.

Classroom Activities

Five lesson plans are outlined below. This unit is made as an addition to the waves unit already designed for my physics classes. Depending on your students' previous knowledge, it may be helpful to spread out the activities over a few more days. The first lesson especially may need to be broken into smaller lessons if your students have not been previously exposed to wave properties.

Lesson Plan 1: Properties of Waves
<p>Learning Objective</p> <ul style="list-style-type: none">● Students will be able to analyze known wave properties in order to calculate and describe unknown properties.
<p>Materials</p> <ul style="list-style-type: none">● Slinky
<p>Key Terms</p> <ul style="list-style-type: none">● Amplitude● Frequency● Period● Wavelength● Crest● Trough
<p>Do Now</p> <p>What do you already know about waves?</p>
<p>Procedures</p> <ol style="list-style-type: none">1. The teacher should begin with a lecture on the properties of waves. Definitions of the key terms should be explained. Both written definitions and pictures of waves should be used to ensure understanding.2. The teacher can then use a slinky to demonstrate the difference between longitudinal and transverse waves. A student volunteer can be used to hold one end of the stretched slinky. The teacher can apply forces in various directions to produce both longitudinal and transverse waves.3. Finally, the teacher should demonstrate how to solve problems related to wave properties.

4. The teacher and students should participate in guided practice of various wave property questions and problems.
5. The lesson should end with independent practice on wave property questions and problems.

Assessment

Exit ticket: A sound wave traveling in air has a wavelength of 0.08m. Calculate its frequency.

Homework

The teacher should assign practice questions and problems on wave properties.

Rationale

This lesson sets the groundwork for the rest of the unit. It is important that students understand wave basics and how different wave characteristics are related to each other. It may be necessary to break this lesson into a few smaller lessons if your students do not have any background in waves.

Lesson Plan 2: The Doppler Effect of Sound

Learning Objective

- Students will be able to investigate the Doppler effect of sound in various scenarios in order to calculate and analyze the perceived frequency of a sound.

Materials

- Video

Key Terms

- Doppler shift
- Source
- Observer

Do Now

How does an ambulance or police siren sound as it approaches and then passes you? Hypothesize why you think this happens.

Procedures

1. The teacher should begin with a sharing of student answers to the Do Now question.
2. The teacher should then show a video on the Doppler effect of sound.

3. Finally, the teacher should lecture on the Doppler effect and demonstrate how to solve problems related to the Doppler shift of sound.
4. The teacher should then guide students through solving more problems related to the Doppler shift, gradually releasing more responsibility to the students. The teacher may even allow some time for students to explain their methods of solving each problem to their peers.
5. Students should be given time to solve problems on their own before the end of class to ensure they fully understand the Doppler effect of sound.

Assessment

Exit Ticket: An ambulance emits a sound with frequency of 350 Hz. What frequency do you hear standing on the sidewalk as the ambulance moves towards you at 15 m/s? As it moves away from you at 15 m/s?

Homework

Doppler Effect Lab (see appendix)

This is a great lab that demonstrates the Doppler effect. Students can see and hear the frequency/pitch change in real time. This activity may also be completed in class. However, any outside noise affects the readings, so student groups will need to spread out throughout the school. Depending on the age, maturity and responsibility of your students, this may not be feasible. It will also be helpful to demonstrate with a student exactly what they should be doing in the lab to make sure they understand how to complete it.

Rationale

This activity introduces the Doppler effect. Students should be familiar with the idea, although they may not have known the name for the phenomenon. You may want to reference the sound of cars driving by or ambulance sirens, etc. As for the video, there are a few free videos on the internet that have great graphics that explain the perceived change in frequency. This may also be replaced with the student resource created by McGraw Hill. Finally, it is also important to practice solving problems, as some students may struggle with the algebra when completing the lab activity.

Lesson Plan 3: Doppler Shift of Light

Learning Objective

- Students will be able to connect what they have learned about the Doppler Effect of Sound to the Doppler Effect of Light in order to hypothesize how light is shifted.

Key Terms

- Redshift
- Blueshift
- Electromagnetic spectrum

Do Now

A police siren emits a sound at a frequency of 300 Hz. After it passes you standing on a sidewalk, you measure a frequency of 280 Hz. How fast was the police car moving?

Procedure

1. The teacher should begin with a sharing of student answers to the Do Now question.
2. The class should then have a discussion about the lab results. Topics to cover should include the following:
 - a. Experimental Results
 - b. Theoretical Results
 - c. Difficulties in completing the lab
 - d. Sources of Error
 - e. Improving the Lab / Possible Supplemental Lab Activities
3. The teacher should then transition to a lecture on the Doppler shift of light. The teacher can begin by stating that light and sound behave in similar ways. The following question should be posed to the class: If light behaves similarly to sound, how could astronomers use light from a distant galaxy to determine the motion of the galaxy? The teacher should solicit various responses.
4. Finally, the teacher should lecture on the Doppler effect and demonstrate how to solve problems related to the Doppler shift of light. The electromagnetic spectrum should be used, especially to explain the relevance of the names “redshift” and “blueshift”.
5. The teacher should then guide students through solving more problems related to the Doppler shift, gradually releasing more responsibility to the students. The teacher may even allow some time for students to explain their methods of solving each problem to their peers.
6. Students should be given time to solve problems on their own before the end of class to ensure they fully understand the Doppler effect of sound.

Homework

Doppler Shift Practice Problems (Sound and Light)

Rationale

The class discussion should help students understand the results from the lab and to solidify their understanding of the Doppler effect of sound. It is also important to understand sources of error and how these could be reduced or eliminated in future

trials. As the discussion transitions onto light, students should be given ample time to brainstorm ideas with their peers. Finally, the teacher and students should complete practice problems on the Doppler shift of light. This should give students plenty of practice with the algebra involved with solving Doppler effect problems.

Lesson Plan 4: Galaxy Redshift Research

Learning Objective

- Students will be able to analyze data of light from distant galaxies in order to calculate the galaxy's velocity in reference to Earth.

Materials

- Computers: <http://skyserver.sdss.org/dr12/en/tools/chart/navi.aspx>

Key Terms

- Redshift
- Blueshift
- Observed frequency
- Source frequency
- Speed of Light

Do Now

What is redshift? What is blueshift?

Procedure

1. The teacher should begin with a sharing of student answers to the Do Now question.
2. The teacher should then review expectations for the lab. The teacher should also demonstrate how to use the website. The teacher should also use this time to explain how wavelength relates to the Doppler effect equation.
3. Students will work in pairs to complete the lab activity to determine the velocity of galaxies.
 - a. They should begin by determining the speed of a predetermined galaxy. Answers should be shared as a class to ensure everyone knows how to use the website and complete the calculations.
 - b. Students should then complete calculations for their own galaxy. Students can choose a galaxy or the teacher can assign various galaxies to students.
4. Students should share their data with the class. This can be done on a poster or whiteboard OR, preferably, on a shared Google docs document or similar online format.

Homework

Complete any remaining work from the lab assignment.

Rationale

It is imperative that students understand the relationship between wavelength and frequency. They will be accustomed to obtaining a change in frequency from their past work with the Doppler effect. They also need to understand that this leads to a change in wavelength as well. The data collected will be the wavelengths of various spectra. As frequency decreases, wavelength increases.

In order to increase student engagement and buy-in, it may be helpful to allow students to explore the skyserver program. As they look through the universe, they will see pictures of many different objects that may pique their interest. Once they have been given ample time to explore, they can be prompted to choose a galaxy and begin calculations. This may also lead to different galaxies being studied, and therefore, more data to use for observations.

One question asks students to use algebra to prove that the math they did makes sense. The original Doppler effect equation explained at the beginning of this paper can be rewritten by substituting in the wave equation.

$$\frac{v}{\lambda'} = \frac{v}{\lambda} \left(\frac{v}{v \pm v_s} \right)$$

Since we are determining the speed of the galaxy in relationship to Earth, we make v_o zero to simplify the mathematics. With a little bit of algebra manipulation, you can rearrange the equation to solve for v_s .

$$v_s = \left(\frac{\lambda'}{\lambda} v \right) - v$$

Factoring out v leads to the following:

$$v_s = v \left(\frac{\lambda'}{\lambda} - 1 \right)$$

Finally, the equation can be rewritten to show the math that is completed in the activity.

$$v_s = v \left(\frac{\lambda' - \lambda}{\lambda} \right)$$

Lesson Plan 5: Galaxy Redshift Research Discussion

Learning Objective

- Students will be able to analyze data collected from various galaxies in order to make a prediction about the movements of our universe.

Key Terms

- Redshift
- Doppler Effect of Light
- Big Bang Theory

Do Now

What were some trends from the data collected from the class? What does that tell you?

Procedure

1. The teacher should begin with a sharing of student answers to the Do Now question, which should lead into a class discussion. The goal is for the students to realize that all of the galaxies are moving away from the Earth. This should lead them to the idea that the universe is expanding.
2. The teacher should then begin a discussion on the Big Bang theory. The discussion can begin with students sharing what they already know or have heard about the Big Bang. The teacher should then guide the students to understand how our data helps to give evidence of the Big Bang theory. (Note: It may be necessary to distinguish between religious beliefs and science theories. Science is another way that people explain how things happened before there was recorded history. Teachers may want to maintain a safe space in the classroom so that students feel comfortable learning the material without feeling like their beliefs are wrong.)
3. The teacher can also introduce the concept of the Hubble expansion at this time. By analyzing the data collected by the students, the class should be able to prove that the speeds of the galaxies are proportional to their distance from Earth.
4. Finally, students should prove their learning from the lesson. This may be done as a presentation or in written form. One example is described in the exit ticket below.

Assessment

Exit Ticket: Based on the data collected from the class, what can you conclude about our universe? Explain using appropriate theories, laws, equations, etc. to back up your claims.

Rationale

This concluding activity helps to wrap everything up. Students should be able to explain their learning in some way and understand how scientists develop theories and laws.

Annotated Bibliography / Resources

Reading List

Tennyson, Jonathan. *Astronomical Spectroscopy: An Introduction to the Atomic and Molecular Physics of Astronomical Spectra*. London: Imperial College, 2005. Print.

- This book gives a good explanation of spectroscopy and how it is used to make astronomical measurements, including a brief description of Doppler redshift.

Teacher Resources

“A visual demo of the Doppler effect.” Papacosta, Pangratos, *The Physics Teacher*, 48, 420-420 (2010).

- This article explains a quick demo that teachers can use in class to explain the Doppler effect of sound.

“A different viewpoint on Doppler-effect calculations.” Hoyt, Daniel, *The Physics Teacher*, 40, 14-16 (2002).

-This article explains the calculations involved in the Doppler effect equation and how common sense can be used to determine sign conventions.

Student Resources

PhET: Free Online Physics Simulations. < <https://phet.colorado.edu/> >

- This website offers many simulations that can be applied to various physics lessons. Each simulation also includes handouts created by teachers that can be downloaded and modified to fit your objectives. The simulations named “Sound” is especially relevant to this unit.

McGraw Hill Education.

http://highered.mheducation.com/olcweb/cgi/pluginpop.cgi?it=swf::800::600::/sites/dl/free/0072482621/78778/Doppler_Nav.swf::Doppler%20Shift%20Interactive

- This simulation allows students to control whether the source or the observer are moving. It shows the wave changing in real time as the source and/or observer move. It also includes an exercise tab that walks students through the activity if the teacher does not want to make their own.

Standards

Portions of this unit align to the Pennsylvania Common Core standards and the Next Generation Science Standards shown below.

- PA: 3.2.P.B5: Explain how waves transfer energy without transferring matter. Explain how waves carry information from remote sources that can be detected and interpreted. Describe the causes of wave frequency, speed, and wavelength.
- NGSS: HS-PS4-1. Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media.
- NGSS: HS-ESS1-2. Construct an explanation of the Big Bang theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matter in the universe.

Appendices

Appendix I: Doppler Effect Lab

Name: _____

Purpose: Students will be able to investigate the Doppler effect of sound in order to calculate the speed of the source and observer.

Materials: smartphones with ability to download applications

Directions:

1. Partner 1, search for and download a “frequency detector” application on your smart phone. The application should be able to detect the frequency of sound. (Partner 1 is the “observer”.)
2. Partner 2, search for and download a “frequency generator” application on your smart phone. The application should allow you to generate sound at a desired frequency.
3. Partner 2, set the frequency to a number between 1500 and 2500 Hz. Turn the volume up as high as it can go. Partner 2 is the “source”.
4. Trial 1: Partner 1 stands still as Partner 2 sprints towards Partner 1. Make sure Partner 2 moves in a straight path towards partner 1 and runs at a constant speed. Partner 1 records the frequency detected as Partner 2 is sprinting.
5. Trial 2: Partner 2, now sprints at a constant speed in a straight path away from partner 1 as partner 1 remains stationary. Partner 1 records the frequency detected as partner 2 is sprinting.
6. Trial 3: Now have partner 2 stand still and generate a sound at a certain frequency. Partner 1 sprints at a constant speed in a straight path toward partner 2. Record the frequency detected as you are sprinting toward your partner
7. Partner 1 now sprints at a constant speed in a straight path away from partner 2 as partner 2 remains stationary. Record the frequency detected as partner 1 is sprinting.
8. Complete the necessary calculations and record your data in the table.

Note: It is important that the partner that is moving in each trial is going as fast as they can without endangering themselves. They also need to be moving at a constant speed and try not to swing their arms. Distance of 10 – 20 meters may work best.

Trial	Source Frequency (Hz)	Observed Frequency (Hz)	Source Speed (m/s)	Observer Speed (m/s)
1				0
2				0
3			0	
4			0	

What happens to the observed frequency if the source and observer approach each other?

What happens to the observed frequency if the source and observer move away from each other?

The Doppler effect can be described by the following formula:

$$f' = f \left(\frac{v \pm v_o}{v \pm v_s} \right),$$

where f' represents the shifted frequency, f represents the frequency of the source, v is the speed of the wave, v_o is the speed of the observer, and v_s is the speed of the source.

Use the above formula to calculate the respective speeds for each trial. Show all work below. (Note: Use 340 m/s as the speed of sound. v_o is added if moving towards and subtracted if moving away from the source. v_s is added if moving away and subtracted if moving towards the observer.)

Appendix II: Galaxy Shift Lab

Name: _____

Purpose: Students will be able to investigate the Doppler effect of light in order to make observations about the motion of our universe.

Procedure:

1. Go to <http://skyserver.sdss.org/dr12/en/tools/chart/navi.aspx>.
2. Scroll around the sky until you find a galaxy you would like to investigate.
3. Select the area where the galaxy is located (click on the galaxy). Click “Explore”, located on the right side of the page.
4. If the following conditions are met, you may move on to the next step. Otherwise, you will need to go back to find a new location in the sky.
 - a. Type: Galaxy (not Star)
 - b. There are no Warnings on the page.
 - c. There is an Optical Spectra Chart on the page
5. Click the Optical Spectra Chart to open it.
6. Locate H-alpha. Record its wavelength.
7. Locate H-beta. Record its wavelength.
8. Calculate the fractional shift for each line. Note how they compare.
9. Calculate the velocity of the galaxy.
10. Share your data on the Google doc.

Line	Rest Wavelength	Galaxy's Observed Wavelength (nm)	Shift (nm)	Fractional Shift	Velocity (km/s)
H- α	656 nm				
H- β	486 nm				

Show calculations below:

Shift: Difference between observed wavelength and rest wavelength.

Fractional Shift: Shift in Wavelength / Rest Wavelength (Hint: The answer can be confirmed on the galaxy's data page)

Velocity: Fractional Shift * Speed of Light

Use the Doppler equation and wave properties to prove that the calculations you did above represent the velocity of the galaxy. (Hint: Use algebraic manipulations and substitution to isolate v_s . v_o is considered 0 since we are calculating the galaxy's speed in reference to Earth.)

How do the observed wavelengths compare to the rest wavelengths? What does that tell you about the motion of the galaxy?

What trends do you notice about the data from the other galaxies uploaded onto the Google docs by your peers? What can you conclude about the motion of our universe?