A LIVELY ELECTRONIC COMPENDIUM OF RESEARCH, NEWS, RESOURCES, AND OPINION
Astronomy Education Review
Volume 7, Aug 2008 - Jan 2009
Issue 2

A Doppler Shift Speed Gun

by **Reid Sherman**
University of Chicago
Received: 07/16/08, Posted: 09/08/08

The Astronomy Education Review, Issue 2, Volume 7:141-146, 2009

Abstract

This is a fun and educational lab for any audience at the middle school level and above to learn about the Doppler shift and waves in general. The participants should review the basic properties of waves and, with some Socratic questioning, form their own hypothesis of what will happen to a sound wave when it is emitted by a moving object. Participants then construct their own instrument and test their hypothesis in both a qualitative and quantitative manner. The main part of this lab involves using a computer program and simple math to correctly measure the speed of an object, using only the waves emitted from it.

1. BACKGROUND

The Doppler shift is one of the most fundamental physics concepts in astronomy and is used in some form or another by almost all astronomers and astrophysicists in each of their papers. This hands-on lab could be used as part of a curriculum in astronomy or physics, as a stand-alone demonstration, or as a lead-in to all kinds of specific topics, like the expansion of the Universe or thermal broadening of spectral emission and absorption lines. What works so well in this lab is the use of computers and real observations to measure the effect and its relation to astronomical observations.

Materials:

Wiffle ball cut in half
Buzzer
9-volt battery
Battery clip
Switch
Wire strippers
Twist connectors
String

Meter stick
Tape
Stopwatch
Computer
Sound analysis software
Microphone

2. PROCEDURE

(1) Build Doppler Ball (optional)

The ball can be constructed ahead of time for a basic, instantly ready demonstration, but I find that having students build their own tools to the extent possible is always instructive and engaging. In addition, premade devices that would work are available in educational stores and online (for instance, at Arbor Scientific, http://www.arborsci.com), and Doppler balls can be made of different things, like tennis balls, as long as they make a loud sound at constant pitch and can be swung. The important part of the lesson is the quantitative analysis.

The easiest method that I have found, which I derived by combining easily accessible materials, is to make a simple circuit with a battery, a switch, and a buzzer and put it into a Wiffle ball cut in half. The Wiffle ball is then taped back together, with the buzzer and battery inside and the switch sticking through one of the holes.

If you have students make their own Doppler balls, important things to keep in mind are ensuring that the circuit is secure and tested to withstand the stress of being swung around and ensuring that the switch button is on the outside of the ball before taping it up. Attach at least 1.5 meters of string to the ball. Record the buzzer's nominal frequency and mark it on the outside of the ball (e.g., 3500 Hz).

(2) Empirically Observe Doppler Shift of Sound

Once the Doppler balls and buzzers are assembled and working, go outside (or somewhere with plenty of room) to experiment with them. In a clear area *with no one in the way*, double check that everything is secure, and then one participant should twirl the ball around his or her head. Once you are confident that the assembly will stay together, turn on the buzzer and have someone twirl the buzzer assembly around his or her head, with others standing several feet away. Try to swing it at a constant rate. What does the swinger hear? What do the listeners hear? Describe how the sound changes. Is the pitch/frequency constant? The volume? Try to swing it at a few different speeds. Make sure that every participant gets to swing the ball, listen from the center, and listen from the outside. Have partners listen from two directions and see if they hear the pitch change in the same way and at the same time.

This is a very important step of the lab for correcting student misconceptions. At the start of this demonstration section, even after a lecture topic, many students did not understand how crucial it is to consider relative positions and relative velocities. Many students were surprised, for instance, to find that they did not hear any Doppler shift when swinging the ball around their own head. Many also were surprised to find that two people standing on opposite sides of the person swinging the ball would hear the pitch change differently. This is why it is important to make sure that each student gets to swing the ball and stand in different places. Having students stand on different sides and raise and lower their hands with the pitch gives a good illustration of the phase shift in the pitch variation, depending on the direction in which the observer is standing.

(3) Getting Quantitative

Now it's time to quantify the Doppler shift, in three steps:

1. Measure the speed of the swinging buzzer
2. Use calculations to predict what the actual Doppler shift is
3. Directly measure the Doppler shift of sound

Use the meter stick to measure a set length of string so that the radius of the ball's circular path is known. A designated swinger should practice swinging the assembly at a steady constant rate, with arm and wrist held steady. Once the group feels that the buzzer can be consistently swung at a steady rate, swing the buzzer at that constant rate and time how long 10 complete cycles take.

The average speed can be easily calculated with the distance that the ball traveled through 10 cycles (derivable from the radius) and the time it took to do so.

(4) Equations, Calculations, and Predictions

Mathematically, the Doppler shift that you observed may be described by the following equations:

Source moving *toward* you: f' observed frequency

$$f' = f / [1 - (v/v_s)]$$

Source moving *away* from you: f' observed frequency

$$f' = f / [1 + (v/v_s)]$$

f = source frequency in Hertz (Hz)
f' = perceived frequency (Hz)
v = speed of source
v_s = speed of sound

The speed of sound depends on the weather (temperature and humidity), but a decent approximation is that the speed of sound is v_s = 350 m/s.

Students can then calculate the expected perceived frequency of your buzzer by using the above equations and the average speed from your earlier measurements. The human ear can hear sounds ranging from 20 Hz to 20,000 Hz. It is most sensitive to frequencies between 500 and 4,000 Hz and can distinguish between sounds that are a few Hertz different. With this information, participants can predict whether they should be able to detect the Doppler shift of the swinging ball.

(5) Computer Measurements

Use sound analysis software to record the buzzer both at rest and while swinging it at constant speed. The software will measure both the intensity and frequency of sound waves. Most spectral analysis programs should be useable for this. I have used Spectra Plus (free 30-day trial; see Figure 1) for PCs and Audio Xplorer for Macs. The key is to be able to see a running graph of intensity versus frequency; note that the spike at the buzzer's frequency bounces left and right as the ball is swung. The highest and lowest frequencies should be easily recordable by pausing the graph at different points in time.

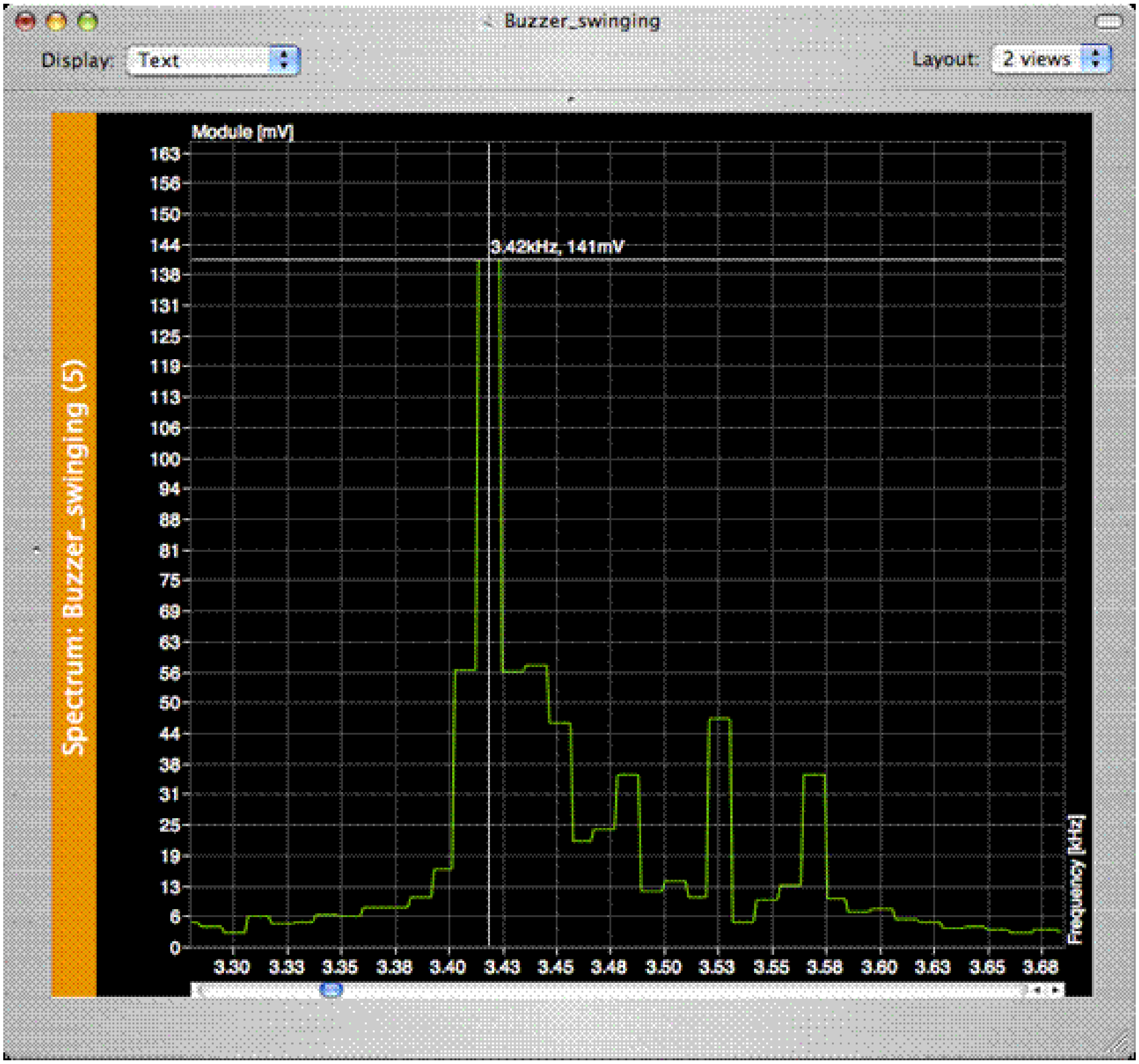

Figure 1. A screen shot of Spectra Plus software. It shows the signal from the Doppler ball while it is being swung, and the identification of the shifted frequency.

Analyzing the graph is a good opportunity to review both qualitative (What does the graph look like when the ball is moving toward the microphone?) and quantitative (What is the frequency shift, and does it agree with the predicted shift?) aspects of understanding the Doppler shift and to discuss accuracy and equipment (Was the unshifted frequency of the buzzer what the manufacturer said? Did the frequency shift the same amount on every cycle?).

This computer analysis was also useful for addressing student misconceptions. One common issue that comes up involves students confusing amplitude and pitch of sound. When students examine a graph that represents amplitude versus frequency while hearing the sound, they can see that the frequency moves up and down while the amplitude stays steady. This can be used to help the students understand that the Doppler shift depends on velocity, not distance; when students look at the spectrum with the buzzer close to and far away from the microphone, they see that the amplitude may diminish with distance, but the frequency stays the same.

3. APPLICATIONS TO BROADER SCIENTIFIC CURRICULA

There is an endless supply of scientific and everyday uses of the Doppler effect. I have had the most success in teaching with the redshift and blueshift of different sides of an edge-on spiral galaxy (it parallels the swinging ball nicely); radar guns used by police on highways to catch speeders; and Doppler radar used in weather stations.

4. CONSIDERATIONS

1. This lab can be done essentially in reverse by measuring the frequency shift, calculating the speed from that frequency shift, and then finding if the speed calculated from the Doppler shift matches the speed measured with the stopwatch and meter stick.
2. A foam ball or tennis ball can easily substitute for the Wiffle ball in constructing the Doppler ball. A tennis ball offers better protection for the circuit inside if the ball is dropped, but the sound will be muffled somewhat, and a Wiffle ball has convenient holes for the button on the switch to be placed through.
3. More advanced students might be able to derive the Doppler shift equations on their own with a little guidance and a good diagram.
4. Although the lab involves projectiles, because the buzzing ball is not very heavy or sharp, safety is not much of an issue. I have run through the lab many times and have yet to have a ball fly off the string. Cutting the Wiffle ball in half requires a very sharp knife, so this should be done beforehand.
5. This lab is very adaptable to different circumstances. It can take anywhere from a 45-minute class (if the balls are premade) to a daylong seminar or multiclass lab if every step is considered in detail or if students are allowed to extend the investigation to suit their curiosities.
6. The cost of the lab is reasonable, though it does require computer availability for the quantitative part. All other materials are inexpensive and easy to find.
7. This was not developed as part of a class curriculum, so we did not quantifiably test how well this lesson worked with student comprehension. It would be interesting to give a quiz after teaching the concept but before the hands-on demonstration and computer analysis, and another quiz after completing the entire lab to see how many misconceptions were addressed.

Notes

This lab was developed as part of a larger curriculum on the nature of light. The goal was to help students understand waves and how the wave nature of light can explain natural phenomena, even as they observe and learn in another lab that only a light with a particle nature could explain the photoelectric effect. We found this to be a generally productive and enjoyable lesson on its own. It was taught to a group of students who ranged in age from 12 to 17, and the lesson seemed to work equally well for all of them. We hope that it also works well for you.

Acknowledgments

Special thanks to Randy Landsberg for help in lab development and to Walter Glogowski, Robert Friedman, and Sarah Hansen for help in teaching. Thanks to the Kavli Institute for Cosmological Physics for the opportunity to work with a wonderful group of students and teachers on astrophysics education.

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