# Demonstrating Cosmological and Doppler Redshift in the Classroom

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## Abstract

Cosmology is often a difficult subject to teach as it can involve many confusing and sometimes abstract concepts. One particular topic with many existing misconceptions and difficulties surrounding it is redshift, specifically the difference between Doppler shift (due to the peculiar velocities of galaxies) and cosmological redshift (due to the expansion of the side). Redshift of galaxies, despite being an extremely useful and interesting scientific tool, can often become a tedious subject to teach as it is largely theoretical and usually does not include demonstrations or interaction in the classroom. It can be challenging to understand, and therefore also challenging to explain, the differences between Doppler and cosmological redshift, often leading to this distinction being overlooked entirely. The set of demonstrations developed during this astrophysics masters project, along with the accompanying presentation, worksheet, and teacher notes, aim to explain both Doppler and cosmological redshift clearly and in an engaging and memorable way. The demonstrations use remote control vehicles to represent peaks of a travelling wave of light. When demonstrating Doppler shift, the vehicles are released from a plastic board that is being pulled away, representing a receding source of light. When demonstrating cosmological redshift, the vehicles are driven along a wide stretchy exercise band, representing a section of the expanding Universe through which this wave of light is travelling. This teaching resource will introduce interactive learning, proven to be very effective when teaching astronomy, and provides a useful and fun physical analogy to demonstrate an often-misunderstood subject.

**Keywords**
Cosmology, classroom, demonstrations, interactive, redshift

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## 1. Introduction

### 1.1. Pedagogical motivations

Cosmology can be a daunting subject [1] with many existing misconceptions [2]. The topic is often taught using purely theoretical and numerical methods, making it difficult for teachers and students alike to stay focused and interested. It has been shown that interactive learning is very effective in teaching astronomy [3]–[5] therefore the teaching materials described in this paper are focused around interactive demonstrations.

### 1.2. Scientific motivation

Redshift is an important tool for research in Astrophysics [6],[7], and when being taught in schools it should be done correctly. Doppler shift is covered in most school physics curricula, so students will likely be comfortable with the idea of Doppler redshift of galaxies (due to the peculiar velocities of the galaxies) however, cosmological redshift (due to the expansion of the Universe) is often either not explained in schools, or is taught inaccurately, resulting in misunderstandings. For example, if the redshift used in Hubble's law is explained as being a Doppler shift this leads to students and teachers confounding the concepts of cosmological redshift and Doppler shift. This paper describes a set of teaching resources that will explain both of these effects behind redshift.

## 2. Redshift

When observing galaxies, astronomers often split up the light to display its constituent wavelengths, creating a spectrum. The amount of light emitted and absorbed by a galaxy at each wavelength is determined by the galaxy's chemical composition. Astronomers know which spectral line positions and spacings are expected when looking at a galaxy because they know what the chemical composition is likely to be. However, when galaxies are observed, almost all of them have spectral lines at a longer (redder) wavelength than expected, a visual example of this effect can be seen in Figure 1. This effect is called redshift.

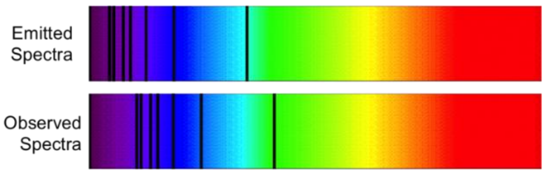


**Figure 1. A representation of spectral lines on both an emitted spectra and a redshifted observed spectrum**

The redshifting of light from galaxies is due to a combination of both Doppler shift and cosmological redshift.

### 2.1. Doppler Shift

Classical Doppler shift is the effect that causes the variation in pitch you hear when a fast car is passing you. The sound waves are compressed in front of the car (making the wavelength shorter), and stretched out behind the car (making the wavelengths longer), this is shown in Figure 2.

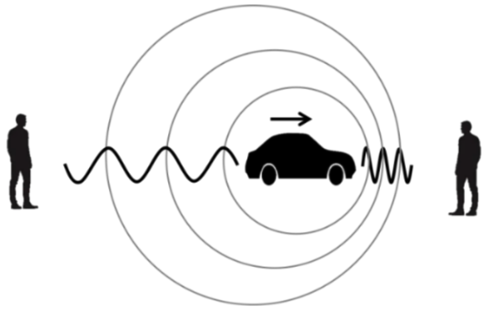

**Figure 2. Doppler shift changing the pitch of the sound of a fast car**

Figure 2 shows that when the car is moving away from the observer the wavelength is longer, so the pitch will be lower. When the car is moving towards the observer, the wavelength is compressed so the pitch will be higher.

This same effect can be seen with the light from galaxies, as shown in Figure 3. When galaxies are moving away from us the light observed from them will shift towards longer (redder) wavelengths, and when galaxies are moving towards us the light observed will shift towards shorter (bluer) wavelengths.

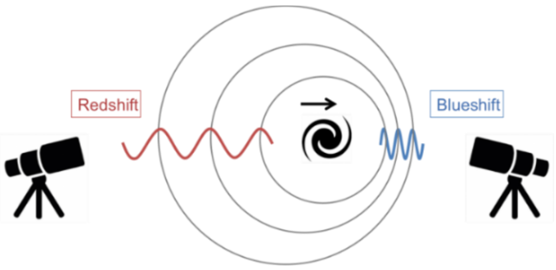


**Figure 3. Doppler shift changing the colour of the light being observed from a moving galaxy**

The motions that cause Doppler shift of galaxies are called peculiar velocities; for example, motion due to gravitational attraction between galaxies. Note that this is an effect that is not seen in day-to-day life on earth due to the large velocities required.

### *2.2. Cosmological Redshift*

Cosmological redshift is another method by which the wavelength of light travelling from a galaxy may be lengthened. This lengthening of wavelength is due to the expansion of the Universe. The basic idea behind why the expansion of the Universe shifts light to a longer wavelength can be explained as follows: Imagine two galaxies; galaxy A and galaxy B, as represented by the black galaxies in Figure 4. There is a large enough distance between the galaxies that the gravitational attraction between them is not significant. Some pulse of light travels from galaxy A to galaxy B. If the distance between A and B is constant with time then the light will arrive at B with the same wavelength that was emitted from A. However, if the distance between A and B is increasing, as in Figure 4, the wavelength of light must also increase. The space through which the light is travelling is expanding, and therefore the wavelength also expands. The light will reach galaxy B with a longer wavelength than when it was emitted from galaxy A.

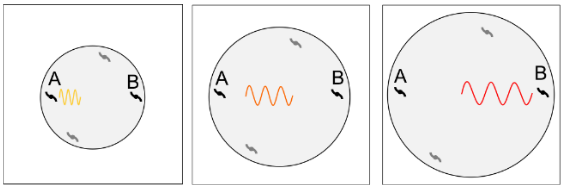


**Figure 4. A 2 dimensional diagram showing cosmological redshift.**

The grey circle in Figure 4 represents a random section of the expanding Universe and each image in the figure represents a `snapshot' in time.

## 3. Demonstrations

In order to demonstrate redshift, a physical analogy was created. In this analogy, three remote control vehicles are used to represent the peaks of a wave of light, as seen in Figure 5.

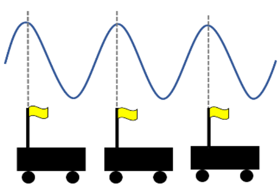

**Figure 5. remote control vehicles representing the peaks of a wave of light**

A photo of one of the vehicles, along with the controller, can be seen in Figure 6.

**Figure 6. One LEGO vehicle and the controller**

Instructions for assembling the vehicles along with a kit list detailing the equipment needed and approximate cost can be found at the following website:

www.orielmarshall.com/redshift

Once the vehicles are assembled it is important to ensure you can control them reliably and effectively. All three vehicles will be controlled with the same controller, and must move at the same time. It is recommended you practice using the vehicles before the lesson. At the website linked above, there is also a trouble shooting document that may help to address any practical issues you have with assembling or operating the vehicles.

### *3.1. Demonstrating Doppler Shift*

For Doppler redshift, there must be a wave of light moving towards an observer, and the source of the light must be moving away from the observer. For this demonstration, the vehicles represent the wave of light, and a plastic board represents the galaxy. The vehicles all begin on the board, spaced evenly and relatively close together. The board is pulled slowly at a constant speed away from the observer, while the vehicles are all driven at the same speed off the board towards the observer. This process is shown in Figure 7.

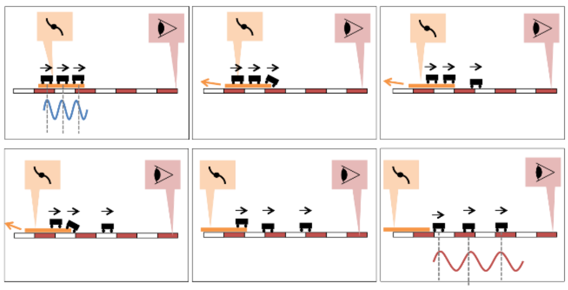

**Figure 7. Step by step diagrams showing the doppler shift demonstration.**

The orange board represents the galaxy emitting light, the observer in this analogy would be stationary at the right end of the table.

As seen in Figures 7 the spacing at the beginning of the demonstration is relatively small. Once all of the vehicles have travelled off the board, the spacing between them is larger and will remain at this larger spacing regardless of the distance they travel. Before and after photos of the demonstration can be seen in Figure 8, with the positions of the vehicles being measured against the measuring tape on the table. The increase in spacing of the vehicles is analogous to the wavelength of light from a galaxy increasing as it leaves a galaxy that is receding from the observer.

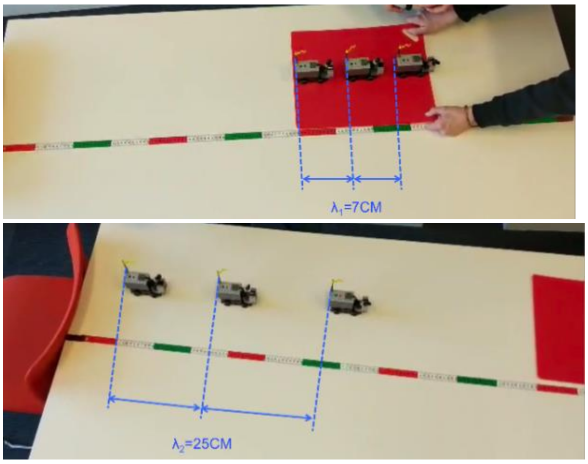


**Figure 8. Video stills from the beginning (top) and the end (top) of the doppler shift demonstration**

A video of the demonstration for Doppler redshift can be found at:

https://vimeo.com/702909321

### *3.2. Demonstrating Cosmological Redshift*

In order to demonstrate cosmological redshift, we must show a wave of light travelling through an expanding Universe. This is done by placing the three vehicles, representing the peaks of a wave of light, onto a wide exercise band, representing a one-dimensional section of the expanding Universe. The band is continuously stretched while the vehicles travel along it, thus resulting in the spacing between the vehicles increasing. The set up and equipment for this can be seen in Figure 9.

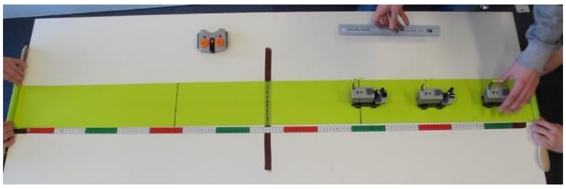

**Figure 9. Photo of the setup and equipment for demonstrating cosmological redshift**

The setup is operated by three people, one person to control the vehicles, and two to hold the handles at each end of the band. The band must be and stretched consistently and evenly as the vehicles travel across it, this can take a little practice. Figure 10 shows a diagram of the demonstration in action.

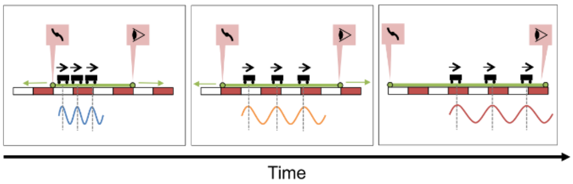


**Figure 10. A step-by-step diagram showing the cosmological redshift demonstration**

It can be seen in Figure 10 that the constant stretching of the band as the vehicles travel along it results in the distance between the vehicles increasing. The left end of the band that the vehicles are travelling away from represents the source of the light (e.g. the galaxy). The right end of the band that the vehicles are travelling towards represents the observer.

Stills from a video of the cosmological redshift demonstration in action can be seen in Figure 11.

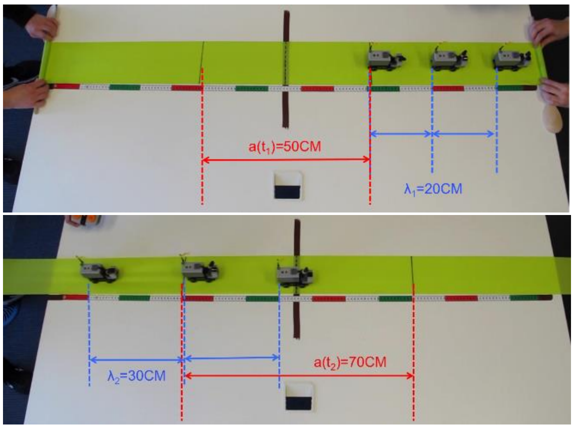


**Figure 11. Video stills from the beginning (top) and the end (top) of the cosmological redshift demonstration**

In Figure 11 the `light source' is on the right-hand side; the `observer' on the left. The green strip is the stretchy band representing a one-dimensional section of the Universe. The band is wrapped around wooden spoons at each end, these spoons act as handles. During the demonstration, the vehicles travel from right to left, and the volunteers holding the handles walk backwards to stretch the band. It can be seen in Figure 11 that by the time the vehicles have travelled across the stretching band, the spacing between them is larger, as expected. This is analogous to a wave of light travelling across a section of the Universe, and the light being redshifted as the Universe expands.

A video of the cosmological redshift demonstration can be found at:

https://vimeo.com/702909575

## 4. Discussion

### *4.1. Limitations of the analogies*

The demonstrations explained in this paper act as physical analogies for redshift. As with all analogies it is important to be aware of their limitations in order to understand the extent of their pedagogical impact. Additionally, there are many existing misconceptions in cosmology [2], so it is important these are not perpetuated by these demonstrations.

#### *4.1.1. There is no center of the Universe*

As seen in Figure 9 there is a dotted like drawn along the middle of the band. The central line is used to ensure the band is being stretched evenly from both sides and is for practical purposes only. When this demonstration is being presented to the class, it should be made clear that there is no centre to of the Universe, and that the Universe does not expand from a central point, but expands everywhere all at once. It should be stated that this central line is drawn on due to the limitations of the analogy, and should not be applied to their understanding of the Universe.

#### *4.1.2. One-dimensional demonstrations as analogies for three dimensional effects*

Another limitation of these demonstrations is the dimensionality. Both of the demonstrations are using a one-demonstrational analogy to explain a three-dimensional effect. For the Doppler shift demonstration, it is not as difficult to translate to an analogy as the Doppler effect is only present along the same direction as the movement of the source of the wave of light. However, for cosmological redshift, the expansion of the Universe is occurring in all three dimensions, and the demonstration is only showing the effect in one dimension. Due to this, it is important to try to explain to the students that in this demonstration we are only mimicking the effect in one dimension. In reality cosmological redshift would be occurring in every direction at the same time, and would look the same regardless of what section of the Universe it was in.

### *4.2. Benefits of the analogies*

As well as pointing out the limitations of the analogies, it is also important to be aware of the aspects in which the demonstrations act as effective analogies. In addition to the clear benefit that the analogies may help students to understand the effects that cause redshift, the demonstrations may also help students to better understand the scale factor of the Universe, and the difference between Doppler shift and cosmological redshift over long distances.

#### *4.2.1. Scale factor of the Universe*

In the cosmological redshift demonstration, there are two dashed lines on either side of the centre, seen in Figure 9. These are used to compare with the measuring tape on the table to keep track of how much the band has expanded over time, this is analogous with the scale factor of the Universe a(t). The scale factor of the Universe is a value used to track the relative size of the Universe over time, and is found by taking a ratio of the value a(t) at two different times. This value is used in the cosmological redshift equation, so by having a physical measurement that can be used to show the scale factor of the Universe this can help students understand the concept.

#### *4.2.2. Differences over long distances*

One of the key differences between Doppler shift and cosmological redshift are their limiting variables, and how they act over long distances. Doppler shift is calculated using only the speed of light and the speed that the light source is moving at. The speed of light is constant, and galaxies have a peculiar velocity of the order of $100kms^{-1}$, so there is a limit on how large redshift due to the Doppler effect can be. Cosmological redshift is calculated using a ratio of the scale factor of the Universe at two different times, therefore the only limit on how large this can be is time between the light being emitted and observed. These differences can be understood further through a simple thought experiment based on the demonstrations.

Imagine that in each demonstration you have an infinitely long table. For the Doppler demonstration, once the vehicles have left the board, they will remain at that same spacing regardless of how long they travel for. Their spacing is determined by, and capped by, the speed of the board's movement, and is not changed once all the vehicles have left the board. For the cosmological redshift demonstration, as long as the band continues to stretch as the vehicles are travelling, the spacing between them will continue to grow indefinitely. There is no limiting factor on how much the spacing can increase by, just as there is no limit to how much light can be cosmologically redshifted by.

## 5. Conclusions

The results of this project consist of two hands-on interactive demonstrations explaining both cosmological redshift and Doppler redshift and the differences between them. These are accompanied by a lesson plan, a presentation, a student work sheet, and detailed instructions on how to assemble and use the demonstrations. These resources can all be found at:

www.orielmarshall.com/redshift

Although there are inherit limitations to the physical analogies used in the demonstrations, they clearly show how both effects can result in an observed wavelength from a galaxy that is longer (towards the red) than the emitted wavelength from the galaxy. This set of resources allows students to learn about the causes and limitations behind the important astronomical tool of redshift. The demonstrations show how the expansion of the Universe can increase the wavelength of light in cosmological expansion, and how the receding peculiar velocity of a galaxy can cause the wavelength of light from a galaxy to increase through Doppler shift.

Were there time available, the next steps in this project would be to validate the materials by testing them in schools and make adjustments and adaptations to the teaching resources and demonstrations based on feedback from both the students and teachers.

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**References**

[1] H. Kragh, "Cosmology and Science Education: Problems and Promises," *can be accessed at: arXiv:1212.1592*, Dec. 2012, Accessed: Jan. 17, 2019.

[2] C. S. Wallace, E. E. Prather, and D. K. Duncan, "A Study of General Education Astronomy Students' Understandings of Cosmology. Part IV. Common Difficulties Students Experience with Cosmology," *Astronomy Education Review*, vol. 11, no. 10104, p. 106, 2012.

[3] A. Lightman and P. Sadler, "Teacher Predictions Versus Actual Student Gains," *The Physics Teacher*, vol. 31, pp. 162–167, 1993.

[4] R. R. Hake, "Interactive-engagement versus traditional methods: A six-thousand-student survey of mechanics test data for introductory physics courses," *Citation: American Journal of Physics*, vol. 66, p. 595, 1998.

[5] E. E. Prather, A. L. Rudolph, and G. Brissenden, "Teaching and Learning Astronomy in the 21st Century," *Physics Today*, vol. 62, no. 10, pp. 41–47, 2009.

[6] Dark Energy Spectroscopic Instrument (DESI), https://www.desi.lbl.gov/. accessed Jan. 17, 2019.

[7] Sloan Digital Sky Survey (SDSS), https://www.sdss.org. accessed Jan. 17, 2019.