ANOMALIES & TENSIONS IN COSMOLOGY · COSMOVERSE

CosmoVerse Adventures

Cosmic Redshift

COST
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

Funded by
the European Union

The classroom

Introduction: Doppler Effect

Teacher :

Good morning, students! Today, I have a little surprise for you. I want you to close your eyes and listen closely.

*[**Sound of a siren** from a speeding ambulance fades in and then out]*

Teacher :

Alright, open your eyes. Can anyone describe what they just heard?

Student 1 :

It sounded like an ambulance siren, but the pitch changed as it passed by.

Student 2 :

Yeah, it started high-pitched and then became lower as it moved away.

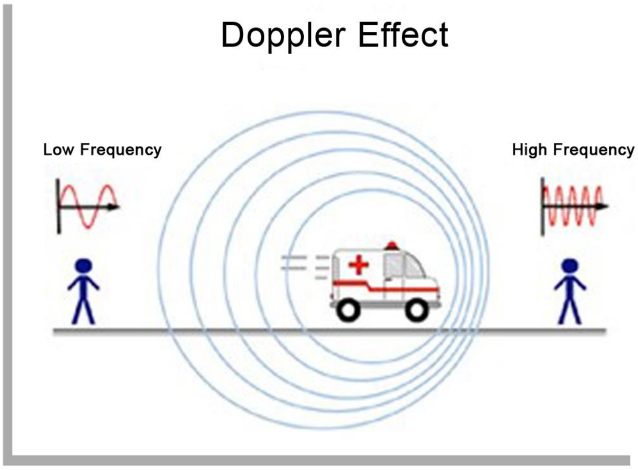


Figure 1: How sound wave frequencies are affected (and perceived) as a siren approach or travels away from an individual.

Teacher :

Exactly! But did you know that the siren's pitch from the ambulance itself never changed? What you heard was a perceived shift in sound due to the Doppler effect.

Student 3 :

The what effect?

Teacher :

The Doppler effect! It's defined as the apparent change in frequency of a wave caused by the relative motion between the wave's source and the observer. When the object emitting the wave moves towards an observer, the waves bunch up, resulting in a higher frequency. When it moves away, the waves stretch out, causing a lower frequency.

Student 4 :

So that's why the ambulance siren sounded different when it passed by us?

Teacher :

Precisely! Here's a simpler way to picture it. Imagine a bug in a puddle of water. Every time the bug moves its arms and legs, it makes waves. If the bug remains stationary, the waves spread out uniformly. But if the bug moves, the waves bunch up in the direction it's moving and spread out in the opposite direction. That's the Doppler effect in action!

Student 3 :

That's cool! But why does this matter?

Teacher :

Great question! The Doppler effect isn't just about ambulances. It has many applications. For instance, police use radar guns to determine the speed of moving vehicles. They send out microwave frequencies that bounce off cars. When these frequencies return, they might be different due to the car's motion. This difference helps determine the vehicle's speed.

Student 2 :

So, they use the Doppler effect to give out speeding tickets?

Teacher :

Exactly! And here's a fun fact: For the most accurate reading, police officers should stand facing an oncoming vehicle. If they're off to the side, they might get a slightly different speed because not all of the car's motion is towards the radar gun.

Teacher :

Doppler effect has also medical applications as it is used in echocardiograms to generate an assessment of the speed and direction of a blood flow.

Student 2 :

Wait a minute! Sound is just a wave, right? So, does this mean the Doppler effect applies to light as well?

Teacher :

Brilliant observation! Yes, it does. And that's where things get cosmically interesting. To truly grasp how this plays out with light, you'll need to join Quark on his Spaceship of Imagination. Ready for an interstellar adventure?

Students (In Unison) :

"Yes!"

Spaceship of Imagination

Cosmic Redshift

[Spaceship engines roar, then calm down]

Quark :

Look below! We're hovering above a highway. Do you see that noisy car?

[Sound of a car engine revving and zooming past]

Student 1 :

Yeah! Just like the ambulance in class. As it approached, the pitch rose, and as it moved away, the pitch fell.

Quark :

Precisely! That's the Doppler effect in action. But what if I told you the same thing happens with light? Meet the "Luminoscope."

[Sound of a device activating]

Student 1 :

Whoa! My eyes... everything seems so vibrant.

Quark :

The Luminoscope enhances your eyes' sensitivity to light. Look at the car now.

Student 3 :

It's... slightly blue as it comes towards us and turns slightly red as it moves away!

Quark :

That's right! Just like sound waves, light waves can be compressed and stretched. This changes the light's colour. Now, look up at that beautiful rainbow.

Figure 2: How light wave frequencies (colours) are affected as a car approach or travels away from an individual. Credit to "Into the universe" Discovery Channel documentary.

Quark :

Each colour you see represents a different frequency in the electromagnetic spectrum. Blue has a higher frequency, while red has a lower frequency.

When something in space is moving towards us, we see a blueshift. But when it's moving away, we see a redshift.

Student 3 :

So, galaxies moving away from us would appear... red?

Quark :

Exactly! Let's journey across the universe.

[Spaceship engines roar, stars whizzing past]

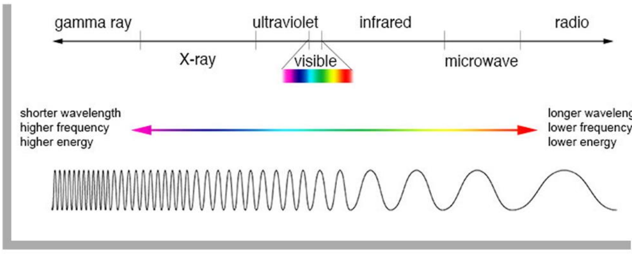


Figure 3: Comparison of wavelength, frequency and energy for the electromagnetic spectrum. (Credit: NASA's Imagine the Universe)

Quark :

Everywhere you look, most galaxies appear redshifted. This observation, first made by Dr. Edwin Hubble, indicates that they're moving away from us. The farther a galaxy is, the faster it's moving away. This tells us that our universe is expanding, as we've learned in our previous adventures.

Student 3 :

But... wait. Over there! That galaxy isn't red. It looks blue!

Quark :

Ah, the Andromeda Galaxy, your galactic neighbour. While most distant galaxies move away due to the universe's expansion, neighbouring galaxies like Andromeda, bound by gravity, can move towards us, so that its speed falling towards us is greater than the expansion speed of the universe, hence the blueshift.

Student 1 :

What will happen in the future?

Quark :

In about five to seven billion years, Andromeda will collide with our Milky Way. Imagine two majestic dancers, spiralling and twirling, their stars intertwining but rarely touching. A cosmic ballet of light and gravity. This titanic dance will birth a new galaxy, a union of two great cosmic entities.

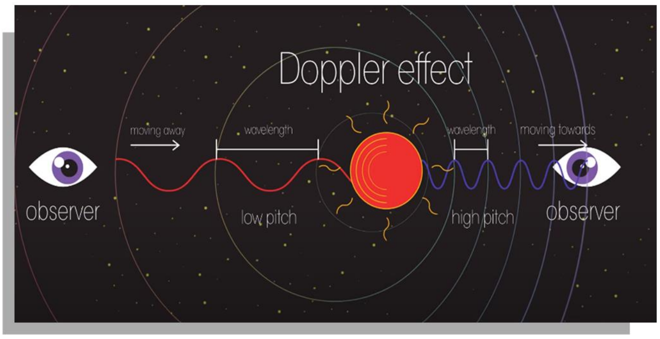


Figure 4: Doppler effect in action. Credit to Bing Rijper.

Student 4 :

It's so mesmerizing.. But how did scientists see these colours without the Luminoscope?

Quark :

Excellent question! To understand that, we need to meet the brilliant minds behind something we call spectroscopy!!

Meet a scientist

Spectroscopy and Cosmic Redshift

Quark :

Welcome to the Hall of Luminary Minds, where we meet the greatest scientists of all time! Today, we have two very special guests: Robert Bunsen and Gustav Kirchhoff, the pioneers of spectroscopy!

Bunsen :

Greetings, young explorers!

Kirchhoff :

It's a pleasure to meet you all.

Student 1 :

Sirs, we've been learning about redshift and we're curious: how did scientists manage to see the redshift effect?

Bunsen :

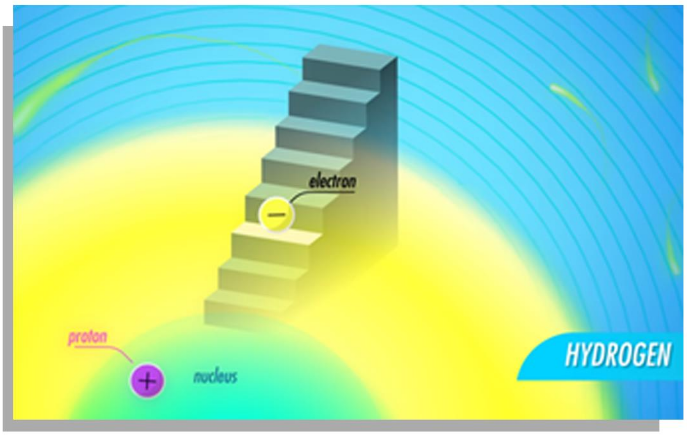
Ah, a brilliant question! To understand that, we must first delve into the atomic structure. Atoms are the building blocks of matter, comprising protons, neutrons, and electrons.

Kirchhoff :

Yes, and while protons and neutrons stay in the nucleus, electrons move around them. However, they don't just move anywhere. They exist in very specific energy states, much like the steps of a staircase.

Student 2 :

So electrons can move between these steps?



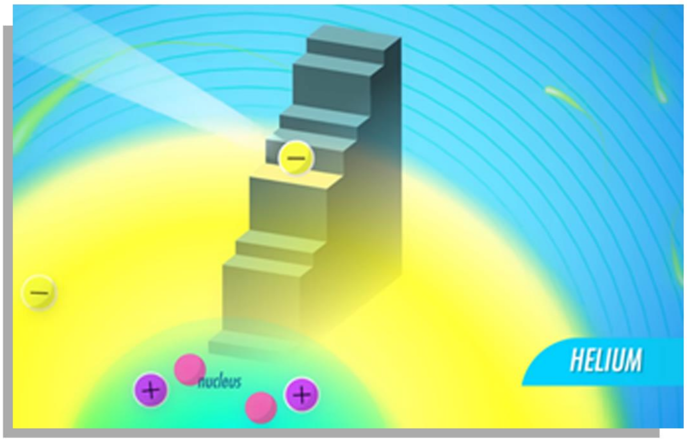


Figure 5: The staircase analogy of Hydrogen and Helium's atomic structures. Credit to PBS Digital Studios.

Bunsen :

Precisely! But to do so, they need the exact amount of energy. Light provides this energy. If light has just the right amount of energy, an electron will absorb it and move to a higher step.

Student 3 :

And what happens when it moves back down?

Kirchhoff :

It emits light of a specific colour or energy. Different atoms have different steps, so they emit different colours.

Quark :

This ability to determine the colours emitted by different elements is the foundation of spectroscopy!

Student 4 :

But how does this relate to redshift?

Bunsen :

To understand that, you need to grasp absorption spectra. Each chemical has a unique pattern of colours called spectral lines. When light from celestial objects, like our Sun, reaches Earth, it doesn't arrive uniformly. Some wavelengths or colours are missing.

Kirchhoff :

That's right. These missing wavelengths manifest as dark lines on the spectrum. This pattern of dark lines is unique for each element, like a fingerprint.

Student 2 :

So, these dark lines tell us about the composition of the star?

Bunsen :

Precisely! For instance, our Sun emits light across various wavelengths. But due to the elements present in it, like hydrogen, certain specific wavelengths get absorbed. This leads to those characteristic dark lines in the Sun's spectrum.

Student 3 :

How does this relate to other stars or galaxies?

Kirchhoff :

Great question! Let's consider hydrogen, which is abundant in our Sun. Hydrogen emits very specific wavelengths of light. On Earth, when we observe the Sun, we see these specific wavelengths. But, when we look at distant galaxies, which also have stars composed of hydrogen, we notice something peculiar.

Student 3 :

The wavelengths are shifted?

Bunsen :

Exactly! For instance, if we compare the hydrogen spectra from our Sun to a distant star, we'd notice the same pattern of lines, but they appear shifted towards the red end of the spectrum in the distant star.

Student 3 :

So, the hydrogen in that distant galaxy emits the same light, but by the time it reaches us, it's redshifted?

Kirchhoff :

Precisely. The key here is the movement and expansion of space. As light travels vast cosmic distances, the expansion of the universe stretches its wavelengths, making them longer and hence, more red.

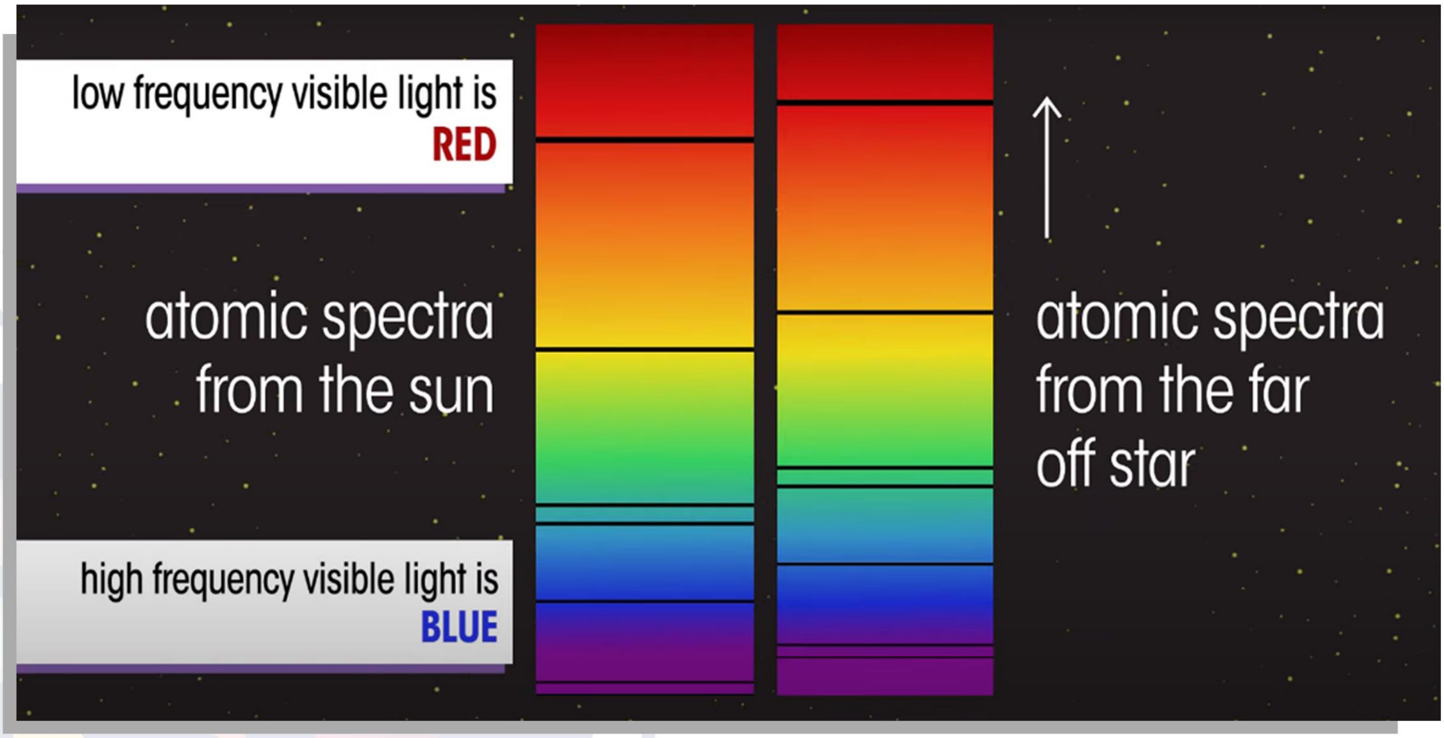


Figure 6: The atomic spectra of the Sun vs the atomic spectra of a distant star. Credit to Bing Rijper.

Student 4 :

It's like the universe is telling us its story through these spectral lines!

Student 1 :

That's fascinating! But how did you measure these colours precisely?

Bunsen :

We used a tool called a spectrometer, which can distinguish and measure the specific colours or wavelengths emitted or absorbed by atoms. By attaching a spectrometer to a telescope, we can determine the composition of distant stars, galaxies, and nebulae.

Student 4 :

So, with spectroscopy, we can " taste " the universe?

Kirchhoff :

A delightful way to put it! Yes, we can indeed taste the cosmic bakery and savour its diverse flavours.

Bunsen :

Always remember, the universe speaks in colours and wavelengths. With the right tools and curiosity, you can listen and decode its stories.

Building Space Telescope Imaging Spectrograph
Image credit to NASA, 1996.

Figure 7: Building Space Telescope Imaging Spectrograph. Image credit to NASA, 1996.

Action Lab

Activity: A Simple Spectrometer

Objective :

Build a simple spectrometer using household materials to observe different light sources inspired by **Exploratorium.**

Preparation Time : 10 minutes

Activity Time : 45 minutes

Materials Needed :

- A compact disc (CD)
- A cardboard tube that's at least 12 inches long (approximately 30 centimetres) and 3 to 4 inches (7.5 to 10 centimetres) in diameter
- Two covers for the cardboard tube—we suggest two flat pieces of cardboard large enough to cover each end of the tube, or you can also use the plastic covers that come with a cardboard packing tube.
- Razor knife such as an X-ACTO knife
- Tape
- Access to fluorescent light
- Saw
- Cutting guide (scaled for a 3-inch tube)—**PDF included**
- Access to a printer

Procedures :

- Print the cutting guide and wrap it around your tube. We've scaled the guide for a standard 3-in packing tube. If needed, you can scale the guide to ensure it wraps around your tube without a gap or overlap (see figure 8).

Figure 8.

- Use a saw to cut the tube at an angle along the curved line on the cutting guide (see below). The cut will make the CD tilt at an angle approximately 30 degrees from the end of the tube (see figure 9).

Figure 9.

- Use a razor knife to cut the rectangular viewing hole—the black square on the cutting guide. You can remove the cutting guide now (see figure 10).

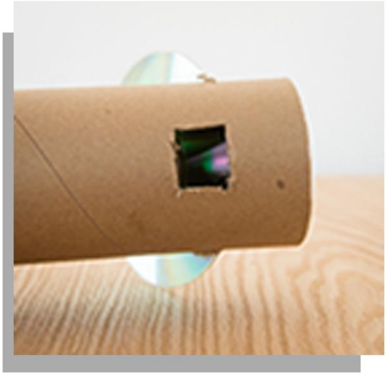


Figure 10.

- Next, cut a clean slit less than 1 mm wide and 5 cm long in one of the pieces of flat cardboard (or plastic tube cap). Tape the flat cardboard onto the end of the tube furthest from the CD—the top of the tube. Hold the tube as shown below and align the slit horizontally.
- Tape the second flat piece of cardboard (or plastic tube cap) over the bottom end of the tube, behind the CD, to exclude any stray light.
- Insert the CD into the CD slot, so that it reflects the light coming through the top slit into your eye. (see figure 11).

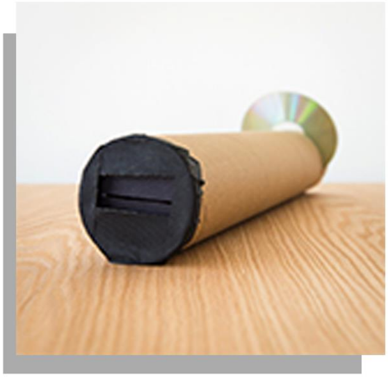


Figure 11.

To Do and Notice :

- Hold the tube upright and point the top slit at a fluorescent light.
- Press your eye to the viewing hole.
- On the CD, look for a clear, solid line of light broken up into coloured bands: this is the spectrum of light reflected from fluorescent light onto the CD.
- Adjust the angle at which you look through the viewing hole at the CD to find the best view of the light spectrum.
- Experiment by pointing the slit at various light sources (e.g., incandescent bulbs, LED lights, sunlight through a window) and observe the differences in the spectrum.

Observation and Discussion:

Teacher :

Now that we've observed the spectrum from a fluorescent light, what differences did you notice when you pointed the spectrometer at other light sources?

Student 1 :

The spectrum from the incandescent bulb seemed warmer with more reds and yellows.

Teacher :

Exactly! Incandescent bulbs emit light by heating a wire filament, which gives off a warmer colour spectrum. How about LED lights?

Student 2 :

I noticed more blue and green bands in the spectrum when observing the LED light.

Teacher :

That's a great observation! LED lights operate differently and often have a cooler colour spectrum. And what did you observe with sunlight?

Student 3 :

The sunlight seemed the most balanced. I could see a wide range of colours from red to violet.

Teacher :

Sunlight, or natural light, is often considered "white light" because it contains a balanced spectrum of colours. By using our spectrometer, we can break down this light and see its individual components.

Student 4 :

It's amazing how different light sources can have such varied spectra!

Teacher :

Indeed! And just as we've observed these differences on Earth, astronomers use similar principles to study light from stars and galaxies, helping us decode the mysteries of the universe.

Conclusion :

Teacher :

Before we conclude what we have learned today, can someone tell me (see figure 12) what is the position of Galaxy A in the graph 'Galaxy Speed vs. Distance' and why is it positioned there compared to the other galaxies??

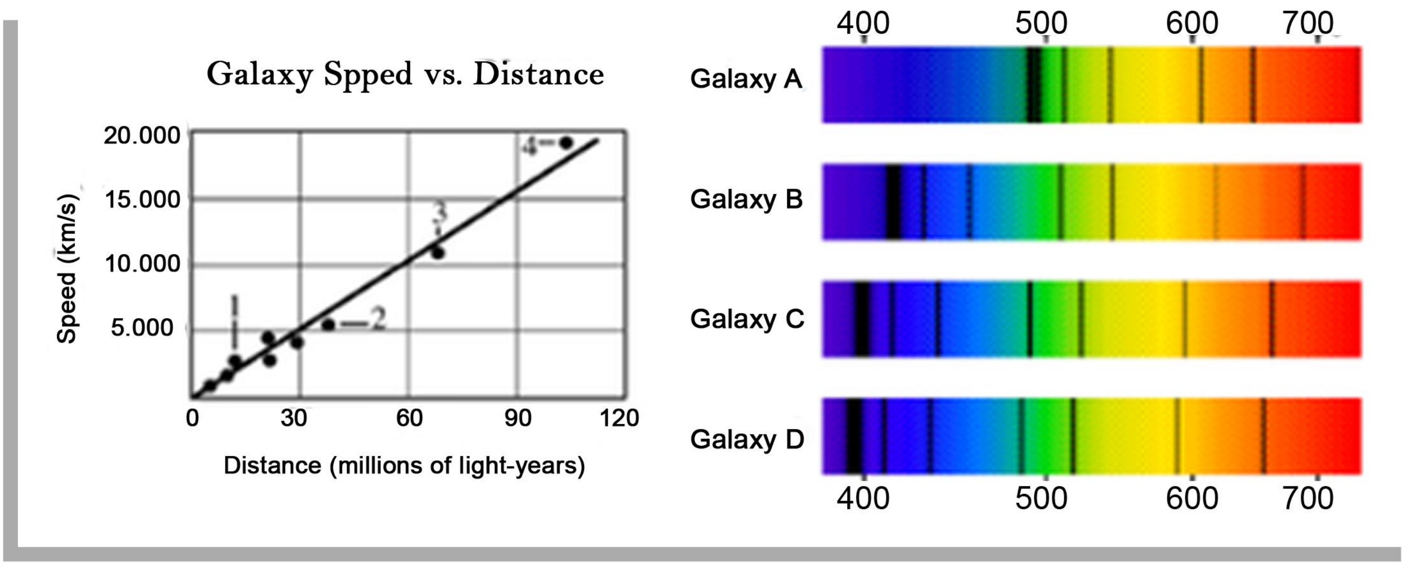


Figure 12.

Student 1 :

The correct answer is: Galaxy A would be at location #4 Galaxy A is the most " red-shifted " because the black absorption bands in the spectrum are located more toward the red end of the spectrum compared to the other galaxies. Therefore, Galaxy A is the most moving away from Earth.

Teacher :

Brilliant, Student 1! Today in our CosmoVerse adventure, we journeyed from the classroom's familiar sounds to the vast cosmos, uncovering the mysteries of cosmic redshift. Guided by Quark's Spaceship of Imagination and the brilliance of Bunsen and Kirchhoff, we explored the Doppler effect, the dance of electrons in spectroscopy, and the unique light signatures of galaxies. Through observation and hands-on experimentation, we've seen that even in the vastness of the universe, with curiosity and the right tools, we can decipher its most intricate secrets.

Cosmic Library

Videos :

How the Doppler effect works
What is Doppler Effect? Ambulance siren and Police Radar Gun
What is REDSHIFT?
Red shift | Astrophysics
Doppler Effect, Red Shift & The Big Bang Theory
GCSE Physics - What is Red Shift?
Red shift | Scale of the universe Khan Academy
Light: Crash Course Astronomy
Introduction to spectroscopy | Khan Academy
Spectroscopy, Explained
Redshift: Motion and colour

Interactive :

Analyzing Light: Spectrum of the Star Altair
Cosmological RedShift Simulator
Readymag: Redshift

Website :

Spectroscopy: Reading the Rainbow
Spacebook: Redshift

Documentaries :

Journey to the Edge of the Universe
Everything and Nothing
Atom: Clash of Titans

Articles :

What is cosmological redshift?
ESA: What is 'red shift'?

Infographics

What is Cosmological RedShift?

Glossary

Doppler Effect: The change in frequency or wavelength of a wave concerning an observer due to the relative motion between the source of the wave and the observer.

Blue Shift: A decrease in the wavelength of light emitted by an approaching celestial body, indicating motion towards the observer.

Cosmic Redshift: The shift of light from celestial objects towards the red end of the spectrum, indicating that the object is moving away from the observer.

Electromagnetic Spectrum: The entire range of wavelengths or frequencies of electromagnetic radiation, including radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, and gamma rays.

Absorption Spectra: The range of wavelengths (or colours) of light that a substance absorbs. It appears as dark lines on a continuous spectrum.

Emission Spectra: The range of wavelengths (or colours) of light that a substance emits.

Quantum Mechanics: A fundamental theory in physics that describes the behaviour of matter and energy on the scale of atoms and subatomic particles.

Spectrometer: A device used to measure properties of light over a specific portion of the electromagnetic spectrum.

Spectroscopy: The study of interactions between matter and electromagnetic radiation, often used to determine the composition of materials.

This article/publication is based upon work from COST Action CA21136 – “Addressing observational tensions in cosmology with systematics and fundamental physics (CosmoVerse)”, supported by COST (European Cooperation in Science and Technology)

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