The Doppler Effect and the Expanding Universe

When driving on a highway, it is common practice to move to the side when one hears an ambulance siren. Making way for emergency responders is a sign of respect. However, this simple interaction demonstrates a fundamental principle of physics, the Doppler effect. As the ambulance approaches, the siren's pitch increases, and as it moves further away, the pitch decreases. This same phenomenon plays a crucial role in astronomy and allows scientists to study movement patterns of distant objects and, most importantly, the universe.

Discovered by the Austrian mathematician, Christian Doppler, the Doppler effect is the change in frequency of a wave when there is relative motion between a moving object and an observer. This applies to sound waves, as seen with the ambulance, but also with light waves. This frequency shift can help determine whether the object is moving towards or away from the observer. When the distance between the source and observer is constant, there is no shift in frequency, and therefore, there is no Doppler shift. On the other hand, when motion is added, many changes occur.

When the source begins moving in the direction of the observer, the new waves are emitted at a position closer to the observer than the previous waves. This causes the distance between waves to decrease, meaning that more waves hit the observer in the same amount of time. This means that the observer sees a wave frequency that is higher than what the source emitted in a phenomenon called blueshift. When the source of light begins to move away from the observer, successive waves are emitted further and further from the observer. The observer perceives a lower wave frequency than emitted by the source, resulting in redshift. These terms were quickly adopted to describe Doppler shifts in not only light, but all types of waves.

In 1929, American astronomer Edwin Hubble discovered that the universe is constantly expanding. In an observatory, Hubble found that all galaxies experience cosmological redshift; however, the further a galaxy is, the more redshift is visible, meaning that farther galaxies move away from the observer faster than closer galaxies. This relationship between the distance of an observer and the moving galaxy and the speed at which the galaxy moves is known as Hubble's Law. Although this discovery suggests that galaxies are moving outward and away from a single point, the reality is more complex. The expanding universe is caused, not by the movement of galaxies, but by the expansion of space. As waves travel this constantly expanding space, the wavelength is also stretched, resulting in the redshift.

A good analogy to help describe this is what happens when a balloon is blown. If someone draws black dots spaced apart on a balloon and the balloon is then inflated, the distance between the dots increases. The reason why the space between the dots increases is due to the expanding balloon, because as the balloon is expanding, it takes the dots along with it. Similarly, galaxies are not just drifting apart in space. Instead, the distance between galaxies is growing over time due to the expansion of space itself.

While analogies build a strong intuition of the subject, scientists prefer to use mathematical models to explain the Doppler effect and Hubble's Law to understand the expansion of the universe more precisely and concretely.

The mathematical definition of redshift, which is denoted as z, measures how much the wavelength of light has shifted from when it was originally emitted. Cosmically, redshift measures expansion in the universe. The equation for redshift is defined as follows:

$$z = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}$$

In the equation, λ (lambda) represents the wavelength, typically in nanometers (nm). To better understand how this equation is used in practical applications, consider the following example.

In a high-altitude observatory, scientists measured a wavelength of 550 nm from a source that typically emits 500 nm. When using the formula:

$$z = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}} = \frac{550 - 500}{500} = \frac{50}{500} = 0.1$$

It was discovered that the redshift of the wave was 0.1 or 10 percent. This means that the source of the wavelength is moving away from the observer. If the answer to the redshift equation is ever negative, the source is instead blueshifted, meaning that it is moving closer to the observer. If the wavelength increased by 10 percent, it can be estimated that the universe also expanded by about 10 percent. A larger redshift results in a greater amount of expansion.

Measuring redshift in the universe is an extremely important tool that astronomers use to calculate how the universe is expanding as a large-scale system. However, the redshift equation only tells astronomers about how much the universe is expanding. Many times, astronomers want to measure how fast objects are moving and how far they are from an observer. This connection between the velocity of an object and the distance between it and the observer is known as Hubble's Law. Hubble's Law makes use of a unit of measurement called the Hubble constant, which represents the current expansion of the universe. It's a constant in a mathematical equation, but the measured value of it always varies. Hubble's Law is defined as:

$$v = H_0 d$$

In the equation, "v" represents recessional velocity, "d" represents the distance between the moving object and observer, and H_0 is the Hubble constant, currently equal to 70-76 kilometers per second per megaparsec (one million parsecs or around 3.26 million light-years). In the simple example, consider a galaxy that is 100 Mpc away from the observer. For simplicity, the Hubble constant will be 70 km/s/Mpc. Its recessional velocity can therefore be calculated as

$$v = H_0 d = 70 \times 100 = 7000$$

This means that this galaxy is moving away from the observer at a speed of roughly 7000 kilometers per second. If the distance from the observer was lower, the speed would have decreased, reinforcing the idea that more distant galaxies move away from observers faster.

Together, redshift and Hubble's Law provide useful tools for astronomers to understand the structure and behavior of the universe. Redshift connects the stretching of wavelengths of light to the expansion of the universe, while Hubble's Law connects the expansion of the universe to the distance between galaxies and their recessional speed. When these two equations are combined, they show that galaxies are not only moving away from us, but they also move in a way that depends on their distance. In this method, the Doppler effect becomes more than a measure of frequency shift, but also a piece of evidence that supports a progressive, expanding universe.

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