Cosmological Red Shift

Red shift is a general short term for a situation in which the *wavelength* of a light wave has become *longer* (Figure 1). Our eyes have adapted to see light waves of between 400 nm (blue) and 700 nm (red), one nanometre being 10^{-9}m. If blue light is 'red shifted' then it might become green, yellow or red depending on how much shift has taken place.

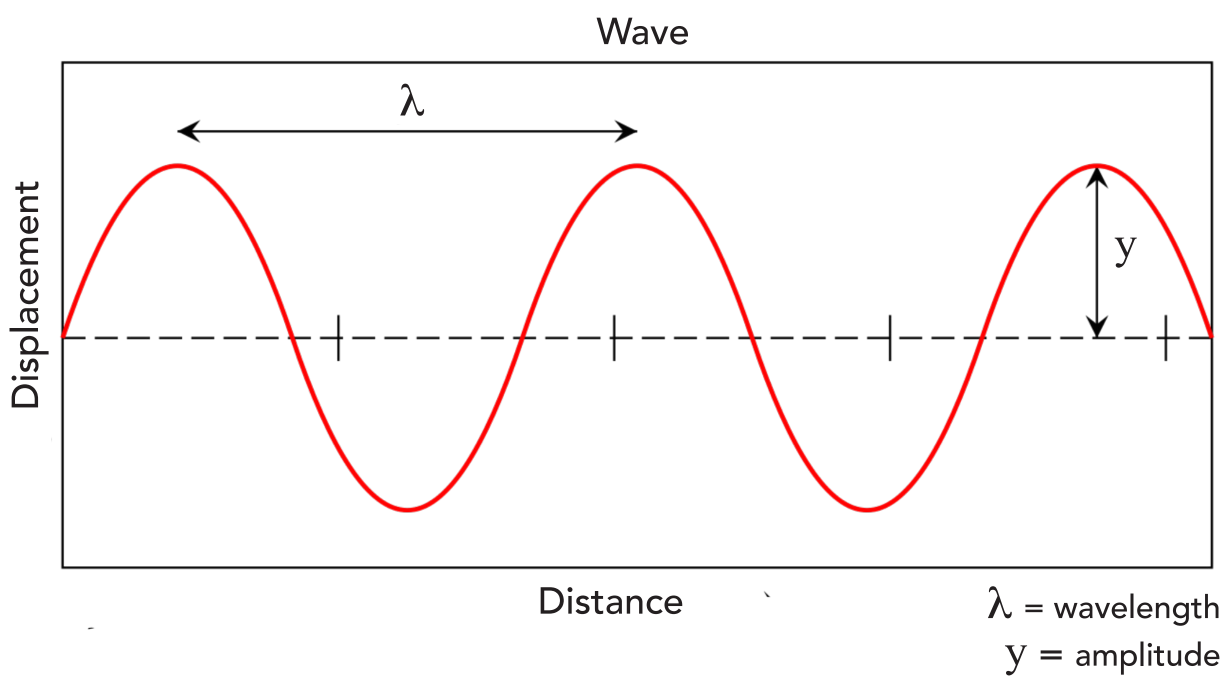

Figure 1: The wavelength and amplitude of a (transverse) wave.
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Light waves are electromagnetic in nature and so are more complicated than Figure 1 suggests, but the basic idea of wavelength is the same.

The red shift is formally defined as the fractional change in wavelength:

$$z = \frac{\lambda_2 - \lambda_1}{\lambda_1} = \frac{\Delta\lambda}{\lambda}$$

and it comes about due to three different physical mechanisms, depending on the situation. Only one of them is applicable to the evidence for the Big Bang, known as the cosmological red shift.

1. Doppler shift – the change in wavelength of a wave due to the movement of the object emitting the wave (Figure 2).

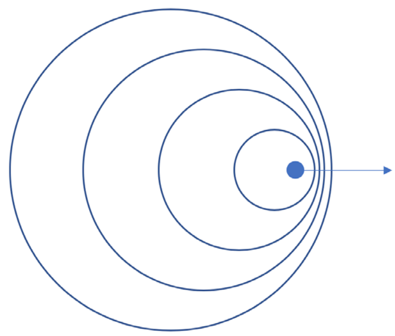

Figure 2: The Doppler effect for a moving source, which catches up on waves that it has already emitted in one direction and leaves them behind in the other.

For the Doppler shift of light, $z \approx v/c$ where v is the velocity of the source and c the speed of light. This is an important relationship, but it is an approximation to the true equation from the special theory of relativity.

Galaxies do show some red shift due to the Doppler effect, but it is generally small compared to the cosmological red shift, unless the galaxy happens to be close by. The nearest galaxy to us (the Andromeda galaxy) is actually blue shifted as its motion through space is carrying it closer to us.

In some simple accounts, the cosmological red shift is explained in terms of the Doppler effect, but this is not the correct physical mechanism.

2. Gravitational red shift – a ray of light moving away from a gravitational source will have its wavelength stretched out in escaping from the gravity well. This is a general relativistic effect, but it can be plausibly explained by considering a ball thrown up into the air. The ball leaves the hand with its maximum velocity (and hence kinetic energy), climbs to a height at which it momentarily stops and then falls down again. During the flight, kinetic energy is turned into gravitational potential energy. A light ray will not fall back down again but, as it climbs, kinetic energy is lost. For light (or a photon, if you prefer), kinetic energy is not directly related to speed, so the wave does not slow down as it loses energy, but its wavelength does get longer, according to the de Broglie relationship:

$$E = hc/\lambda$$

3. Cosmological red shift – the stretching out of the wavelength of light emitted from distant galaxies due to the expansion of the universe.

In 1929, Edwin Hubble discovered that the red shift shown in the light from distant galaxies was proportional to the distance that light had travelled to get to us from that galaxy. This is now known as Hubble's law. Using the approximate relationship , Hubble was able to plot recessional velocity against distance to show a linear relationship with a gradient , which is now known as the Hubble parameter[1].

The explanation for this effect comes from applying Einstein's theory of gravity (known as general relativity) to the universe as a whole. In the solutions to the resulting equations, the universe is expanding. This does not mean that the galaxies are moving away from each other through space, but rather that space is getting bigger. The standard analogy is to imagine a balloon being inflated. Thinking of the surface of the balloon as some sort of two-dimensional (2D) universe, we can see that a collection of ants would be able to crawl across the surface of the balloon. Their motion would be like that of galaxies genuinely moving through space. However, if you superglued two ants in place[2], then as the balloon inflated, the ants would be getting further apart, but not due to any movement on their part. In our universe, the galaxies are flowing away from each other to the expansion of the space between them.

There are several things wrong with this analogy (aside from the cruelty to the ants). Firstly, an ant is a 3D creature so can't really occupy a 2D universe. More importantly, the surface of the balloon is still a 'thing', not the expanding empty space of the real universe.

If we accept the basic notion of an expanding universe, then the red shift comes about as the light travelling through this space is also stretched by that expansion. Compare two galaxies A and B, where B is twice as far away from us as A. The light from B will take twice as long to get to us as that from A. In this time, the universe will have expanded twice as much and so the light from B will be red shifted by twice that from A. This is Hubble's law in a nutshell.

Turning the argument around, interpreting Hubble's law in terms of cosmological red shift provides evidence for the expansion of the universe. It is often the case in science that theory provides a context for interpreting evidence, which in turn backs up the theory.

[1] In some accounts, this is referred to as the Hubble constant (for historical reasons), but the value changes with time, so it is more in the nature of a parameter.

[2] No ants were harmed in carrying out this thought experiment…