Girls'Day: Expansion of the Universe

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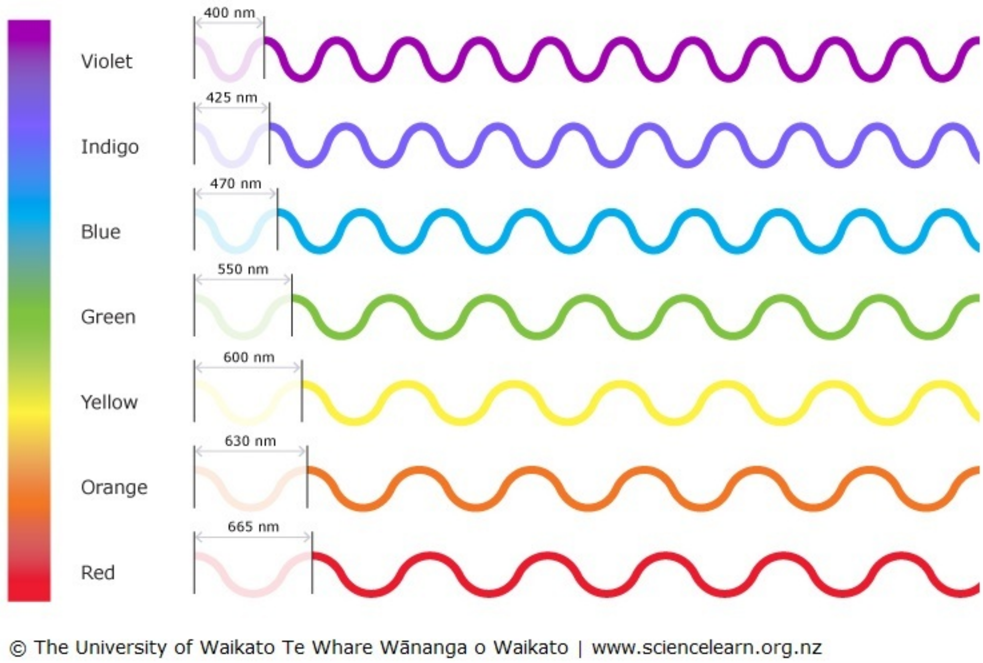
How do we measure distances to galaxies? How do we know the universe is expanding? What is the Big Bang? - This exercise sheet will help you to get an idea about how observations of distant galaxies tell us the answers to these questions. Have fun!

1 Light and Magnitudes

We observe distant galaxies by detecting their light. So what is light? The light you see all around you consists of waves of energy. The colours you see depend on the wavelength of the light, as shown in the picture below. Of the colours we can see, violet light has the shortest wavelength, and red has the longest. The wavelength is the length of a single cycle of the wave. It is measured in nanometres (nm): 1 nm = 1 cm / 10.000.000 or in Ångström (Å): 1 Å = 0.1 nm. There is also light with much smaller or much larger wavelengths than those shown here, but your eye is not able to see them.



a) Warm-up question: What is the wavelength range the human eye is sensitive to?

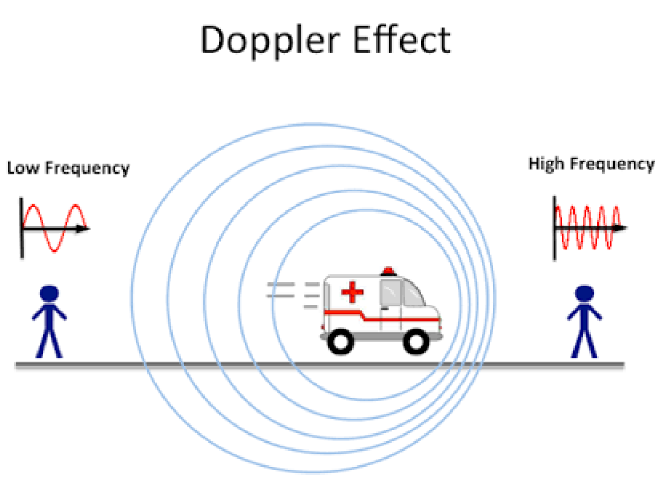
Astronomers measure how bright galaxies appear using ***magnitudes***. Confusingly, objects with higher magnitudes are less bright, and those with smaller (or negative) magnitudes are more bright. It is important to remember that magnitudes measure how bright an object appears to us, not how much light it actually emits. So if an object is farther away, it will appear fainter, which means it has a higher magnitude. Therefore, we can use an object's magnitude to help figure out how far away it is. The following are examples of some interesting magnitudes:

- The Sun: -26.7
- Full moon: -13
- Mars and Jupiter: -3
- Sirius (the brightest star in the Northern sky): -1.5
- Polaris (Polarstern): 2
- Andromeda (the brightest galaxy in the sky): 3.5
- Neptune: 8
- Proxima Centauri (closest star to solar system): 11
- Callirrhoe (moon of Jupiter): 21
- Limiting magnitude of Hubble Space Telescope: 32

b) Now discuss with your partner and guess: What is the magnitude limit of the human eye?

2 Redshift

Did you ever notice that an ambulance car sounds different when it moves towards you or when it moves away from you? This is the so-called Doppler effect: The sound waves in the direction of movement are squished and therefore have a higher frequency, while the sound waves behind the car are stretched and have a lower frequency.



The same happens with light! When a light source (like a star or galaxy) is moving away from us, the light waves are stretched to longer wavelengths. This is called ***redshift***.

c) Suppose a galaxy emits light in the yellow band. On Earth, we observe it in the red band. Is the galaxy moving away or towards Earth?

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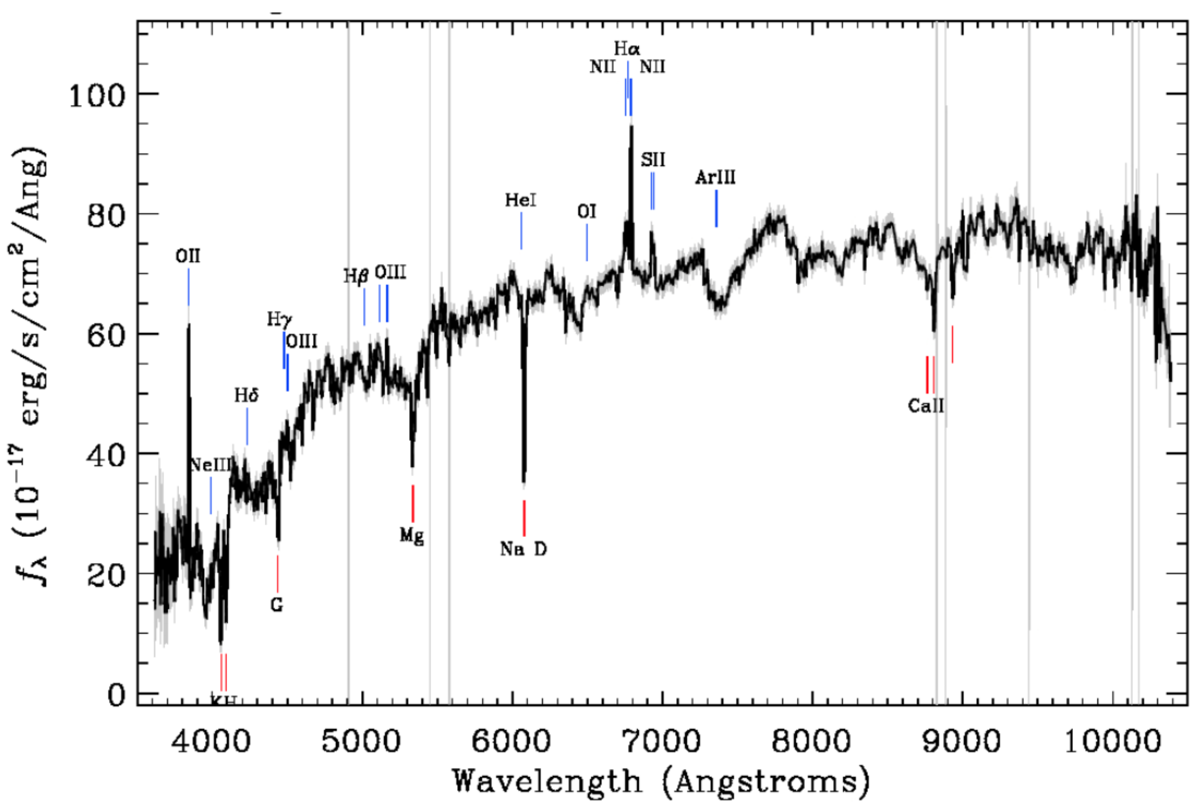
Cosmological objects do not only emit light at a single wavelength. They actually emit spectra of light that span a range of wavelengths. Now, we will have a look at a spectrum of a real galaxy, the so-called Tadpole galaxy, observed with the Sloan Digital Sky Survey DR14 [1]. Different elements emit light in different wavelengths, so by looking at the peaks in these spectra, we can work out what the object we are observing is made of. Some of the peaks have been labelled with the elements they correspond to. See if you recognise any of the symbols. Additionally, if the peaks are at longer wavelengths (further to the right) than we expect, we know that the object is moving away from us.



d) At what wavelengths do we observe the peaks of the H , OII, and SII ? Write your measurements in the following table:

[1] https://skyserver.sdss.org/dr14/en/tools/explore/summary.aspx?ra=241.5162842886600&dec=+55.4254411390800

Peak	onEarth (Angstrom)	measured (Angstrom)	redshift
H	6564.6		
OII	3727.1		
SII	6718.3		

e) Are these measured wavelengths larger than what is measured on the Earth? Is that the case for all the peaks?

The redshift z is related to the measured wavelength and on-earth wavelength by

$$z = \frac{\text{measured}}{\text{onEarth}} - 1:$$

f) Now you can compute the redshift of the Tadpole galaxy! Write your answers in the table above (use a calculator).

3 Hubble-Lemaître diagram

In this section, we will look at real data from distant galaxies taken from the original article that found evidence for the *accelerated* expansion of the universe[2]. The following table shows redshifts and magnitudes of supernova explosions in distant galaxies. A supernova is the explosion of a massive star at the end of its lifetime, that means when the star has burnt all its hydrogen. Supernovae are extreme and very bright events and can be used to infer the redshift and magnitude to very distant galaxies.

Object name	redshift z	magnitude
SN 1992bc	0.020	34.87
SN 1992P	0.026	35.76
SN 1994S	0.016	34.27
SN 1995D	0.008	33.01
SN 1995E	0.011	33.60

g) Draw a diagram on an extra sheet of paper with redshift z on the x-axis and magnitude [3] on the y-axis. What is the relation between redshift and magnitude?

[2]Riess et al. 1998, `https://iopscience.iop.org/article/10.1086/300499`

[3]μ is actually the distance modulus, which is defined as: $\mu = m - M$, where m is the apparent magnitude (the magnitude measured on earth) and M the absolute magnitude of the supernova. Since supernovae are so-called *standardizable candles*, their absolute magnitude can be calibrated, and one can infer μ from m.