Episode 702: Red shift

Changes in wavelength of spectral lines allow us to determine the motion of astronomical objects relative to ourselves.

Summary

Discussion: Red shift. (10 minutes)

Discussion: The Doppler effect. (10 minutes)

Demonstration: Doppler effect for sound. (20 minutes)

Demonstration: Doppler effect with microwaves. (20 minutes)

Discussion: Speed and frequency. (10 minutes)

Student questions: Binary stars. (20 minutes)

Discussion:

Red shift

The wavelengths of spectral lines emitted by atoms in an astronomical object are often *increased* compared to a similar source in the laboratory. We see the same pattern of lines (so we can recognize the elements from which they arise), but the whole pattern is shifted to longer wavelengths. The colour is not necessarily actually red, or even visible. Red shift simply means an increase or s*hift* to a longer wavelength. (For visible light, this means towards the red end of the spectrum.)

There are two distinct explanations: the *Doppler effect* (due to relative motion of source and observer) and the *Cosmological Red Shift* (due to the expansion of space).

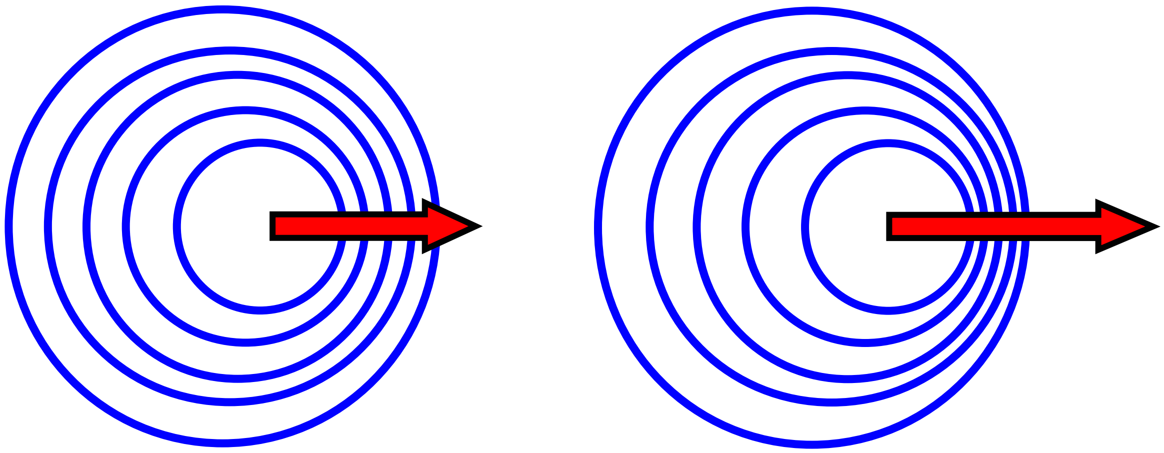
Both effects result in the same formula for calculating speed v of the object emitting the light.

Discussion:

The Doppler effect

The Doppler effect is common to all types of wave motion. It is characteristic of a wave that:

- Its frequency depends on its source.



- Its velocity depends on the medium through which it moves. (Its velocity is not affected by the motion of the source.)
- It is the wave's wavelength that is affected by relative motion.

Demonstration:

Doppler effect for sound

Show the Doppler effect for sound using a whirling loudspeaker.

When approaching you (the detector), the crests bunch up as the source is catching up with the wave; λ gets smaller, so f gets larger because $f\lambda$ is a constant c, i.e. pitch rises.

Travelling away from the detector, source gets away from the wave, crests stretched out and the pitch drops.

TAP 702-1: The Doppler effect

Demonstration:

Doppler effect with microwaves

You can show the Doppler effect for microwaves reflected by a moving barrier.

TAP 702-2: Doppler shift using microwaves

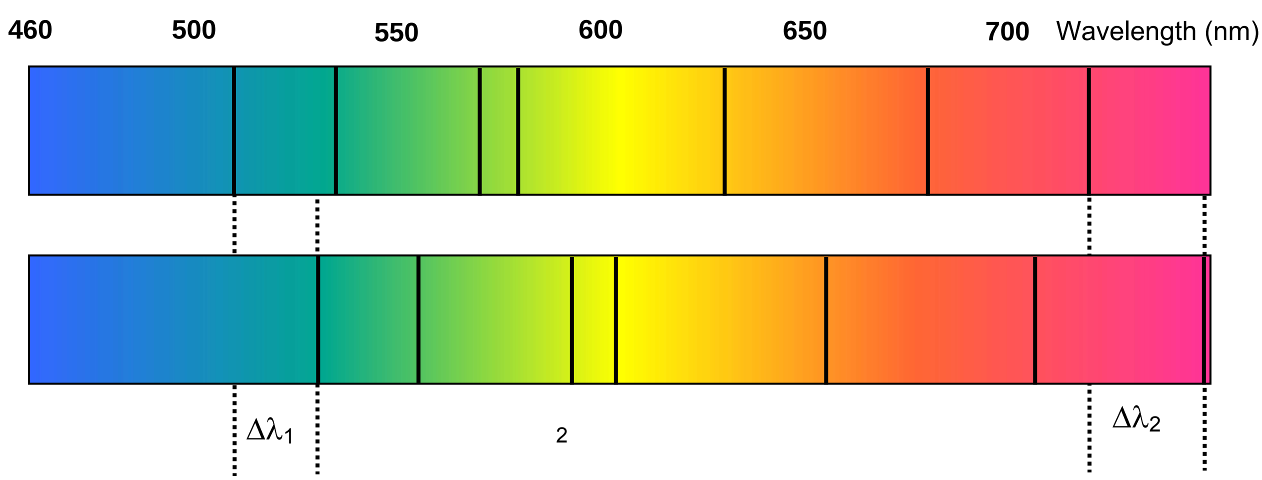
Discussion:

Speed and frequency

Derive the relationship $\Delta\lambda / \lambda = \Delta f / f = v / c$. This says that the fractional change in wavelength or frequency is equal to the ratio of the speed of the source to the speed of light.

TAP 702-3: Doppler derivation for light

TAP 702-4: The Doppler shift



The consequence is that the frequencies of spectral lines change in proportion. NB many text books have diagrams that do not really show the increasing separation of spectral lines with wavelength, as though all the lines in a spectrum were shifted by an equal amount rather than by an equal fraction. The diagram above shows the correct version.

An interesting example: the Sun rotates, and its light is therefore Doppler shifted. The radiation from the side approaching the Earth is blue shifted; the radiation from the side moving away from the Earth is red shifted. The speed of rotation can be determined from these frequency shifts.

TAP 702-5: Doppler shifts from part of a galaxy

Student questions:

Binary stars

When two stars orbit about one another, one may be moving towards us (blue shift), and the other away (red shift).

TAP 702-6: Binary stars

TAP 702- 1: The Doppler effect

You will need

- ✓ Multimedia Sound CD-ROM
- ✓ multimedia PC with microphone and speakers

Either:

- ✓ 2 m of rubber tubing
- ✓ whistle attached to the end of the tubing

or

- ✓ 2 m of strong cord or rope
- ✓ small electronic buzzer and battery attached to end of cord

or

- ✓ 2 m of strong cord or rope
- ✓ small loudspeaker attached to end of cord
- ✓ long leads
- ✓ signal generator

What to do:

1. To demonstrate the Doppler effect, either attach a whistle to a long flexible rubber tube and blow down it while whirling the whistle in a horizontal circle

   and/or

2. Firmly attach a battery-operated buzzer, or a small speaker connected to a signal generator with long lead

Safety

Do this outside, and make sure that the listeners stand well away from the whirling object.

3. As an extension, you could use the Multimedia Sound CD-ROM to record and display sounds that illustrate the Doppler effect (e.g. from passing vehicles).

You have learned:

That a variation in pitch occurs as the source of sound moves towards and away from the observer.

External reference

This activity is taken from Salters Horners Advanced Physics, section SPS, activity 22

TAP 702- 2: Doppler shift using microwaves

The frequency shift in waves reflected from a moving reflector

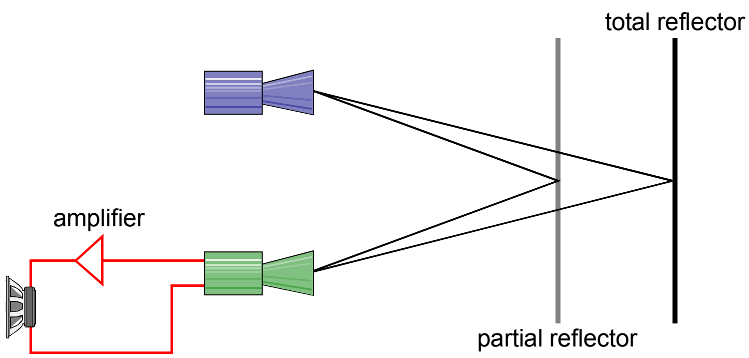
In this experiment, a moving metal sheet is used to reflect microwaves and, because the sheet is moving, the frequency of the reflected waves is shifted. The frequency shift depends on the speed and direction of the movement.

You will need

- ✓ microwave transmitter
- ✓ microwave receiver
- ✓ audio amplifier
- ✓ loudspeaker (if not built into amplifier)
- ✓ metal reflector about 0.3 m square
- ✓ hardboard reflector about 0.3 m square

The experiment

Set up the apparatus as shown below:



If necessary, set the transmitter to unmodulated microwaves. Put the hardboard sheet near the transmitter and receiver. Make sure that you have room to swing the metal sheet and then move it as fast as possible away from the hardboard.

Try to explain your observations. Why is the hardboard sheet necessary? The diagram above gives a clue.

You have learned

1. That when the metal sheet is moved away from the hardboard, a sound is heard from the loudspeaker.
2. That this sound is the result of a frequency shift in the waves reflected from the metal sheet produced by the movement of the sheet.

Practical advice

The effect here is produced by the beats between the microwaves reflected from the hardboard and from the metal sheet being converted into an audio signal by the loudspeaker. No beats are produced when the reflector is stationary because the reflected frequencies from both hardboard and metal are the same.

The beat frequency is given by

$| f_1 - f_2| / 2$

where f_1 and f_2 are the frequencies reflected from the hardboard and the metal sheet. So there is no audible difference between the sound heard when the sheet is moved away from the hardboard compared with when it is moved towards it despite the fact that the Doppler shift is in different directions in the two cases. This may need careful explanation for some students who may expect a higher pitched sound when the sheet is moved towards the hardboard compared with when it is moved away.

Social and human context

There are many everyday examples of Doppler shifts with sound such as the passing of racing cars. It is important to emphasise the difference between these and the Doppler effect with electromagnetic waves. The speed of sound waves is affected by the motion of the air, whereas the speed of light is constant for all observers.

External reference

This activity is taken from Advancing Physics, chapter 12, 120D

TAP 702- 3: Doppler derivation for light

Consider a star or galaxy moving away from us with speed v and emits light of frequency f and wavelength λ.

In 1 second there are f waves and these will cover a distance of v + c where c is the speed of light. (Speed = distance/time and time = 1 second)

The apparent wavelength observed on earth in line with the motion is λ_a and is given by

$\lambda_a = (v + c)/f$ but $f = c/\lambda$ so $\lambda_a = (v + c)\,\lambda/c = (v/c + 1)\,\lambda$

so

$\lambda_a - \lambda = v\lambda/c$ differences in wavelength can be written as $\Delta\lambda$ so ($\lambda_a - \lambda = \Delta\lambda$) so $\Delta\lambda = v\lambda/c$

or

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

An object moving away has the wavelength shifted towards longer wavelengths ("the red end of the spectrum") whilst an object moving towards us has an apparent smaller wavelength. In this case f waves will travel a distance of $c - v_t$ where v_t is the objects speed in a line towards us.

So apparent wavelength λ_a is given by

$\lambda_a = (c - v_t)/f = (c - v_t)\,\lambda/c$ as $f = c/\lambda$ so $\lambda_a = \lambda - v_t\lambda/c$ so $\lambda_a - \lambda = v_t\lambda/c$ but $\lambda_a - \lambda = \Delta\lambda$ so

so $\Delta\lambda / \lambda = v_t\lambda/c$ which is similar to before except for speed direction so in general

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

represents both situations if you consider speed.

Note that this is the expression for $v \ll c$

A side note:

Spectral lines are in fact broadened since some molecules of gas are moving towards the observer and some moving away the change in wavelength is the same size for molecules approaching as molecules receding so the width of a spectral line is given by

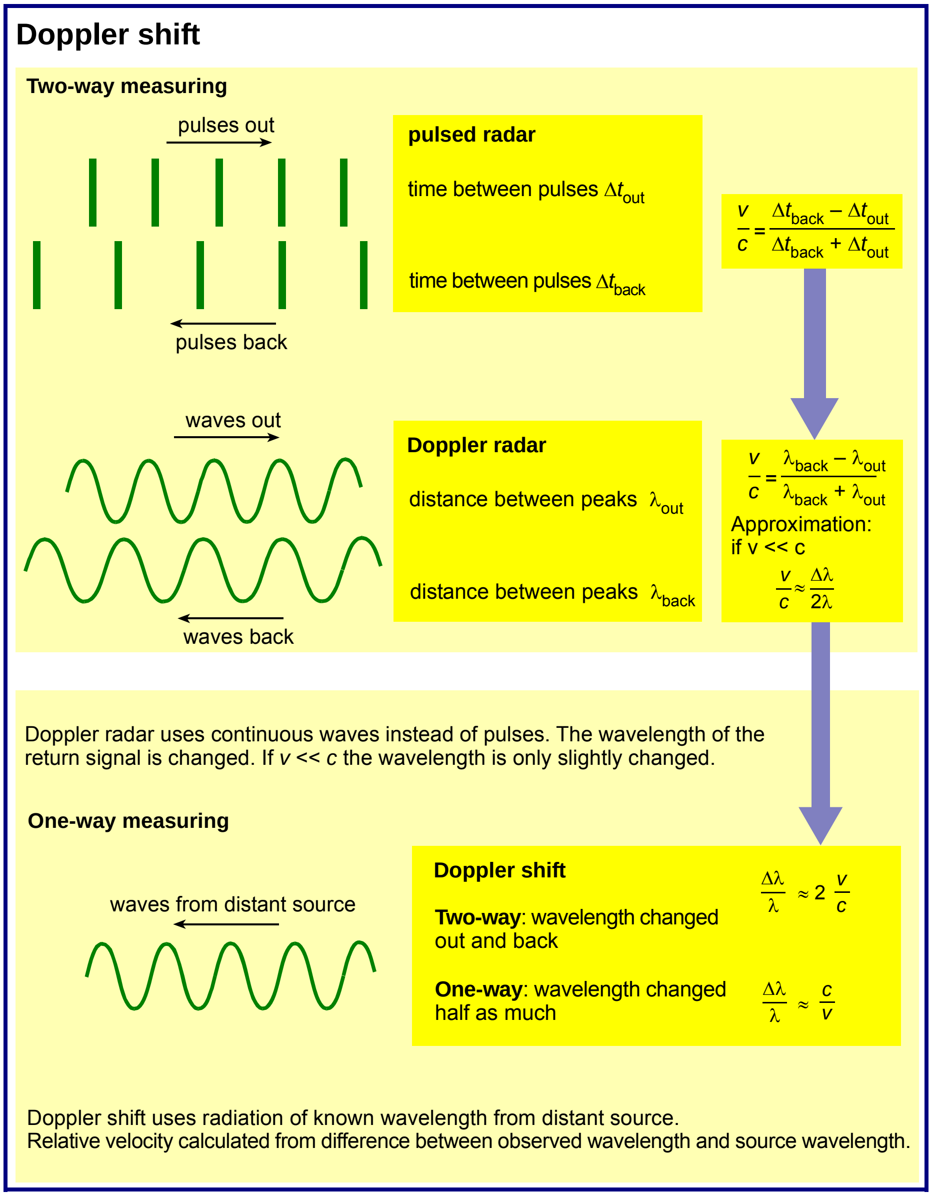
$$linewidth = \Delta\lambda = \frac{2\lambda v}{c}.$$

Here v would be the root mean square speed of the molecules. By measuring the line width and using kinetic theory, temperatures can be estimated.

Practical advice

A derivation is reproduced here so that you can discuss it with your class if required.

TAP 702- 4: The Doppler shift



This diagram shows how trip times for pulses relate to measurements on wavelengths, leading to changes in wavelength where relative movement plays a part.

Practical advice

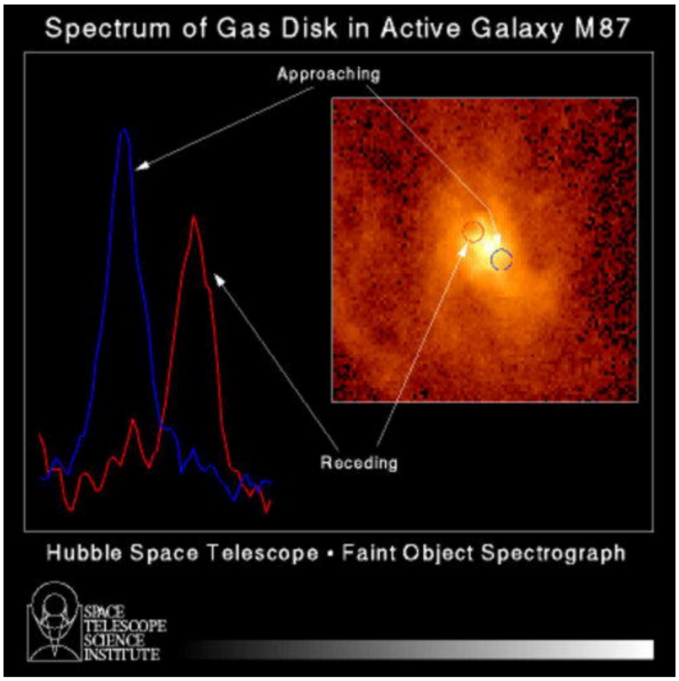
This diagram is reproduced here so that you can discuss it with your class if required.

External reference

This activity is taken from Advancing Physics, chapter 12, 120O

TAP 702- 5: Doppler shifts from part of a galaxy

Images of the central gas disc of galaxy M87 and the spectra of emission line gas from that central disc, showing both red shifts and blue shifts. These show that one side of this gas disc is approaching us whilst the other side is receding. The disc seems to be rotating at a speed of about 550 km s^{-1}. There is no evidence that the whole galaxy is rotating.



Practical advice

These images of M87 are taken by the Hubble Space Telescope. The large image shows the nuclear regions as well as the prominent optical jet. The inset shows the nucleus and the central gaseous disc of the galaxy in more detail.

The second image shows the spectra from emission line gas in the central disc of the galaxy on either side of the nucleus at the locations indicated in the diagram. The gas on one side of the galaxy is strongly red shifted and on the other side blue-shifted, showing that the disc is rotating at a speed of about 550 km s^{-1}.

Note that M87 itself does not rotate – the centre part does.

Social and human context

Exploration of the Universe requires inferences from observations. We do not know that the galaxy is rotating, but how else can we explain the observations?

External reference

This activity is taken from Advancing Physics, chapter 12, 130s

(Photograph courtesy of NASA/STScI)

TAP 702- 6: Binary stars

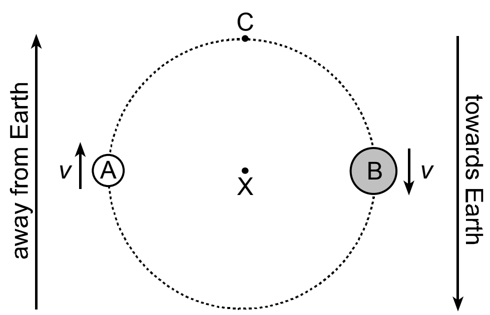
Orbiting binary stars:

A type of variable star.

This type of variable star consists of two stars orbiting around each other. When the dimmer star is in front of the brighter one, the observed intensity is at a minimum, and when the two stars are side by side, the observed intensity is at a maximum.

Relative velocities in an orbiting binary star system.

The two stars in this question are similar in mass, but star B is cooler and dimmer than star A. They orbit about their common centre of gravity X, as shown in the diagram.



In one such pair of stars, the time for one revolution is 73 days.

The stars are a distance of 1×10^{11} m apart.

1 day = 8.64×10^{4} s

1. What are the velocities of stars A and B, relative to the point X?

2. What is the velocity of star A, relative to star B?

The point X is not still with respect to Earth. It is moving at a velocity of 64 km s^{-1} in the direction away from Earth.

3. What are the velocities of stars A and B, relative to Earth?

4. What is the velocity of either star, relative to Earth, when it is at the position C?

The Doppler shift in wavelength for a star moving at a velocity *v* relative to the observer is

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

if the speed *v* is small compared with the speed of light, *c*. The speed of light, *c*,

is 3.0×10^8 m s^{-1}.

5. Find the wavelength shift $\Delta\lambda$ that an astronomer (on Earth) would observe in a spectral line of wavelength 589.0 nm from star A in the position shown in the diagram. Is this a red shift or a blue shift?

6. Find the wavelength shift $\Delta\lambda$ that an astronomer (on Earth) would observe in a spectral line of wavelength 589.0 nm from star B in the position shown in the diagram. Is this a red shift or a blue shift?

7. Find the wavelength shift $\Delta\lambda$ that an astronomer (on Earth) would observe in a spectral line of wavelength 589.0 nm from either star when it is in the position C on the diagram. Is this a red shift or a blue shift?

8. In many binary stars, the two stars are not perfectly lined up when seen from Earth. This means that there will not be any dimming or brightening of the light, because the dimmer star will not block out the light from the brighter one. How might an astronomer tell, from the spectrum, that there are in fact two stars moving about their common centre of mass as described in this question?

Hints

1. You can quickly find out how far each star goes in 73 days. Don't forget that velocity is measured in metres per second (m s^{-1}), and it has a direction.
2. Imagine you are on Star B. How fast, and in which direction, does star A seem to move?
3. If the binary star is moving, it means that the point X is moving at that velocity. You can easily combine the answers to part 1 with 64 km s^{-1} (taking care of units!) to get the answer here.

4. You need to combine 64 km s^{-1} with the component, in the direction towards / away from Earth, of the velocity of a star when at C.

5. This question, and the following two, follow from the results of question 3 and 4. Red shifts are due to stars moving away from Earth, blue shifts are due to stars approaching.

6. Is it approaching, or retreating? Is the wavelength being stretched, or squashed?

7. If you've done question 6, this should be fairly obvious.

8. Although the intensity will not change with time, the spectrum will – provided that the stars are not moving perpendicular to the line of view.

Practical advice

Fairly straightforward applications; difficulties arise in visualising the movement and the magnitudes of distances and velocities involved. Note that some binary stars, e.g. Capella (Aurigae) orbit in a plane perpendicular to our line of sight, and so do not show this phenomenon. The formula used for the wavelength shift

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

is justified due to the low speeds involved. Note that there is a relativistic transverse Doppler shift (a time dilation effect) that affects the answer to question 7. However, again due to the small speeds involved, this effect is negligible.

Algol (β Persei) is the classic eclipsing system; with a period of about 3 days. Details are given in most astronomy books, e.g. Norton's 2000, or virtually any encyclopaedia.

Or see:

http://www.solstation.com/stars2/algol3.htm

http://en.wikipedia.org/wiki/Beta_Persei

http://domeofthesky.com/clicks/algol.html

Alternative approaches

A battery-operated buzzer in a net bag, tied to a strong cord and whirled around the head, shows this effect quite nicely. Note that the Doppler effect for sound is dependent on the motion of the medium so that it is not strictly the same as the Doppler effect considered here. Safety note: do not smack anyone around the head with the whirling buzzer!

TAP 702-1: The Doppler effect

Social and human context

Historical perspective: the Doppler measurements are typical of the sort of discoveries made with the Doppler effect, once the resolution of the spectrometers was up to fractions of a nanometre.

Answers and worked solutions

1. The speed of stars in orbit is equal to $\pi D / T$:

$$v = \frac{\pi D}{T} = \frac{\pi \times \left(1 \times 10^{11}\ \text{m}\right)}{73\ \text{days} \times 8.6 \times 10^{4}\ \text{s day}^{-1}} = 5.0 \times 10^{4}\ \text{m s}^{-1}$$

Therefore the velocity of A relative to X is + 5.0 × 10^4 m s^{-1} and the velocity of B relative to X is – 5.0 × 10^4 m s^{-1} where the positive direction is the direction away from the Earth.

2. The velocity of A relative to B is (+ 5.0 × 10^4 m s^{-1}) – (– 5.0 × 10^4 m s^{-1}) which is equal to + 1.0 × 10^5 m s^{-1} with directions defined as in question 1.

3. Adding the velocities in question 1 to 6.4 × 10^4 m s^{-1} gives

$$\begin{aligned}\text{Velocity of A relative to Earth} &= +\,5.0 \times 10^{4}\ \text{m s}^{-1} + 6.4 \times 10^{4}\ \text{m s}^{-1} \\ &= 1.1 \times 10^{5}\ \text{m s}^{-1}.\end{aligned}$$

$$\begin{aligned}\text{Velocity of B relative to Earth} &= -\,5.0 \times 10^{4}\ \text{m s}^{-1} + 6.4 \times 10^{4}\ \text{m s}^{-1} \\ &= 1.4 \times 10^{4}\ \text{m s}^{-1}\end{aligned}$$

with directions defined as in question 1.

4. Here the component of the velocity of each star, relative to X, in the direction defined in question 1, is zero, so each star has a velocity relative to Earth which is the same as that of X, i.e. 6.4 × 10^4 m s^{-1}.

5.

$$\begin{aligned}\Delta\lambda &= \frac{\lambda v}{c} \\ &= \frac{\left(589.0 \times 10^{-9}\ \text{m}\right) \times \left(1.1 \times 10^{5}\ \text{m s}^{-1}\right)}{3.0 \times 10^{8}\ \text{m s}^{-1}} \\ &= 2.2 \times 10^{-10}\ \text{m} \\ &= 0.22\ \text{nm}\end{aligned}$$

This is a red shift, because the star is moving away from the Earth, and so the wavelength is ‘stretching’.

6.

$$\begin{aligned}\Delta\lambda &= \frac{\lambda v}{c} \\ &= \frac{\left(589.0 \times 10^{-9}\ \text{m}\right) \times \left(1.4 \times 10^{4}\ \text{m s}^{-1}\right)}{3.0 \times 10^{8}\ \text{m s}^{-1}} \\ &= 2.8 \times 10^{-11}\ \text{m} \\ &= 0.028\ \text{nm}\end{aligned}$$

This is a red shift for the same reason as question 5.

7.

$$\begin{aligned}\Delta\lambda &= \frac{\lambda v}{c}\\ &= \frac{\left(589.0\times10^{-9}\ \text{m}\right)\times\left(6.4\times10^{4}\ \text{m s}^{-1}\right)}{3.0\times10^{8}\ \text{m s}^{-1}}\\ &= 1.3\times10^{-10}\ \text{m}\\ &= 0.13\ \text{nm}\end{aligned}$$

This is also a red shift for the same reason as question 5.

8. When the stars are at C and the point diametrically opposite to C respectively, then both will have their 589.0 nm spectral line red shifted by 0.13 nm, as both will have the same velocity relative to the Earth (question 4). When they move towards A and B, however, their velocities relative to Earth increase and decrease respectively, causing the spectral line to be red shifted by different amounts, so it will split into two distinct spectral lines. These will merge into one as the stars line up in the direction of Earth once more. Should the two stars be moving in a circle whose plane is perfectly perpendicular to the Earth, however, like the stars in the Capella binary system, then there will be no splitting of the line, as the velocity relative to Earth in the perpendicular direction will not change during the orbit.

External References

This activity is taken from Advancing Physics, chapter 12, 60S