20 COSMOLOGY (THE BIG BANG)

20.1 Astronomical distances

Specification reference: 5.5.3

Learning outcomes

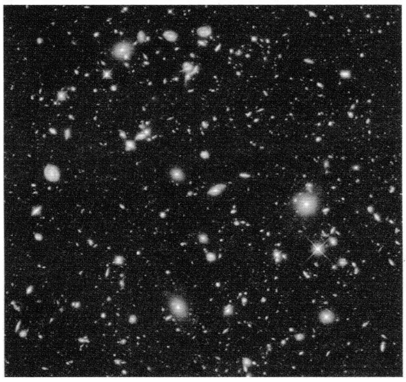
Demonstrate knowledge, understanding, and application of:

- → distances measured in astronomical units, light-years, and parsecs
- → stellar parallax
- → the equation relating the parallax *p* in seconds of arc and the distance *d* in parsec.

Astronomical numbers

The Hubble Ultra Deep Field is a famous image taken by the Hubble Space Telescope in 2004. It shows a tiny region of space in the southern-hemisphere constellation of Fornax. The image of this tiny square of sky has an angular spread of just 2.4 minutes of arc (**arcminutes**) from edge to edge – about 0.04° or 7.0×10^{-4} radians, about equivalent to a patch of sky covered by a grain of sand held at arm's length.

Despite being so tiny, the image contains around 10 000 galaxies. We use the **cosmological principle** to assume that there is nothing special about this part of the sky. This typical patch of sky highlights the absolute vastness of our Universe and the incredible number of galaxies it must contain.



▲ **Figure 1** *The Hubble Ultra Deep Field shows some of the oldest galaxies in the Universe, some over 13 billion years old*

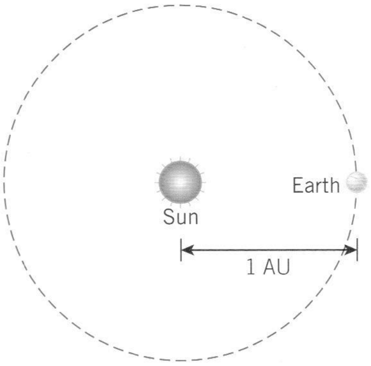
Units of distance

Astronomical distances can be expressed in metres using standard form. However, the distances are so vast that it is like giving the distance from Moscow to New York in millimetres. Instead, we use three main specialist units. In order of increasing length, they are the **astronomical unit**, the **light-year**, and the **parsec**.

The astronomical unit (AU)

The astronomical unit is the average distance from the Earth to the Sun, 150 million km, or 1.50×10^{11} m (Figure 2).

The astronomical unit is most often used to express the average distance between the Sun and other planets in the Solar System.



Sun and Earth not to scale

▲ **Figure 2** *As the Earth orbits the Sun in an ellipse, 1 AU is defined as the average distance from the Earth to the Sun*

The light-year (ly)

The light-year is the distance travelled by light in a vacuum in a time of one year.

$$\text{distance} = \text{speed} \times \text{time} = 3.00 \times 10^{8} \times (365 \times 24 \times 60 \times 60)$$
$$= 9.46 \times 10^{15}\,\text{m}$$

The light-year is often used when expressing distances to stars or other galaxies (see Table 1 for examples).

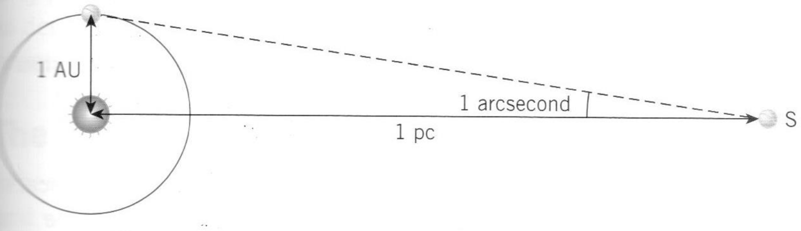
▼ **Table 1** *Distances to some objects visible in the sky*

Object	Distance / ly
Proxima Centauri (nearest star to the Sun)	4.24
Rigel (blue supergiant star in Orion's foot)	860
Diameter of the Milky Way	100 000
Andromeda galaxy (furthest object visible with the naked eye)	2 500 000

The parsec (pc)

Before defining the parsec, you need to be aware that professional astronomers prefer to measure angles not in degrees but arcminutes and arcseconds. There are 60 arcminutes in 1°, and 60 **arcseconds** in each arcminute. Therefore, 1 arcsecond = $\left(\frac{1}{3600}\right)^{\circ}$.

The parsec is defined as the distance at which a radius of one AU subtends an angle of one arcsecond.



▲ **Figure 3** *The parsec is defined using the astronomical unit*

You can determine the value of 1 pc in metres by using the triangle in Figure 3, $\tan(1\text{ arcsecond}) = \frac{1\text{ AU}}{1\text{ pc}}$.

Therefore

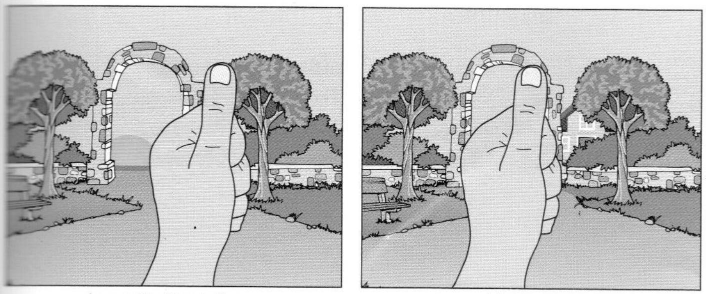
$$1\text{ pc} = \frac{1.50 \times 10^{11}}{\tan\left(\frac{1}{3600}\right)} = 3.1 \times 10^{16}\text{ m (about 3.26 ly)}$$

It is worth looking more closely at Figure 3. Because the angle at point S is very small, the small-angle approximation ($\theta \approx \tan\theta$) can be used. If point S is at a distance of 2 pc, the angle subtended by the radius will be $\frac{1}{2}$ arcsecond, if 3 pc then $\frac{1}{3}$ arcsecond, and so on. If the point S is at a distance d parsec, then the angle subtended is simply $\frac{1}{d}$ arcsecond. This relationship will be useful in the next section.

Using stellar parallax to determine distances

Stellar parallax is a technique used to determine the distance to stars that are relatively close to the Earth, at distances less than 100 pc.

Parallax is the apparent shift in the position of a relatively close star against the backdrop of much more distant stars as the Earth orbits the Sun. You can mimic this effect by holding your thumb at arm's length in front of your face. First view the thumb with only your left eye, then the right. You will notice an apparent shift in the position of your thumb against the background (Figure 4). This illusion is exactly the same as the effect used for measuring stellar distances (Figure 5).


view with the left eye
view with the right eye

◀ **Figure 4** *Demonstrating parallax*

Synoptic link

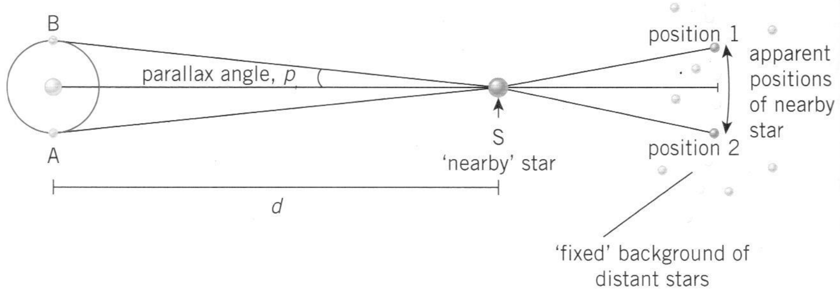
You have already seen the astronomical unit used in Topic 18.4, Kepler's laws.

Study tip

Remember the light-year is not a unit of time, but one of distance.

Study tip

Seconds of arc and arcseconds are the same quantity.



▲ **Figure 5** *Carefully recording the position of a nearby star in the sky against stars much further away allows the distance to the star to be determined using stellar parallax and simple trigonometry*

In Figure 5, when the Earth is in position A, the nearby star S appears in position 1. Six months later when the Earth is in position B, the star appears in position 2. Precise measurements can determine the **parallax angle** p. If p is measured in arcseconds, the distance to the nearby star in parsecs is given by

$$d = \frac{1}{p}$$

This is the equation you met in the previous section.

This technique is limited to stars less than 100 pc from the Earth, because as d increases the parallax angle decreases, eventually becoming too small to measure accurately, even with the most advanced astronomical techniques.

Study tip

When using $d = \frac{1}{p}$, make sure d is in parsecs and p is in arcseconds.

Summary questions

1 Explain what is meant by stellar parallax. *(2 marks)*

2 Calculate the distance from the Earth in parsecs to a star that makes a parallax angle of 0.018 arcseconds. *(2 marks)*

3 Using the data in Table 1, if needed, show that:
   a the Earth is approximately 8 light-minutes from the Sun; *(2 marks)*
   b Proxima Centauri is around 1.3 parsecs from the Earth. *(2 marks)*

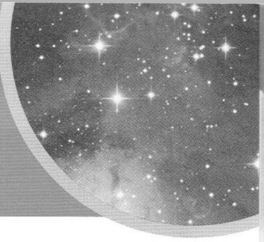
4 Calculate the distance from the Earth in ly to a star that makes a parallax angle of 1.56×10^{-5}°. *(4 marks)*

5 The intensity of the light received from a star 16 ly away is measured as $2.3 \times 10^{-13}\,\mathrm{W\,m^{-2}}$. Calculate the luminosity of the star. *(4 marks)*

6 A tennis ball has a diameter of 6.75 cm. Calculate how far the ball would need to be from an observer to subtend an angle of 2.4 arcminutes. *(4 marks)*

20.2 The Doppler effect

Specification reference: 5.5.3

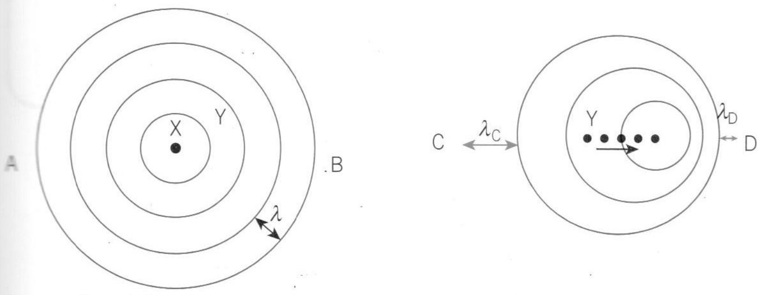


Much more than racing cars

The familiar 'neeeeeeeeaaawwwwwww' sound of a racing car moving past a stationary TV camera is perhaps the best known example of the **Doppler effect**, but there are many more. The Doppler effect is used to determine the speed of moving objects ranging from motorists and tennis balls (Figure 1) to rotating galaxies.

The Doppler shift

Whenever a **wave source** moves relative to an observer, the frequency and wavelength of the waves received by the observer change compared with what would be observed without relative motion.



X = stationary source

Y = source moving relative to observers

▲ **Figure 2** *Relative motion and the Doppler effect*

In the first diagram in Figure 2, the wave source is stationary relative to two observers at A and B. Both observers experience waves at the same frequency and wavelength λ as they were emitted from the source.

In the second diagram, the wave source Y is moving away from observer C towards observer D. In this example the waves received by D will be compressed. They have a shorter wavelength λ_D and so a higher frequency (this is the 'neeeeeee...' part as a racing car approaches a stationary observer). For observer C the waves are stretched out, the wavelength λ_C becomes longer and a lower frequency is observed (the '...aaawwwwwww' part as the racing car moves away). The faster the source moves, the shorter λ_D and the longer λ_C are.

In the case of the racing car, the Doppler effect applies to sound waves, but the effect happens with all types of waves. In the example of the radar gun determining the speed of a tennis ball, microwaves are reflected off the moving ball, so the ball acts like a source of microwaves.

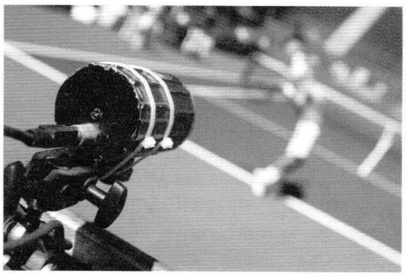
Learning outcomes

Demonstrate knowledge, understanding, and application of:

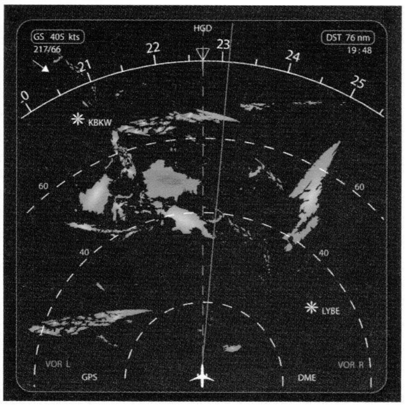
- → the Doppler effect
- → Doppler shift of electromagnetic radiation
- → the Doppler equation for a source of electromagnetic radiation moving relative to an observer, $\frac{\Delta\lambda}{\lambda} \approx \frac{\Delta f}{f} \approx \frac{v}{c}$.

Synoptic link

You will learn about the use of the Doppler effect in medical ultrasonography to measure speed of blood flow in Topic 27.8, Doppler imaging.



▲ **Figure 1** *The speed of a tennis ball during a serve is measured from the Doppler shift of microwaves reflected off the ball*



▲ **Figure 3** *Pilots use information from their weather radar, like this, to navigate around potentially hazardous storms*

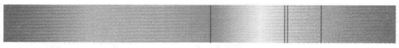
A storm on the way

Some types of weather radar use the Doppler effect to locate areas of precipitation (rain and snow). The radar transmits electromagnetic waves (usually microwaves), which are reflected off the precipitation back to a receiver. The wavelength of the reflected waves is Doppler-shifted, depending on the relative motion of the weather system and the receiver. Software is then used to plot the path of the weather system, and can even determine whether it is rain, snow, or hail. Modern weather radar, such as that found in commercial aircraft (Figure 3), is so sensitive that it can detect the motion of individual rain droplets and determine the intensity of the rain.

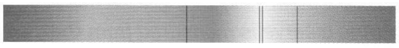
1. Explain how the differences in the reflected microwaves received by a weather radar reveal whether a rain storm is moving towards or away from the receiver.
2. Suggest how it might be possible for a weather radar to be able to distinguish between rain and hail using the intensity of the reflected microwaves.

Synoptic link

You first met electromagnetic waves in Topic 11.6, Electromagnetic waves. You learnt about the spectra of stars in Topic 19.5, Spectra. Remember that these spectra contain absorption lines that occur at specific wavelengths and are unique to the atoms of an element.



receding galaxy – red shift



stationary source – laboratory spectrum

approaching galaxy – blue shift

▲ **Figure 4** *Blue and red shifts*

Doppler shifts in starlight

Light from stars can be analysed in many ways. One technique involves looking at the absorption lines in the spectra from stars.

The Doppler effect can be used to determine the relative velocity of a distant galaxy. First, the absorption spectrum of a specific element is determined in the laboratory. The same spectrum is observed in light from a distant galaxy. Any difference in the observed wavelengths of the absorption lines must be caused by the relative motion between the galaxy and the Earth.

- If the galaxy is moving towards the Earth the absorption lines will be **blue-shifted** – they move towards the blue end of the spectrum, because the wavelength appears shorter.
- If the galaxy is moving away from the Earth ('receding') the absorption lines will be **red-shifted** – they all move towards the red end of the spectrum, because the wavelength appears stretched.

This technique is very powerful. It can even be used to determine the speed of rotation of stars and galaxies.

A mathematical treatment

How fast the wave source moves relative to the observer affects the size of the observed shift in wavelength and frequency.

For electromagnetic waves, the **Doppler equation** below is very useful.

$$\frac{\Delta\lambda}{\lambda} \approx \frac{\Delta f}{f} \approx \frac{v}{c}$$

where λ is the source wavelength, $\Delta\lambda$ is the change in wavelength recorded by the observer, f is the source frequency, Δf is the change in frequency recorded by the observer, v is the magnitude of the relative velocity between the source and observer, and c is the speed of light through a vacuum ($3.00 \times 10^8\,\mathrm{m\,s^{-1}}$). The Doppler equation can only be used for galaxies with speed far less than the speed of light.

The equation shows that the faster the source moves, the greater the observed change in wavelength and frequency. In Figure 4, the wavelength of each absorption line changes by the same percentage for a particular moving galaxy.

Worked example: Speed of a galaxy

In the laboratory an absorption line of hydrogen is observed at a wavelength of 656.4 nm. In a distant galaxy the same absorption line is observed at 658.1 nm. Calculate the speed of the galaxy and state whether it is moving towards or away from the Earth.

Step 1: Calculate the change in the wavelength

$$\Delta\lambda = 658.1 - 656.4 = 1.7\ \mathrm{nm}$$

The wavelength observed from the galaxy is longer than the wavelength in the laboratory, so the galaxy must be receding. The spectral line has been red-shifted.

Step 2: The Doppler equation $\frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$ can be rearranged to give $\frac{c\Delta\lambda}{\lambda} \approx v$.

Therefore

$$v \approx \frac{c\Delta\lambda}{\lambda} \approx \frac{3.00 \times 10^8 \times 1.7 \times 10^{-9}}{656.4 \times 10^{-9}} = 7.76\ldots \times 10^5\,\mathrm{ms^{-1}} = 780\,\mathrm{kms^{-1}}\ (2\ \text{s.f.})$$

Summary questions

1 A police siren is observed to change pitch as it passes a stationary observer. Use the Doppler effect to explain this observation. *(2 marks)*

2 Explain why the driver of a race car does not experience any Doppler shift in the sounds from the engine. *(2 marks)*

3 Light from a distant galaxy is red-shifted. Suggest how by measuring the red shift of different parts of the galaxy astronomers are able to determine the speed of rotation of the galaxy. *(4 marks)*

4 A particular absorption line is measured in a laboratory at a frequency of 5.12×10^{14} Hz. Calculate the frequency and wavelength associated with the same line in:
- **a** a galaxy moving towards the Earth at 10.6 $\mathrm{Mm\,s^{-1}}$;
- **b** a galaxy moving away from us at 25% of the speed of light. *(6 marks)*

5 Suggest why the light reflecting off a sprinter running towards a TV camera does not appear to be blue-shifted. *(2 marks)*

6 An absorption line is measured in the lab at a wavelength of 714.7 nm. In a distant galaxy the same absorption line is observed at 707.1 nm. Calculate the speed of the galaxy and state whether it is moving towards or away from the Earth. *(3 marks)*

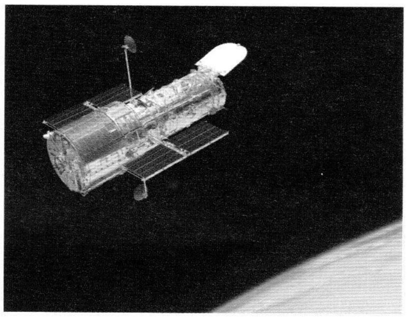
20.3 Hubble's law

Specification reference: 5.5.3

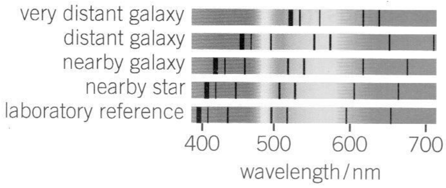
Learning outcomes

Demonstrate knowledge, understanding, and application of:

- → Hubble's law $v \approx H_0 d$ for receding galaxies
- → galactic red shift and the model of an expanding Universe
- → Hubble constant H_0 in km s^{-1} Mpc^{-1} and s^{-1}
- → the cosmological principle.



▲ **Figure 1** *The Hubble Space Telescope, named after Edwin Hubble, has allowed physicists to make huge leaps in our understanding of the Universe*



▲ **Figure 2** *The relative red shifts of near and distant objects revealed to Hubble that objects further away were moving faster relative to the Earth*

The work of Edwin Powell Hubble

Edwin Powell Hubble, an American astronomer, is generally thought of as one of the most important cosmologists of the 20th century. He showed there were many more galaxies in our Universe than people thought, and his work investigating the motion of distant galaxies led to the concept of the expanding Universe and the **Big Bang**.

Hubble's law

During the late 1920s Hubble analysed the Doppler shift in the absorption spectra of many distant galaxies. Using the data available then he made two key observations:

1. He confirmed earlier observations that the light from the vast majority of galaxies was red-shifted, that is, they had a relative velocity away from the Earth.
2. He found that in general the further away the galaxy was the greater the observed red shift and so the faster the galaxy was moving.

Using these observations he formulated what is now called **Hubble's law**: the recessional speed v of a galaxy is almost directly proportional to its distance d from the Earth, that is, $v \propto d$.

On a graph of recessional speed against distance for all galaxies, the plotted data should produce a straight line through the origin. As you can see from Figure 3, the spread in the original data points suggests that Hubble's law is valid, but there is a large uncertainty in the value for the gradient of the best-fit line.

The Hubble constant

The gradient of the graphs in Figure 3 is a constant of proportionality now called the **Hubble constant** H_0. From Hubble's law it follows that

$$v \approx H_0 d$$

The SI unit for the Hubble constant can be determined by dividing $m\,s^{-1}$ by m (the SI units). This gives the unit s^{-1}. However, as you see in Figure 3, cosmologists prefer to express speed in $km\,s^{-1}$ and distance in Mpc, giving an alternative unit of $km\,s^{-1}\,Mpc^{-1}$, which must be equivalent to s^{-1}. In 2013, the most reliable data gave $67.80 \pm 0.77\,km\,s^{-1}\,Mpc^{-1}$ for the Hubble constant, or about $2.2 \times 10^{-18}\,s^{-1}$.

Worked example: Hubble constant units

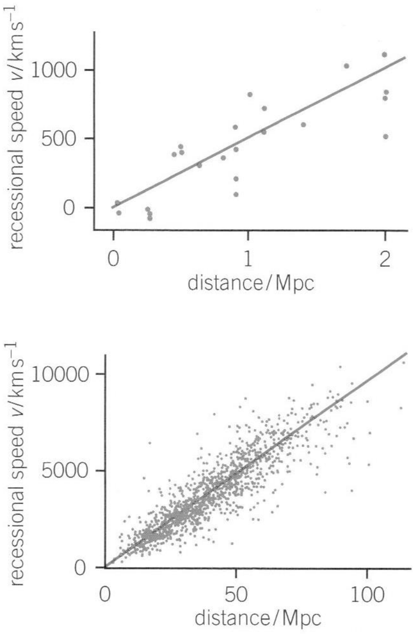
Convert $1\,km\,s^{-1}\,Mpc^{-1}$ into s^{-1}.

Step 1: Convert the speed into $m\,s^{-1}$ and then divide it by the distance of 1 Mpc in metres.

$$1\,km\,s^{-1}\,Mpc^{-1} = \frac{1.0 \times 10^{3}\,m\,s^{-1}}{10^{6} \times 3.1 \times 10^{16}\,m} = 3.2 \times 10^{-20}\,s^{-1}\ (2\text{ s.f.})$$

The expanding Universe

Hubble's law is the key evidence for the Big Bang theory (more on this in Topic 20.4) and the model of the **expanding Universe** following the Big Bang. This model is the most widely accepted explanation of the observation that the light from nearly all the galaxies we can see is red-shifted. It states that the fabric of space, and time, is expanding in all directions. It is not simply the galaxies moving away from each other, but the actual space itself expanding. As a result, any point, in any part of the Universe, is moving away from every other point in the Universe, and the further the points are apart the faster their relative motion away from each other. From our position on Earth this explains why light from more distant galaxies is more red-shifted, indicating that they are moving faster than those nearer to us.



▲ **Figure 3** *Hubble's original 1929 data for the recessional speed v of galaxies against their distance d from the Earth (above) and (below) a plot with more recent data*

The cosmological principle

The **cosmological principle** is the assumption that, when viewed on a large enough scale, the Universe is **homogeneous** and **isotropic**, and the laws of physics are universal.

- The laws of physics can be applied across the Universe. This is a bold assumption. It means that the theories and models tested here on the Earth can be applied to everything within the Universe over all time and space.
- 'Homogeneous' means that matter is distributed uniformly across the Universe. For a very large volume, the density of the Universe is uniform. This means that the same type of structures (galaxies) are seen everywhere.
- 'Isotropic' means that the Universe looks the same in all directions to every observer. It follows that there is no centre or edge to the Universe.

In essence, the cosmological principle means that the Universe would look the same wherever you are.

Study tip

Remember, space itself is stretching, so think of galaxies being carried by the expanding Universe rather than simply moving through space.

Summary questions

1 Sketch a graph of the recessional speed of a galaxy against the distance of the galaxy from Earth, and use the graph to illustrate Hubble's law. *(2 marks)*

2 The value of the Hubble constant is about $2.2 \times 10^{-18}\,\mathrm{s}^{-1}$. Calculate the distance from Earth of a galaxy with the following recessional speed:
a $160\,000\,\mathrm{m\,s^{-1}}$; **b** $7.8 \times 10^{6}\,\mathrm{m\,s^{-1}}$. *(4 marks)*

3 Use the lower graph in Figure 3 to confirm that the value for the Hubble constant is approximately $70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. *(3 marks)*

4 Calculate the recessional speed of a galaxy at the following distances from the Earth:
a $1.50 \times 10^{23}\,\mathrm{m}$; **b** 25.0 Mpc; **c** 40 million ly. *(6 marks)*

5 In the laboratory an absorption line is observed at a wavelength of 638.9 nm. In a distant galaxy the same absorption line corresponds to a wavelength of 675.1 nm. Calculate the distance from the galaxy to the Earth in ly. *(4 marks)*

20.4 The Big Bang theory

Specification reference: 5.5.3

Learning outcomes

Demonstrate knowledge, understanding, and application of:

→ the Big Bang theory

→ experimental evidence for the Big Bang theory from microwave background radiation

→ the idea that the Big Bang gave rise to the expansion of space-time

→ estimation of the age of the Universe

→ $t \approx H_0^{-1}$.

It all started with the Big Bang

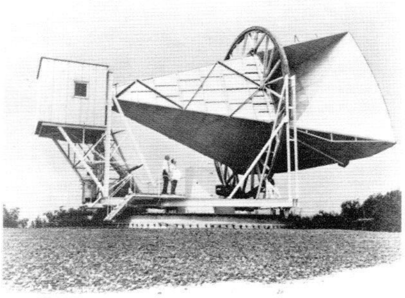
The Big Bang theory is one of the most important ideas in all of science. First proposed by the Belgian physicist and priest Georges Lemaître in 1931, it attempts to describe the origin and development of the early Universe. It suggests that at some moment in the past all the matter in the Universe was once contained in a single point, a singularity. This point is considered to be the beginning of the Universe – the beginning of space and time itself. This region was much hotter and denser than it is today. It then expanded outwards to become the dynamic Universe we see around us today.

In support of the Big Bang

In order to be accepted by the scientific community, any scientific theory needs to be supported by evidence. There are two key pieces of evidence for the Big Bang theory – Hubble's law and the **microwave background radiation**.

You have seen how Hubble's law shows that the Universe is expanding – the galaxies are receding from each other because the space itself is expanding in all dimensions. It follows that, if we could run time backwards, the Universe would be much smaller, denser, and hotter, and would eventually reach a single point. It is this single point that, according to the Big Bang theory, expanded out to form our present-day Universe.

However, the expanding Universe could be explained by other competing theories on the origin of the Universe. So by itself, it does not produce enough to establish the Big Bang. More evidence is needed.



▲ **Figure 1** *This horn antenna at Bell Laboratories in the USA unexpectedly revealed the microwave background radiation from the Big Bang*

Microwave background radiation

The second piece of evidence is the existence of microwave background radiation. In 1964 two American physicists, Robert Wilson and Arno Penzias, were attempting to detect signals from objects in space. They detected a uniform microwave signal they could not account for — not even trapping the pigeons whose droppings coated the antenna helped. Eventually they realised that they had accidentally discovered the microwave background radiation that could only be explained by the Big Bang and the expansion of space.

The Big Bang theory had earlier predicted the existence of this background microwave radiation. Its existence can be explained in two ways.

- When the Universe was young and extremely hot, space was saturated with high-energy gamma photons. The expansion of the Universe means that space itself was stretched over time. This expansion stretched the wavelength of these high-energy photons, so we now observe this primordial electromagnetic radiation as microwaves.

Study tip

Be careful not to fall into the "just a theory" mentality. A theory must have evidence to support it — Fred Hoyle's idea of the Steady State Universe, in which new matter is created as the Universe expands, had to be rejected by scientists as it failed to explain the microwave background.

- The Universe was extremely dense and hot when it was young. Expansion of space over billions of years has reduced that temperature to around 2.7 K. The Universe may be treated as a black-body radiator – at this temperature the peak wavelength would correspond to about 1 mm, in the microwave region of the spectrum.

None of the competing theories had predicted or could explain the origin of the microwave background radiation, so the Big Bang theory became the most widely accepted theory on the origin of the Universe. Penzias and Wilson received the 1978 Nobel Prize in Physics for their discovery.

The age of the Universe

We can estimate the age of the Universe by assuming that it has expanded uniformly over time since the Big Bang. Results from recent observations have shown that this is not the case – in fact, the expansion of the Universe is accelerating, so this assumption is poor, but it will give a crude indication of the age of the Universe.

Hubble's law shows that galaxies are receding from each other. This means that in the past they must have been closer together. If a galaxy at a distance d is moving away at a constant speed v, then a time $\frac{d}{v}$ must have elapsed since it was next to our galaxy. This time is therefore roughly the age of the Universe. The ratio $\frac{d}{v}$ is equal to $\frac{1}{H_0}$, so

$$\text{age of Universe } t \approx \frac{1}{H_0}$$

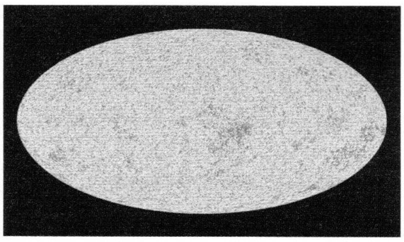
As discussed in Topic 20.3, an accurate determination of the Hubble constant is a considerable challenge for cosmologists. However, using $H_0 = 2.2 \times 10^{-18}\,\text{s}^{-1}$ gives the age as $4.5 \times 10^{17}\,\text{s}$ (~14 billion years).

The ESA Planck mission

In May 2009 the European Space Agency launched the Planck space observatory. Its mission was to measure precisely the tiny variations in the microwave background radiation. These fluctuations are another prediction of the Big Bang theory. It is these ripples which give rise to the present structure of galaxies.

The data collected by the Planck mission suggests that the value for the Hubble constant is $67.80 \pm 0.77\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$.

1. Using the average value of the Hubble constant determined by the Planck mission show that the Universe is approximately 14 billion years old.
2. Figure 2 shows temperature variations of about $\pm 10^{-4}$ K. Assuming Wien's law can be applied to the entire Universe, determine the percentage variation in the peak wavelength of the microwaves.



▲ **Figure 2** *This image produced from Planck data shows the minuscule temperature variations from when our Universe was only 380 000 years old, with 'warmer' areas in red – most of the observations fit the predictions of the model well, but the uneven cold areas (dark blue) are unexpected*

Synoptic link

You met Wien's law in Topic 19.7, Stellar luminosity.

Summary questions

1. State two pieces of evidence in support of the Big Bang theory. *(2 marks)*
2. Explain the importance of the discovery of microwave background radiation. *(2 marks)*
3. If the Universe is between 11 billion and 15 billion years old, calculate the maximum and minimum possible values for the Hubble constant. *(4 marks)*
4. Use the information given in Topic 19.7, Stellar luminosity, on Wien's law to estimate:
   a. the dominant wavelength of the electromagnetic radiation in the Universe when its temperature was 10^{11} K *(2 marks)*
   b. the temperature of the Universe when it was full of visible light. *(2 marks)*

20.5 Evolution of the Universe

Specification reference: 5.5.3

Learning outcomes

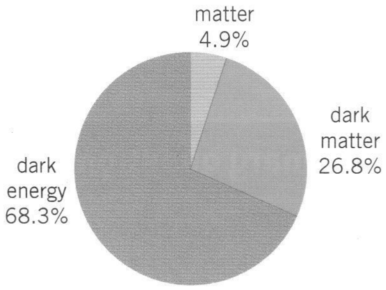
Demonstrate knowledge, understanding, and application of:

- ➔ the evolution of the Universe after the Big Bang to the present
- ➔ current ideas about the composition of the Universe in terms of dark energy, dark matter, and a small percentage of ordinary matter.

We only understand 5% of our Universe!

In the late 1990s the world of physics was shaken by the discovery that the Universe appears to be expanding at an increasing rate. This called our understanding into question and led to the development of completely new ways to think about our Universe.

How this acceleration happens is not fully understood. The most widely accepted theory includes the concept of **dark energy**. It is suggested that this hypothetical form of energy fills all of space and tends to accelerate the expansion of the Universe. This, coupled with the discovery of **dark matter** a few years earlier, means that at our best estimate we currently only understand 5% of the stuff that makes up our Universe.



▲ **Figure 1** *Current theories indicate we do not understand 95% of what makes up our Universe*

The evolution of the Universe

You have seen that the Universe is thought to be 13.7 billion years old. The evolution of the Universe is a story of expansion of space, cooling, and formation of matter, summarised in Table 1.

Our current ideas about the Universe

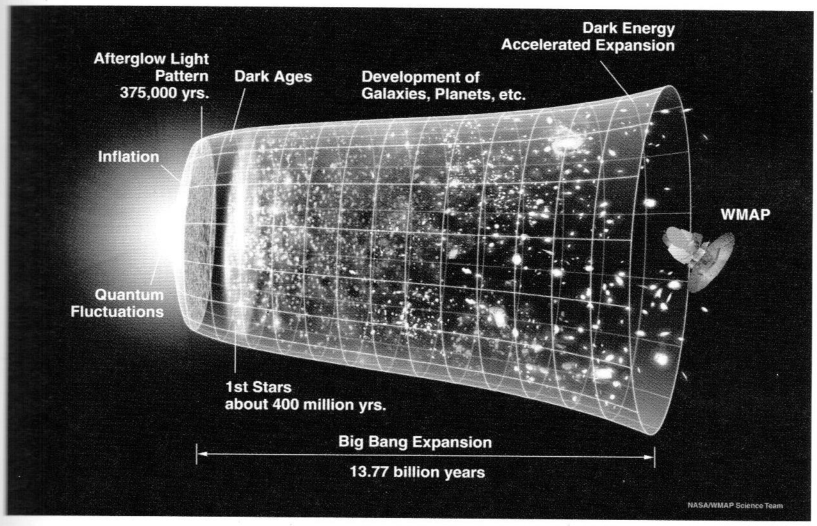
In the past few decades our understanding of the Universe has undergone dramatic changes. The two most significant are the discovery of dark energy and the discovery of dark energy.

▼ **Table 1** *The history of the Universe*

	Time after the Big Bang	Nature of the Universe
↓ decreasing temperature	The Big Bang	Time and space are created. The Universe is a singularity – it is infinitely dense and hot.
	10^{-35} s	The Universe expands rapidly, including a phase of incredible acceleration known as **inflation**. There is no matter in the Universe – instead it is full of electromagnetic radiation in the form of high-energy gamma photons. The temperature is about 10^{28} K.
	10^{-6} s	The first fundamental particles (quarks, leptons, etc.) gain mass through a mechanism that is not fully understood but involves the Higgs boson (discovered in 2013).
	10^{-3} s	The quarks combine to form the first hadrons, such as protons and neutrons. Most of the mass in the Universe was created within the first second through the process of pair production (high-energy photons transforming into particle–antiparticle pairs).
	1 s	The creation of matter stops after about 1 s, once the temperature has dropped to about 10^{9} K.
	100 s	Protons and neutrons fuse together to form deuterium and helium nuclei, along with a small quantity of lithium and beryllium. The expansion of the Universe is so rapid that no heavier elements are created. During this stage, about 25% of the matter in the Universe is helium nuclei (known as primordial helium).

▼ Table 1 *(continued)*

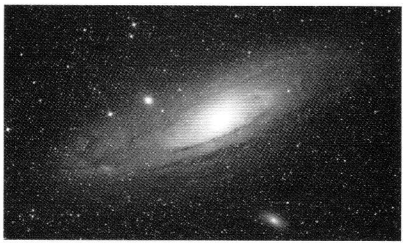
	Time after the Big Bang	Nature of the Universe
← decreasing temperature	380 000 years	The Universe cools enough for the first atoms to form. The nuclei capture electrons. The electromagnetic radiation from this stage of the Universe is what can be detected as microwave background radiation.
	30 million years	The first stars appear. Through nuclear fusion in these stars the first heavy elements (beyond lithium) begin to form.
	200 million years	Our galaxy, the Milky Way, forms, as gravitational forces pull clouds of hydrogen and existing stars together.
	9 billion years	The Solar System forms from the nebula left by the supernova of a larger star. After the Sun forms the remaining material forms the Earth and other planets (around 1 billion years later). It is thought that around 1 billion years after the formation of the Earth (11 billion years after the Big Bang) primitive life on Earth begins.
	13.7 billion years (now)	Around 200 000 years ago the first modern humans evolve, and eventually study physics. The temperature of the Universe is 2.7 K.



▲ Figure 2 *Graphical model of the evolution of the Universe, from the earliest moment we can currently probe (to the left of the Figure). After several billion years of decelerating expansion as matter exerted gravitational force on itself, the expansion has more recently sped up again due to the dominating repulsive effects of dark energy.*

The accelerating Universe

The 2011 Nobel Prize in Physics was awarded for the discovery in 1999 that the expansion of the Universe is accelerating. Physicists Saul Perlmutter, Brian Schmidt, and Adam Riess were investigating the light from distant supernovae. They observed a particular type of supernova, a type Ia supernova, which produces a characteristic kind of light. On studying this light it was found to be less intense than predicted. The only possible conclusion was that the expansion of the Universe was accelerating. This acceleration needed a source of energy, one which had never been detected. They used the term 'dark energy' to describe a hypothetical form of energy that permeates all space. Dark energy is currently the best accepted hypothesis to explain the accelerating rate of expansion. It is estimated that dark energy, which remains as yet undetected, or even understood, makes up around 68% of our Universe.

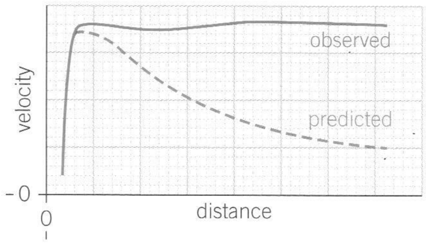


▲ **Figure 3** *The Doppler effect is used to determine the speed of rotation of distant galaxies like the Andromeda galaxy*

Dark matter

In the late 1970s, astronomers studying the Doppler shift in light from galaxies found that the velocity of the stars in the galaxies did not behave as predicted. It was expected that their velocity would decrease as the distance from the centre of the galaxy increases. This is the effect observed in other gravitational systems where most of the mass is in the centre, including our Solar System and the moons of Jupiter.

Figure 4 shows the differences between the predicted and observed velocities of the stars in a galaxy as you move out from the centre.



▲ **Figure 4** *Observations of the velocities of stars in galaxies do not match predictions, leading to the idea of dark matter*

The observations can be explained if the mass of the galaxy is not concentrated in the centre. However, most of the matter we can see is in the centre. The current thinking is that there must be another type of matter which we cannot see. This dark matter is spread throughout the galaxy, explaining the observations. Calculations have shown that the Universe must be made of 27% of this kind of matter.

Not much is known about dark matter. We do know that it cannot be seen directly with telescopes and that it neither emits nor absorbs light. There are exotic speculations as to what it could be: black holes, gravitinos, weakly interacting massive particles (wimps), axions, Q-balls,... the list goes on. The truth is that dark energy and dark matter remain a mystery waiting to be solved by the next generation of physicists.

Summary questions

1 Describe the observations that led to the development of the idea of dark energy. *(2 marks)*

2 Explain why it was not possible for atoms to form until 380 000 years after the Big Bang. *(2 marks)*

3 Describe how the presence of dark matter accounts for the difference between the observation and prediction shown in Figure 4. *(3 marks)*

4 Sketch a timeline with a logarithmic scale to show the evolution of the Universe from the Big Bang until the present. *(4 marks)*

5 The Universe originated from a Big Bang. Table 2 below shows how the temperature T of the Universe has changed with time t since the Big Bang.

▼ Table 2

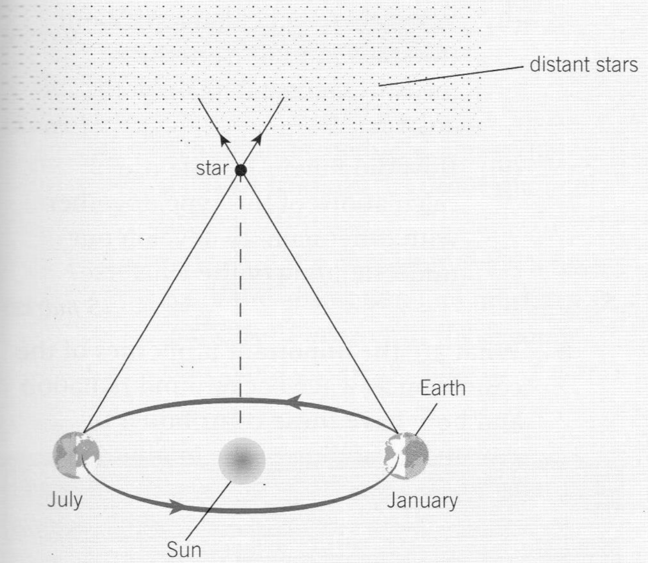
t / s	10^{-35}	10^{-12}	10^{-6}	10	4×10^{17}
T / K	10^{28}	10^{15}	10^{12}	10^{9}	2.7

By plotting a graph of $\lg t$ against $\lg T$, show that the temperature T and the time t are related by the equation $T^n t$ = constant, where n is an integer. Use your graph to determine the value for n. *(4 marks)*

Practice questions

1 a Calculate the distance of 1 light-year (ly) in metres. *(1 mark)*

b Figure 1 shows an incomplete diagram drawn by a student to show what is meant by a distance of 1 parsec (pc).



▲ **Figure 1**

Complete a copy of Figure 1 by showing the distances of 1 pc and 1 AU, and the parallax angle of 1 second of arc (1″). *(1 mark)*

c A recent supernova, SN2011fe, in the Pinwheel galaxy, M101, released 10^{44} J of energy. The supernova is 2.1×10^7 ly away.

(i) Calculate the distance of this supernova in pc.

$1\,\text{pc} = 3.1 \times 10^{16}\,\text{m}$ *(2 marks)*

(ii) Our Sun radiates energy at a rate of 4×10^{26} W. Estimate the time in years that it would take the Sun to release the same energy as the supernova SN2011fe. *(2 marks)*

d One of the possible remnants of a supernova event is a black hole. State **two** properties of a black hole. *(2 marks)*

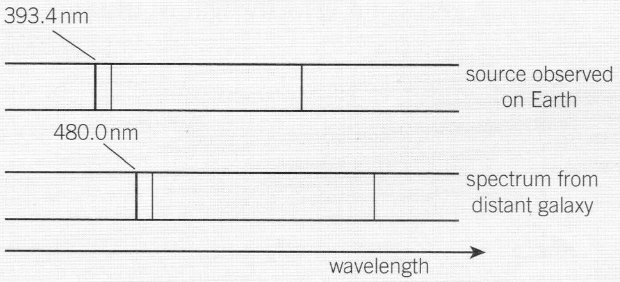
Jun 2013 G485

2 a In the Universe there are about 10^{11} galaxies, each with about 10^{11} stars with each star having a mass of about 10^{30} kg. Estimate the attractive gravitational force between two galaxies separated by a distance of 4×10^{22} m. *(3 marks)*

b Explain why the galaxies do not collapse on each other. *(1 mark)*

c Describe qualitatively the evolution of the Universe immediately after the Big Bang to the present day. You are not expected to state the times for the various stages of the evolution. *(6 marks)*

d Figure 2 shows some absorption spectral lines of the spectrum of calcium as observed from a source on the Earth and from a distant galaxy.



▲ **Figure 2**

(i) Describe an absorption spectrum. *(2 marks)*

(ii) Use Figure 1 to calculate the distance of the galaxy in Mpc. The Hubble constant has a value of $50\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$. *(3 marks)*

Jun 2012 G485

3 a Explain what is meant by the *Doppler effect.* *(2 marks)*

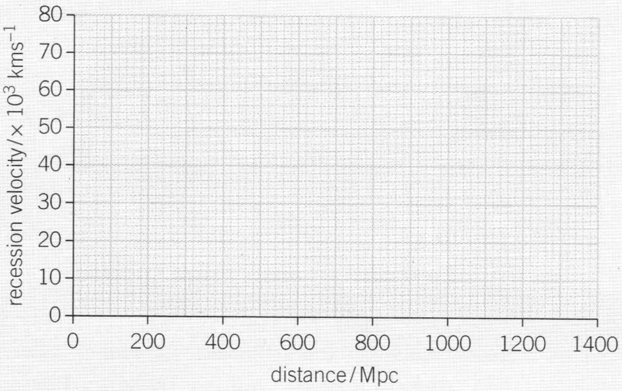
b A line in the spectrum of calcium has a wavelength of 397.0 nm when measured from a stationary laboratory source. The same spectral line is observed in five galaxies, resulting in the data shown in Table 1.

▼ Table 1

galaxy	distance / Mpc	wavelength / nm	velocity of recession / $\times 10^3$ km s^{-1}
A	50	400.3	2.5
B	300	416.9	15.0
C	620	438.0	31.0
D	980	461.8	49.0
E	1300	483.0	65.0

(i) State the equation for the change in wavelength produced by the Doppler effect and use it to explain why the light from galaxy E undergoes a much greater change in wavelength than the light received from galaxy A. *(2 marks)*

(ii) Plot a graph on a copy of Figure 3 of recession velocity against distance. *(2 marks)*



▲ Figure 3

(iii) Use the graph to find a value for the Hubble constant, giving a unit with your answer. *(3 marks)*

c Explain why Hubble's constant may not be a constant at all. *(2 marks)*

d The graph in Figure 3 has been used to support the Big Bang model of the Universe. Describe and explain one other piece of evidence which supports this model. *(3 marks)*

Jan 2010 2825/01

4 a A line in the hydrogen absorption spectrum has a wavelength of 656.3 nm when measured in the laboratory. Observation of a star shows the same absorption line to have a wavelength of 651.0 nm.

(i) Calculate the velocity of the star relative to Earth. *(3 marks)*

(ii) What else can be deduced about the star's motion from these measurements? Explain your answer. *(1 mark)*

(iii) How did Edwin Hubble use calculations of this type, together with other data, to develop our understanding of the Universe? *(5 marks)*

b What are the important properties of the cosmic microwave background radiation and how have these contributed to our understanding of the origin of the Universe? *(3 marks)*

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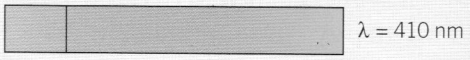
5 a What is meant by the *Doppler Effect*? *(2 marks)*

b Figure 4 shows part of a *continuous spectrum* obtained from a light source in a laboratory. The spectrum is crossed by a single *absorption line* of wavelength 410 nm.

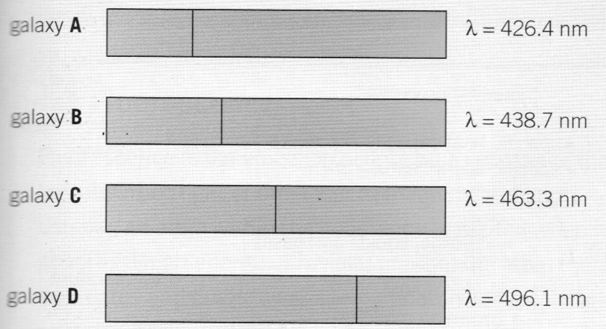


▲ Figure 4

(i) State what is meant by a *continuous* spectrum. *(1 mark)*

(ii) Explain how an *absorption line* occurs. *(2 marks)*

Figure 5 shows another four continuous spectra received from four different galaxies. The spectra are crossed by the same dark line as in Figure 4, but each one has become red shifted. The resulting wavelength is given beside the spectrum.



▲ Figure 5

(iii) What can be deduced about the galaxies from the fact that the lines are red shifted? *(1 mark)*

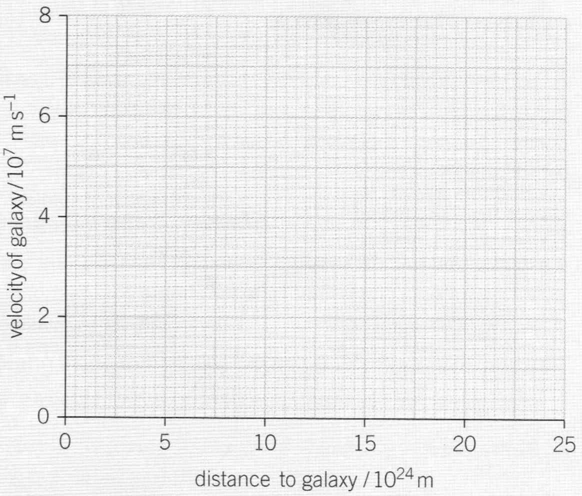
(iv) Calculate the change in wavelength $\Delta\lambda$ of the absorption line in galaxy **D**. Write your answer in the second column of a copy of Table 2. *(1 mark)*

▼ Table 2

galaxy	change in wavelength $\Delta\lambda$ / nm	velocity of galaxy / 10^7 m s^{-1}	Distance to galaxy / 10^{24} m
A	16.4	1.2	4.65
B	28.7	2.2	8.50
C	53.3	3.9	15.1
D			24.4

(v) Use the value of $\Delta\lambda$ to calculate the velocity of galaxy **D** relative to the observer. Write your answer in the third column of your copy of Table 2. *(2 marks)*

c Plot a graph of galaxy velocity against distance on a copy of Figure 6. Draw the best straight line through the points. *(2 marks)*



▲ Figure 6

d Use your graph to estimate the age of the Universe. Give a unit for your answer. *(3 marks)*

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6 a Explain how the surface of a red giant can be cooler than the Sun but it can have a much greater luminosity. *(2 marks)*

b Antares is a bright star in the night sky. It has a parallax of 5.9 seconds of arc, mass of $12M_\odot$ and radius $880R_\odot$ ($M_\odot$ = mass of the Sun and $R_\odot$ = radius of the Sun). Calculate

(i) the distance in metres of Antares from the Earth *(3 marks)*

(ii) the surface gravitational field strength on Antares in terms of the Sun's surface gravitational field strength $g_\odot$. *(2 marks)*