PEARSON

Science

STUDENT BOOK | WESTERN AUSTRALIA

10

WESTERN AUSTRALIAN • CURRICULUM •

TOPIC 7

Big bang theory and the evolution of the universe

The origin and nature of the universe have long been fascinating to humankind. From naked-eye observations to supercomputer-powered analysis of data from highly sensitive telescopes, astronomy has spanned millennia and continues to enthral and challenge us.

There are many feats of observation, deduction and mathematics that have led to the current understanding of the universe. You may be familiar with names such as Galileo and Hubble. You will get to know the work of other astronomers in your upcoming exploration of the universe.

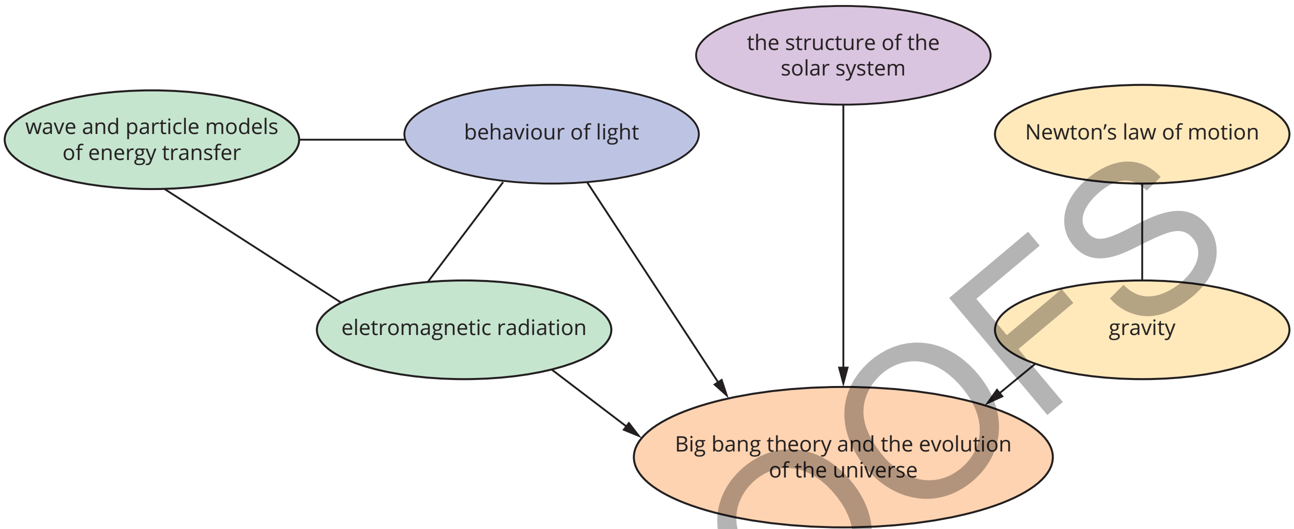
In this topic you will learn about different types of astronomical observations; how astronomers measure the distance to cosmic objects and understand the properties of these objects; what predictions can be made about objects in the universe and how technology has played a role in past discoveries and the exciting developments that lie ahead.

Learning intentions

- ☐ To understand how humans have used observations of objects and events in space to improve their knowledge of components of the universe and to make predictions **xx**
- ☐ To understand how distances in space are measured **xx**
- ☐ To understand how the big bang theory models the origin of the universe **xx**
- ☐ To understand the early history of the universe **xx**
- ☐ To understand what information can be learned about a star from its light spectrum **xx**
- ☐ To be able to use a spectroscope to analyse light from a range of sources **xx**
- ☐ To be able to show how redshift relates to the movement of objects in space **xx**
- ☐ To understand Hubble's observations and what they suggest about the universe **xx**
- ☐ To understand the life cycles of stars **xx**
- ☐ To be able to construct appropriate representations to process data and information **xx**
- ☐ To understand the significance of recent cosmological observations and associated theories **xx**

7 Big bang theory and the evolution of the universe

The key concepts that you will use in this topic:



The following key knowledge questions will help to support your learning in the topic and can be attempted before the first lesson.

Light

1 Describe how light transfers energy.

2 Recall the seven main sections of the electromagnetic spectrum. Describe the similarities and difference between the light in these sections.

The structure of the solar system

3 What force is responsible for keeping the planets of the solar system orbiting around the Sun?

4 How do planets differ to other celestial objects, such as asteroids?

Gravity

5 Using one of Newton's laws, describe the relationship between mass and the force due to gravity.

6 A famous demonstration of the behaviour of falling objects was the hammer and feather experiment performed by Commander Dave Scott on the Apollo 15 mission. Research this demonstration and explain how it impacted understanding of gravity.

7.1 Observing space

Lesson overview

For millennia, humans have observed the night sky in wonder. From the rarity of comets and asteroids to the predictability of the Sun and the Moon, people have observed objects in space and sought to understand their structure and movement (Figure 7.1.1).

FIGURE 7.1.1 Humans have observed the night sky for millennia.

In this lesson you will learn about the observations that have led to different models of the structure of the universe and how observations have been used to make predictions about future astronomical events.

Learning intention

To understand how humans have used observations of objects and events in space to improve their knowledge of components of the universe and to make predictions

Success criteria

SC 1: I can explain how historical models of the universe were supported by the evidence available at the time, such as the apparent motion of the Sun, Moon and stars.

SC 2: I can explain an example of how a key observation was used to develop a hypothesis about a component or structure of the universe.

SC 3: I can explain an example of where an observation of an event, or series of events, in space has been used to make a prediction as to future events.

SC 1 I can explain how historical models of the universe were supported by the evidence available at the time, such as the apparent motion of the Sun, Moon and stars

Scientific models

It is a very important feature of science that models are used to explain the world and to make predictions. A good scientific model allows questions about the world to be turned into questions about the model, and for the model to give accurate answers. An example is, 'Where will the moon be tonight, given where I saw it last night?'. The history of **astronomy** has examples of different models which were left behind as better models came along. Newer models are better at giving clear and simple explanations and making correct predictions. Following is an outline of four important models, with the key supporting evidence for each one.

Key historical models of the universe

Aristotle

Aristotle was an influential Greek philosopher and scientist. His **geocentric model** of the universe had celestial bodies orbiting smoothly in perfect circles around Earth attached to spheres of increasing size (Figure 7.1.2). The order was the Moon, Mercury, Venus, the Sun, Mars, Jupiter and Saturn and three outer spheres; the Firmament (including the **stars**), the Crystalline Heaven, and the Primum Mobile.

He believed that Earth was made of four elements: earth, fire, air and water. In Aristotle's universe, the heavens appeared perfect and unchanging, and he suggested that there was a prime mover that caused the Sun and planets to rotate on their spheres, but the *prime mover* did not move itself.

Aristotle's model was accepted for nearly 2000 years, but as an increasing number of observations were hard to explain with his model, a new model proposed by Copernicus was considered.

KEY TERMS

astronomy the study of space
geocentric model model of the universe with Earth at its centre
star a celestial body consisting of gas and undergoing nuclear reactions in the interior

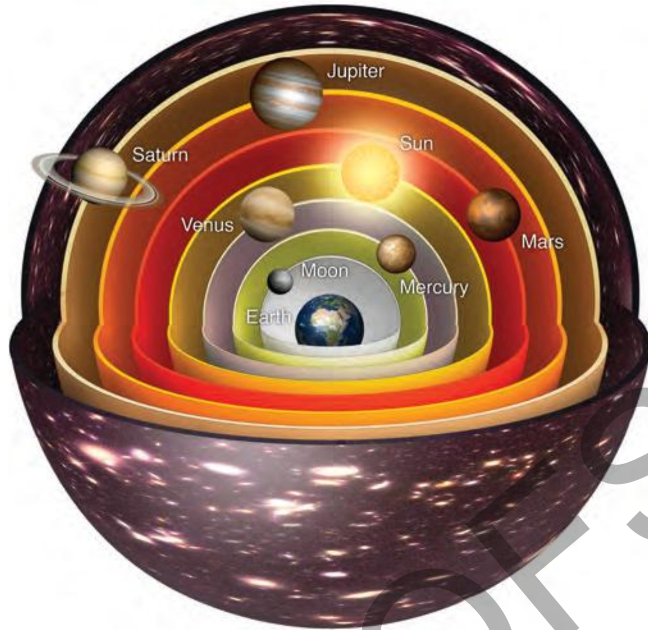


FIGURE 7.1.2 A representation of the geocentric model of the Universe, proposed by Aristotle

Copernicus

Nicolaus Copernicus was a Polish **astronomer** who developed a revolutionary idea: that the Sun was at the centre of the **solar system** (a **heliocentric model**). One important piece of evidence that led to this change was called retrograde motion, when some planets (Mars and Jupiter in particular) seemed to move backwards in their path across the sky.

Copernicus could explain this retrograde motion by proposing that both Earth and the planets move around the Sun (Figure 7.1.3).

KEY TERMS

astronomer scientist who studies the stars, planets and other celestial objects

heliocentric model a model of the solar system with the Sun at the centre

solar system the Sun and all the planets, satellites, asteroids, comets and other bodies revolving around it

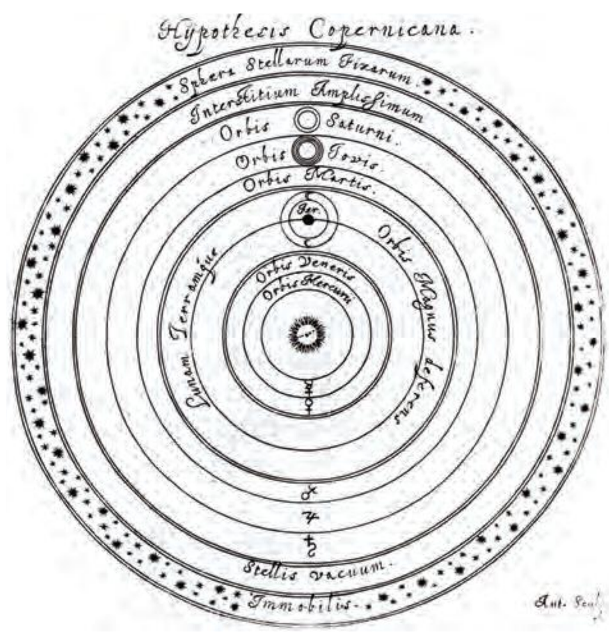


FIGURE 7.1.3 Copernican (heliocentric) system of the universe, showing the orbits of the planets surrounded by the firmament of the fixed stars. From *Selenographia* by Johannes Hevelius. (Gdansk, 1647). Artist: Johannes Hevelius.

Kepler

Johannes Kepler was born in 1571, less than 30 years after Copernicus died. He made important mathematical improvements to Copernicus's heliocentric model of the universe. One key difference was that Kepler proposed the orbits of the planets were **elliptical**, not circular (Figure 7.1.4). Kepler created three laws of planetary motion that gave more accurate predictions about the movements of the planets. However, Kepler's model did not explain why planets stayed in these elliptical orbits.

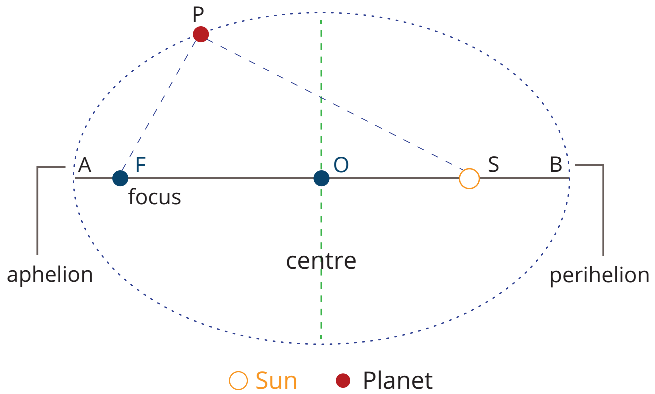


FIGURE 7.1.4 Kepler's first law of planetary motion says that all planets (shown as P) move around the Sun (shown as S) in an elliptical orbit, where the Sun is at one foci of the ellipse.

Newton

The famous English physicist and mathematician, Sir Isaac Newton, was born in 1642, 12 years after Kepler's death. He provided a missing piece of Kepler's model and also contradicted Aristotle's idea that the 'heavens' are governed by different scientific laws to Earth.

Newton proposed the law of universal gravitation, which says that every object attracts every other object with a force that depends on the masses of the objects and how far apart they are from each other (Figure 7.1.5).

This law, and Newton's other laws of motion, allowed precise predictions of the motion and positions of planets, comets and the Moon.

SC 1 CHECK YOUR UNDERSTANDING

Explain how the apparent motion of the Sun, Moon and stars supported the geocentric model.

SC 2 I can explain an example of how a key observation was used to develop a hypothesis about a component or structure of the universe

Galileo's observations

The Italian astronomer Galileo, who died the same year that Newton was born (1642), made a series of very significant observations with his telescope. These helped to support the heliocentric model of the universe that was developed by Copernicus.

DISCOVER MORE

The law of universal gravitation stated mathematically is:

$$F = G \times \left(\frac{m_1 \times m_2}{r^2}\right)$$

where F is the gravitational force, G is a fixed number called the universal gravitational constant, m_1 and m_2 are the masses of the two objects and r is the distance between the two objects.

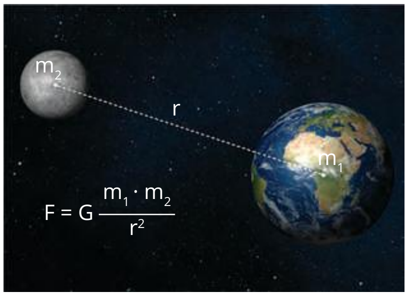


FIGURE 7.1.5 The equation for Newton's law of gravitation applied to the Earth-Moon system

KEY TERM

light energy that allows the human eye to see objects

Galileo observed that Venus goes through phases that are similar to the phases of the Moon. In particular:

- Crescent phase – Galileo observed that Venus has a crescent phase (there is **light** from the Sun visible on only part of it), just like the Moon does at different times in its orbit.
- Full phase – at other times, Galileo noticed that Venus was a fully illuminated circle.

These observations led Galileo to believe that Venus orbits the Sun – its full phase is seen when Venus is on the opposite side of the Sun to Earth, and the crescent phase at other times in its orbit (Figure 7.1.6).

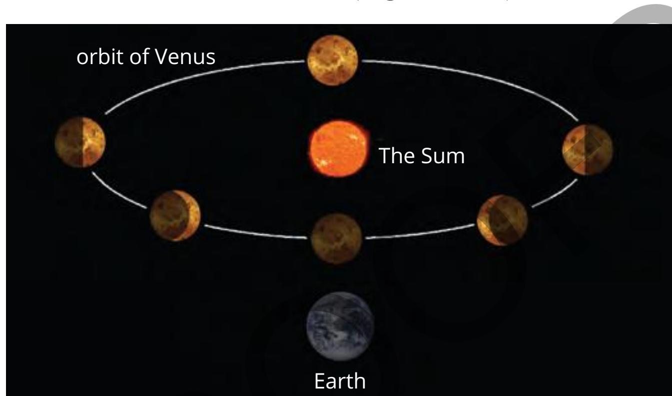


FIGURE 7.1.6 This diagram shows how a heliocentric structure of the solar system explains the phases of Venus as seen from Earth.

Other observations of Galileo's that helped to support the heliocentric model included:

- moons orbiting Jupiter
- moving spots on the Sun
- different apparent sizes of Venus.

These observations gave further evidence that there are objects orbiting things other than Earth, and that everything in the heavens was not perfect, as Aristotle had suggested.

SC 2 CHECK YOUR UNDERSTANDING

Explain how you would use the observation of Jupiter's moons to support the heliocentric model.

SC 3 I can explain an example of where an observation of an event, or series of events, in space has been used to make a prediction as to future events

Using space observations and events to predict future events

Observations of events in space have been very important in expanding human knowledge of the universe and enabling accurate predictions about future astronomical events.

A range of astronomical phenomena such as comets, eclipses (Figure 7.1.7) and asteroids have been observed and used to make predictions, including by Australia's First Nations peoples, who have used these predictions to inform daily and seasonal activities for thousands of years.

FIGURE 7.1.7 A series of images taken during a total solar eclipse

Comets

A comet is a ball of ice, dust and rock that orbits the Sun in a highly elliptical orbit. Astronomers have long been fascinated with comets—they can be an extraordinary sight in the sky, and they take different paths through the solar system.

One of the most famous comets is Halley's Comet (Figure 7.1.8), which returns to Earth's view around every 76 years. It is named after the astronomer Edmond Halley, who accurately predicted its return based on past observations. In 1705, Halley examined the orbits of comets and noticed that several comets observed in 1531, 1607 and 1682 shared similar orbital characteristics. He hypothesised that these observations were sightings of the same comet, which he predicted would return in the future. Halley's prediction was proven correct when the comet made its reappearance in 1758, 16 years after Halley's death. It was last seen from Earth in 1986 and is expected to return in 2061.

FIGURE 7.1.8 Halley's Comet has been observed and documented by astronomers for centuries, with records dating back to ancient civilisations.

Comet Shoemaker-Levy 9 gained global attention in 1994 due to its impact with Jupiter (Figure 7.1.9). Discovered by Carolyn and Eugene M. Shoemaker and David Levy in 1993, Comet Shoemaker-Levy 9 captured the interest of astronomers and the public alike as it broke apart into multiple fragments that then collided with Jupiter in July 1994.

FIGURE 7.1.9 Comet Shoemaker-Levy impacting Jupiter in July 1994. Image obtained by the MPG/ESO 2.2-metre telescope and the IRAC instrument.

KEY TERMS

lunar eclipse when Earth blocks sunlight from reaching the Moon

solar eclipse when the Moon blocks sunlight from reaching Earth

Eclipses

Observations of the Moon and its alignment with Earth have enabled astronomers to make very accurate and long-range predictions about the timing of **lunar** and **solar eclipses**. This information is not only very helpful for scientists who carry out research during these eclipses, but also for many other people who appreciate the wonder of such events.

On average, there are about two to four lunar eclipses each year (Figure 7.1.10). However, not all lunar eclipses are visible from every location on Earth. The visibility depends on the Moon's position and the observer's location.

FIGURE 7.1.10 Total lunar eclipse

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Eclipses and culture

Solar eclipses played a vital role in a number of ancient cultures, with many cultures believing they were a sign of the Gods. By observing solar eclipses, ancient astronomers could predict future eclipses using patterns they noticed. This helped them understand the relative positions and motions of Earth, Moon and the Sun.

FIGURE 7.1.11 433 Eros

KEY TERM

constellation a group of stars which form a recognisable pattern in the night sky

Near-Earth asteroids

An asteroid is an irregular rocky object that orbits the sun. Through ongoing observations of asteroids in the solar system, astronomers can identify near-Earth asteroids that have the potential to come close to Earth. By tracking their paths and making predictions based on gravitational forces, scientists can provide early warnings of potential asteroid impacts, giving time to plan and develop strategies to mitigate any potential risks.

433 Eros is a near-Earth asteroid and the second-largest known asteroid with a diameter of approximately 34 km (Figure 7.1.11). It was discovered in 1898 and has a highly elliptical orbit that occasionally brings it close to Earth. In February 2000, NASA's Near-Earth Asteroid Rendezvous (NEAR) spacecraft successfully reached and orbited Eros, providing valuable data and detailed images of its surface.

First Nations knowledge

First Nations peoples of Australia have rich cultural and spiritual connections to the night sky. They have developed deep understandings of celestial bodies and their movements, using this knowledge in various aspects of daily life. For example, the positions of stars and the Moon are used to navigate the land and sea, determine the seasons for hunting, fishing and harvesting and signal the beginning of events, such as ceremonies. The stars are also used to teach traditional lore with representations of animals that hold the lore in the **constellations**. Furthermore, Torres Strait Islander people use their observations of the amount of twinkling of stars to determine how much moisture and turbulence is in the atmosphere, which is important in predicting weather patterns.

SC 3 CHECK YOUR UNDERSTANDING

Name an astronomical event that has been used to make predictions about future events.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1. Recall the name of the historical model that placed Earth at the centre of the universe.
2. Explain how observations of past solar eclipses allow scientists to predict future solar eclipses.
3. Research and explain how First Nations people of Australian use celestial objects in the nights sky to assist with navigation.
4. The geocentric model was widely accepted until the Renaissance.
   a. Identify the key astronomer who challenged the geocentric model.
   b. Explain how the phases of Venus contradicted the geocentric model.
   c. Explain why this shift in model was significant for current understanding of the universe.

7.2 Distances in space

Lesson overview

Have you ever wondered how astronomers determine the vast distances between celestial bodies? Well, get ready to uncover the secrets!

In this lesson, you will learn about the light year as a unit of measure for vast distances, and you will discover how stellar parallax can be used to measure the distance of objects from Earth. You will explore the mind-boggling scale of the universe and gain a new perspective on the vastness of space. Get ready to expand your cosmic knowledge!

SC 1 I can describe the concept of a light year and explain why this unit is used to measure distances in space

When exploring and studying the universe, distances are so vast that ordinary units of measurement, such as kilometres, are inadequate (Figure 7.2.1).

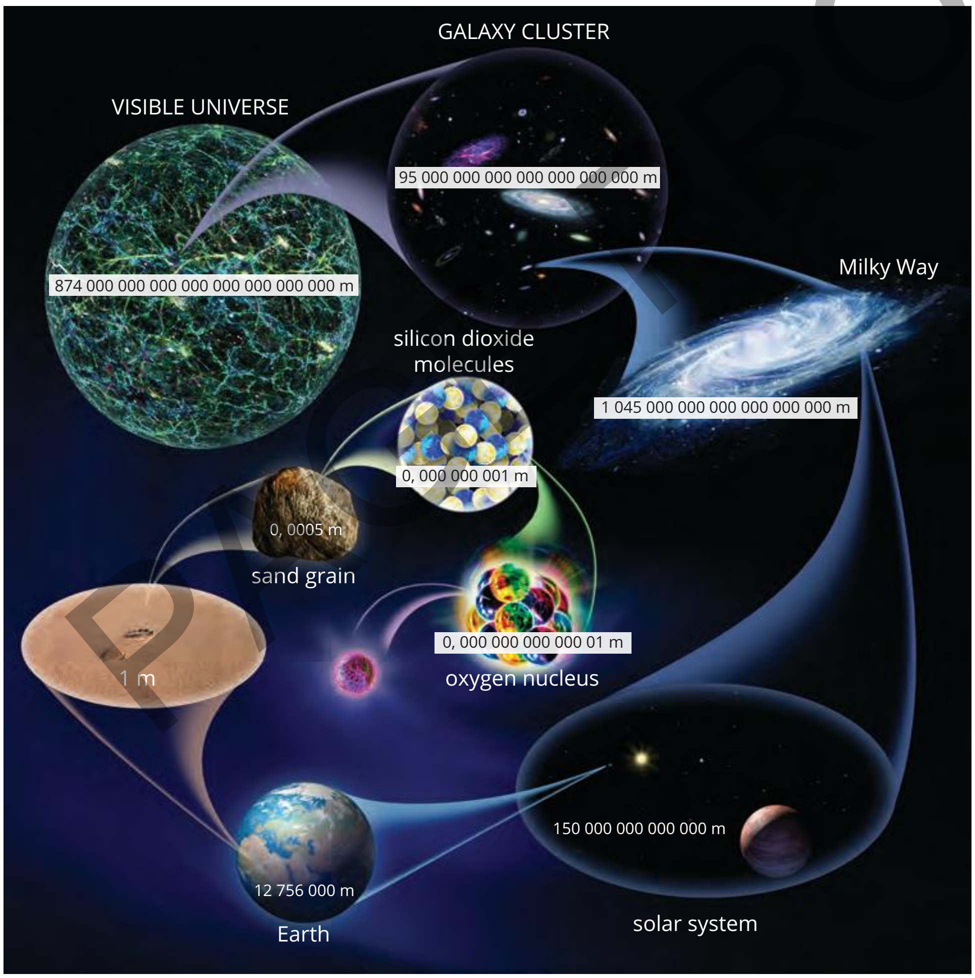

FIGURE 7.2.1 The range of scales in the universe are huge, ranging from the smallest particle inside atoms to the vastness of the observable universe

Learning intention

To understand how distances in space are measured

Success criteria

SC 1: I can describe the concept of a light year and explain why this unit is used to measure distances in space.

SC 2: I can use light years to compare distances between celestial bodies in space.

SC 3: I can explain how stellar parallax can be used to measure the distance of objects from Earth, including limitations of the method.

KEY TERM

light year the distance light travels in one year through space, approximately 9 500 000 000 000 km

To comprehend these immense scales, astronomers use a unit called the **light year**.

Understanding the light year

A light year is defined as the distance that light travels in one year through the vacuum of space. Given that light travels at an incredible speed of 299 792 kilometres per second (through a vacuum), the distance covered in a single year is truly staggering – around 9.46 trillion kilometres. This vast distance is a light year.

To calculate this distance, take the number of seconds in a year and multiply it by the speed of light (in kilometres per second):

$60 \times 60 \times 24 \times 365.25 = 31\,557\,600$ seconds in a year

$31\,557\,600 \times 299\,792 = 9\,460\,716\,019\,200$ kilometres in a light year

Comparing light years to kilometres

To grasp the extent of a light year, consider this example: Earth's nearest neighbouring star, Proxima Centauri, is approximately 4.24 light years away from Earth. This means that the light currently seen from Proxima Centauri actually left the star more than four years ago.

In comparison, the Moon is only 384 400 kilometres away from Earth. It would take less than two seconds for light from the Moon to reach your eyes. This contrast highlights the extraordinary vastness of space and the need for a unit like the light year to measure interstellar distances.

Other astronomical units

There are other units, apart from the light year, that astronomers use to measure distances in space. An example is the astronomical unit (AU), which is defined as the average distance between Earth and the Sun. It is roughly 149.6 million kilometres. The AU is useful for measuring distances within the solar system, such as the average distance of planets from the Sun (Figure 7.2.2).

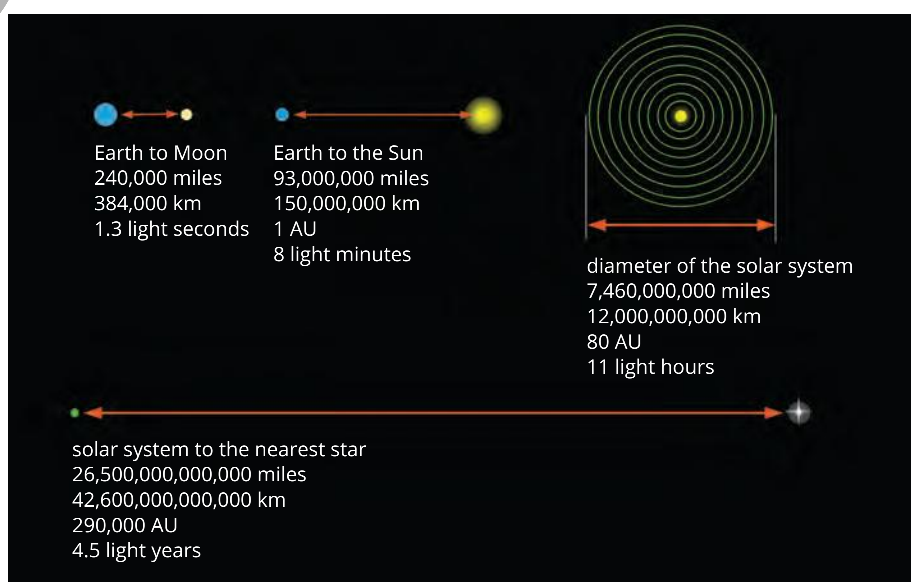

FIGURE 7.2.2 Comparing units of measurement for describing distances in space

For even greater cosmic scales, astronomers employ the parsec (pc). It is equivalent to approximately 3.26 light years or 30.9 trillion kilometres. The parsec is predominantly used in astrophysics and cosmology to express vast interstellar and intergalactic distances.

KEY TERM

parsec an astronomical unit of length equal to 3.26 light years

SC 1 CHECK YOUR UNDERSTANDING

Define a light year.

SC 2 I can use light years to compare distances between celestial bodies in space

When exploring the cosmos, astronomers often encounter the challenge of measuring vast distances between celestial bodies. The speed of light can be used to compare the distances between different celestial objects, ranging from neighbouring planets to distant galaxies. For objects that are relatively close (in the solar system) light minutes or light seconds can be used as units of measurement. In the same way that a light year is the distance that light will travel in a year, a light minute is how far light will travel in a minute, and a light second is how far light will travel in a second.

SkillBuilder

Calculating light speed distances

To convert distances to light seconds, light minutes or light years, you need to know the speed of light. In a vacuum, the speed of light is approximately 299 792 kilometres per second. You can use this value to calculate the time it takes for light to travel a given distance. To calculate the time, begin with the formula for speed ($v = \frac{d}{t}$) and rearrange it to make 'time' the subject ($t = \frac{d}{v}$). Use the speed of light for v.

For example, Alicia was asked to state how far away the Moon is from Earth in light seconds. She was told that the Moon is 384 400 kilometres away. To convert this distance to light seconds, Alicia divided the distance (in km) by the speed of light (in km/s). The result is the time taken for light travel the given distance in seconds:

$$\frac{384\,400}{299\,792} = 1.28 \text{ seconds}$$

So, the Moon is a distance of 1.28 light seconds away from Earth – it takes light 1.28 seconds to go from Earth to the Moon (or vice versa).

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Careers in space

There are multiple disciplines of physics that support space research. Astrophysics involves the study of celestial objects, including investigating the dynamics of galaxy formation and evolution. Cosmology can be thought of as a branch of astrophysics. Cosmologists study the origin, evolution and fate of the universe, and tend to work on projects to do with the Big Bang, cosmic inflation and the nature of dark matter and energy.

Worked example

Calculating light speed distances

Problem

Calculate the distance in light seconds and light minutes between the Sun and Jupiter, with an average distance of 778 547 200 km.

Solution

Thinking	Working
The average distance is stated in kilometres, so you must ensure the speed of light is in kilometres per second when using the formula.	In a vacuum, light travels at 299 792 kilometres per second.
Divide the given distance by the speed of light to get light seconds.	$\frac{778\,547\,200}{299\,792} = 2596.96$ light seconds
Divide by 60 to get the answer in light minutes.	$\frac{2596.96}{60} = 43.28$ light minutes

Try yourself

Calculating light speed distances

The distance between two galaxies is measured as 5 billion kilometres. Determine the distance in light seconds and light minutes.

KEY TERM

stellar parallax the apparent change in the position of a star throughout the year due to Earth's motion around the Sun

SC 2 CHECK YOUR UNDERSTANDING

Explain why the distances between galaxies is normally measured in light ears, instead of light seconds.

SC 3 I can explain how stellar parallax can be used to measure the distance of objects from Earth, including limitations of the method

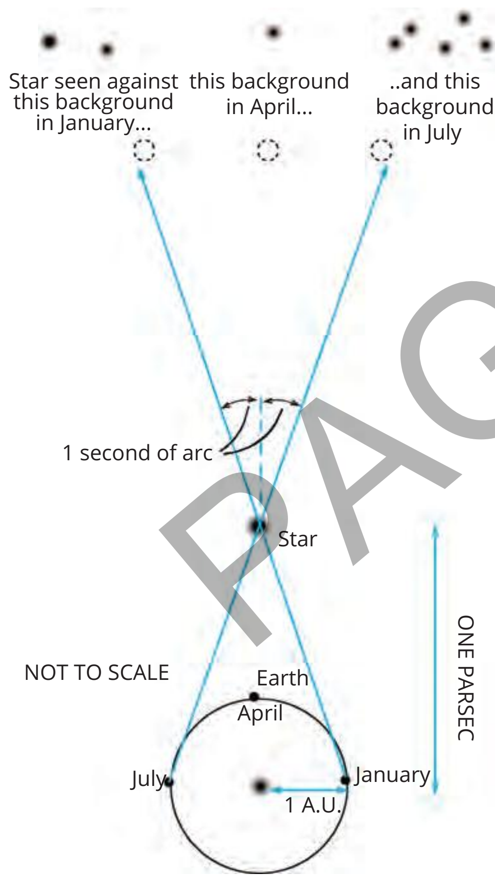

FIGURE 7.2.3 A nearby star viewed from either side of Earth's orbit (lower centre), the largest possible baseline

Stellar parallax

Stellar parallax is a fundamental concept in astronomy that allows scientists to measure the distances between celestial objects and Earth.

Stellar parallax is based on the principle of triangulation. As Earth orbits the Sun, the position of nearby stars appears to shift against the backdrop of more distant stars due to the change in viewing perspective. This apparent shift is known as stellar parallax and can be measured to determine the distance of a star from Earth Measuring these angles creates a triangle and the distance to the object can be calculated using trigonometry (Figure 7.2.3).

Parallax measurements are given in parsecs. A parsec is 30 900 trillion kilometres. Parallax can be detected for stars up to 100 parsecs away.

Everyday parallax

To see parallax for yourself, extend your arm and hold your thumb up. Focus on it with one eye closed. Now, switch eyes and observe how your thumb appears to shift against the background. This shift is due to parallax, where a closer object (your thumb in this case) exhibits a larger apparent shift compared to more distant objects (the background).

KEY TERM

galaxy a large group of stars attracted to one another by gravity

Application in space exploration: Gaia Mission

The Gaia spacecraft, launched by the European Space Agency in 2013, is a revolutionary mission dedicated to precisely measuring the positions, distances, and motions of over one billion stars in Earth's **galaxy**, the Milky Way. Gaia operates with exceptional accuracy, allowing scientists to study the three-dimensional structure of the galaxy and gain information about its evolution.

By observing stellar parallax, Gaia has made significant contributions to understanding of the universe. The spacecraft measures the positions of stars multiple times over several years to detect their parallax shifts, enabling precise distance calculations. Gaia has produced a catalogue of star distances with unprecedented accuracy, enhancing knowledge of stellar properties, galactic structure and cosmic evolution (Figure 7.2.4).

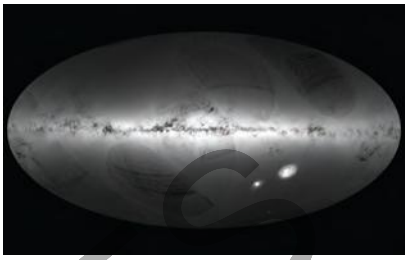

FIGURE 7.2.4 All-sky map of the Milky Way and neighbouring galaxies from observations of the Gaia satellite. Brighter regions indicate denser concentrations of stars and darker regions fewer stars. The Galactic Plane of the Milky Way is seen across the centre. This is about 100 000 light years across and about 1000 light years thick.

Limitations of stellar parallax

While stellar parallax is a valuable technique for measuring distances, it does have limitations. Its effectiveness decreases with increasing distance, as smaller parallax shifts become more challenging to measure accurately. Stellar parallax is most reliable for objects within a few hundred parsecs from Earth. Beyond this range, other methods are employed to estimate distances.

SC 3 CHECK YOUR UNDERSTANDING

Explain why stellar parallax is effective for measuring distances within a few hundred light years, but not for distances greater than this.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1 Explain why a light year is a useful unit for measuring distances in space.

2 Apply the concept of a light year to determine how far light travels in 5 years.

3 Explain how stellar parallax is used to measure the distance to nearby stars.

4 Using light years helps in understanding the scale of the universe.
 a Identify the distance to Proxima Centauri in light years.
 b Conduct some research to find out the distance to the Andromeda Galaxy in light years.
 c Compare these distances to highlight the difference between interstellar and intergalactic scales.
 d Evaluate how the use of light years aids in comprehending these vast distances.

7.3 Big bang theory

Learning intention

To understand how the big bang theory models the origin of the universe

Success criteria

SC 1: I can explain the characteristics and source of cosmic microwave background radiation.

SC 2: I can explain how observation of cosmic microwave background radiation supports the big bang theory.

SC 3: I can compare the big bang theory to steady state theory.

KEY TERM

cosmic microwave background radiation the afterglow of the Big Bang; low-frequency radiation that fills the universe

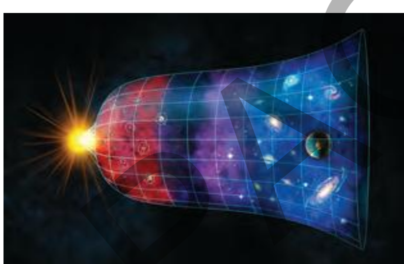

FIGURE 7.3.1 The universe has been expanding since its beginning

Lesson overview

The origin of the universe has captured the thoughts and wonderings of humans for millennia. As science understanding has developed in recent centuries, theories have also been developed, tested and discarded or modified. New technology has provided a wealth of data to inform scientific thinking and has revealed new wonders of the universe.

In this lesson, you will learn about the fascinating Big Bang and how this theory explains the origin of the universe. You will explore the key concepts and evidence that support this widely accepted scientific theory. Specifically, you will delve into the characteristics and significance of cosmic microwave background radiation, a crucial piece of evidence for the big bang theory. Additionally, you will compare the big bang theory to the alternative steady state theory, examining their contrasting views on the universe's origin.

SC 1 I can explain the characteristics and source of cosmic microwave background radiation

Central to understanding the big bang theory is the **cosmic microwave background radiation** (CMB), a remarkable discovery that provides key insights into the early universe. Examining the characteristics and source of CMB unravels the mysteries surrounding the birth and evolution of the cosmos.

The big bang theory

The **big bang theory** proposes that the universe began as an infinitely dense and hot point and has been expanding and cooling ever since. Approximately 13.8 billion years ago, a rapid and immense explosion marked the beginning of the universe, known as the **Big Bang** (Figure 7.3.1). As the universe expanded, it cooled, allowing matter and energy to form.

Cosmic microwave background radiation (CMB)

One of the significant pieces of evidence supporting the big bang theory is the existence of cosmic microwave background radiation (CMB). CMB is the residual electromagnetic radiation left over from the early stages of the universe, when it transitioned from a hot, opaque state to a transparent one. It is often referred to as the 'afterglow' of the Big Bang.

Characteristics of CMB

CMB appears as faint microwaves uniformly spread throughout the universe, with a temperature of approximately 2.7 **Kelvin** (–270.45 degrees Celsius) (Figure 7.3.2). It is observed in all directions, indicating its isotropy, or uniformity, across the sky. This uniformity supports the idea that the universe was once in a highly compressed and homogeneous state.

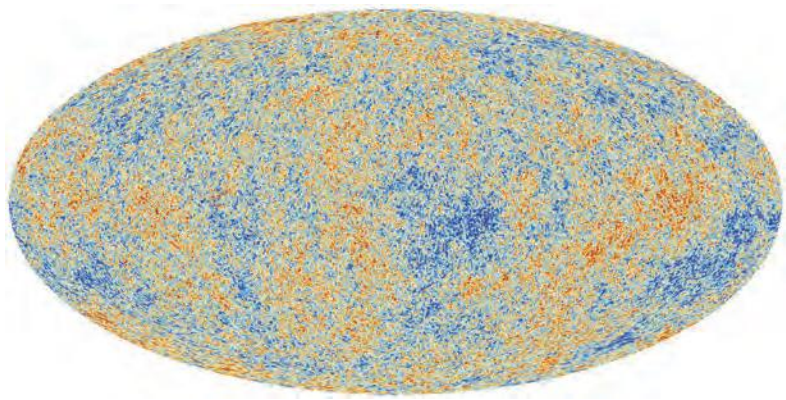

FIGURE 7.3.2 A photo from the European Space Agency of a spectacular map of the 'oldest light' in the sky: the cosmic microwave background radiation (CMB) as observed by the Planck telescope. This photo shows tiny temperature fluctuations that correspond to regions of slightly different densities, representing the seeds of all future structure: the stars and galaxies of today.

Source of CMB

The source of CMB radiation can be traced back to a significant event in the universe's history known as recombination. During recombination, approximately 380 000 years after the Big Bang, the universe cooled enough for electrons to combine with **protons**, forming neutral atoms. This process produced free moving **photons**. The reason photons could move freely after recombination is because neutral atoms are less likely to interact with light than charged particles. The release of these 'free' photons when the universe became transparent is observed today as CMB radiation.

SC 1 CHECK YOUR UNDERSTANDING

State the significance of the cosmic microwave background radiation in cosmology.

SC 2 I can explain how observation of cosmic microwave background radiation supports the big bang theory.

Unravelling the universe's afterglow

The existence of CMB radiation plays a crucial role in supporting the big bang theory – the prevailing explanation for the origin and evolution of the universe. The discovery of the CMB radiation by Arno Penzias and Robert Wilson in 1965 was a pivotal moment in cosmology.

Scifile

Cosmic microwave background radiation

Hiranya Peiris (pictured below) holds a Professorship of Astrophysics at the University of Cambridge, UK. Her field of research is the cosmic microwave background radiation which originates from the heat produced from the Big Bang. Roughly one percent of the snow picked up by an untuned television arises from this radiation.

KEY TERMS

Kelvin a temperature scale based on absolute zero, which is the coldest possible temperature. Zero kelvin is equal to −273.15ºC, and a change of one kelvin is the same as 1 degree Celsius

photon a particle without mass that carries a specific amount of energy representing a minute quantity of light or other electromagnetic radiation

proton a subatomic particle with a positive electric charge, located in the nucleus of an atom

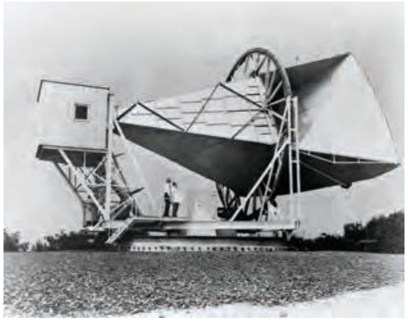

FIGURE 7.3.3 The horn antenna at Bell Telephone Laboratories in Holmdel, New Jersey, USA, which astrophysicists Wilson and Penzias used in 1963–64 to unexpectedly discover the microwave background radiation from the Big Bang.

The discovery of CBR

In the early 1960s, Penzias and Wilson, while working on the radio antenna shown in Figure 7.3.3, noticed an unexpected noise that seemed to come from every direction in the sky. They first thought that there was a problem with the electronics in their receiver, but they couldn't fix the noise via the electronics. They then thought that the poo from pigeons nesting in the antenna was somehow causing the interference, but it was still there after they cleaned off all of the poo! After rigorous analysis, they realised that this mysterious background noise persisted at all times of the day and night, regardless of their antenna's orientation. They contacted a nearby group of cosmologists who knew that the big bang theory predicted a low-temperature, uniform, leftover radiation and realised that they had accidentally discovered this radiation!

Link to predictions of the big bang theory

The discovery of CMB radiation aligned remarkably with the predictions of the big bang theory, proposed decades earlier by scientists like Georges Lemaître and George Gamow. According to the theory, the universe began as an intensely hot and dense state and expanded rapidly from a point of infinite density. As the universe expanded, it cooled, and at a critical moment, about 380,000 years after the Big Bang, it became transparent.

SCIENCE IN SOCIETY

Blackbody radiation as described by Planck

In the early universe, particles and radiation were densely packed and in thermal equilibrium: this means that energy is passed equally back and forth between the particles and the radiation so that they are not heating or cooling each other. When the universe cooled enough, electrons were able to combine with protons to form neutral atoms (a process called recombination). From this point, particles and radiation were no longer coupled together in equilibrium and photons began traveling freely through space. These photons, being in thermal equilibrium just before their 'release', exhibit a distinctive blackbody radiation spectrum—a fundamental concept described by Max Planck, which perfectly matches the observed CMB radiation.

A blackbody is a theoretical object that glows when heated, and the colour of the object's glow depends on its temperature. Figure 7.3.4 shows Dr John Cromwell Mather's work on analysing the cosmic microwave background radiation.

The graph in the background presents data from the COBE (Cosmic Background Explorer) probe, which was launched in 1989. This probe measured the cosmic microwave background radiation. Mather's COBE work helped show the blackbody nature of the radiation (as shown by the graph).

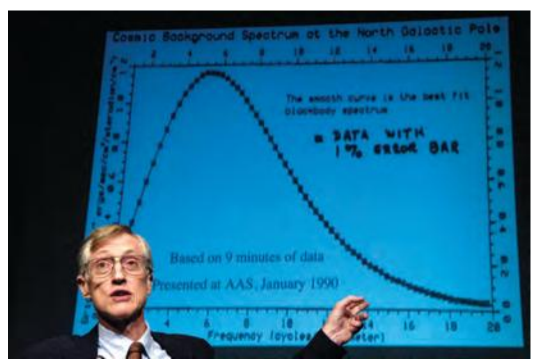

FIGURE 7.3.4 Dr John Cromwell Mather (born 1945), American astrophysicist, cosmologist and Nobel laureate, talking at a press conference about the work he did that helped show the blackbody nature of cosmic microwave background radiation. He was awarded a share of the 2006 Nobel Prize in physics for this work.

SC 2 CHECK YOUR UNDERSTANDING

Describe how the discovery of cosmic microwave background radiation supports the big bang theory.

SC 3 I can compare the big bang theory to steady state theory

In the section you will explore two contrasting cosmological models—the big bang theory and steady state theory—to understand how each one explains the origin and evolution of the universe. While the big bang theory proposes an explosive birth of the cosmos, steady state theory advocates for a constant and eternal universe.

How the origins and expansion are explained

Steady state theory, developed in the 1940s by Hermann Bondi, Thomas Gold and Fred Hoyle, suggests that the universe is in a state of eternal expansion and maintains a constant average density. Steady state theory suggests that the universe has no beginning and no end and has existed indefinitely over time. According to this theory, new matter is continuously created to fill the gaps left by the expanding universe, preserving its uniformity over time.

In contrast, the big bang theory proposes that the universe began as an infinitely dense and hot point, approximately 13.8 billion years ago, and has been continuously expanding and cooling ever since, giving rise to galaxies, stars and all known celestial structures. The big bang theory is currently the most widely accepted theory of the origin and evolution of the universe.

KEY TERM

steady state theory now discounted theory that the universe has always existed in the form that it is in today; also known as the 'infinite universe' theory

Evidence and observations

The discovery of cosmic microwave background radiation (CMB) in 1965 provided strong evidence in support of the big bang theory. The CMB radiation's isotropy and blackbody radiation spectrum align perfectly with the predictions of the theory.

The development of modern measuring techniques has allowed astronomers to gain more information about the universe leading to the dismissal of the steady state theory. One such piece of evidence that discredits the steady state theory is the 1963 discovery of quasars. Quasars are an astronomical object of very high luminosity (brightness). These are observed to only exist very far away from Earth, indicating that the light produced by them was produced billions of years ago. This contradicts the assumption of the steady state theory that the universe has a constant average density – if the universe did have a constant density, then quasars should be observable much closer to Earth (Figure 7.3.5).

FIGURE 7.3.5 Illustration showing the intense brightness of a quasar

SC 3 CHECK YOUR UNDERSTANDING

Describe the evidence that resulted in challenges to the steady state theory.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1 Describe the origin of cosmic microwave background (CMB) radiation.
2 Explain how the big bang theory accounts for the observed expansion of the universe.
3 Compare the predictions made by the big bang theory and the steady state theory regarding the evolution of the universe.
4 Compare the big bang theory and the steady state theory in terms of how they explain the existence of the cosmic microwave background radiation.

7.4 The early universe

Lesson overview

Billions of years ago, long before galaxies and stars filled the cosmos, an extraordinary event called the Big Bang marked the universe's beginning. But what exactly happened during those crucial moments and the process that led to the current state of the universe remains to be fully understood.

In this lesson, you will learn about the key events that occurred in the first few seconds after the Big Bang. You will explore how gravity played a crucial role in shaping galaxies by drawing matter together, creating the awe-inspiring clusters of stars and gases that fill the cosmos. You will also see how gravity influenced the formation of solar systems, including Earth's.

Learning intention

To understand the early history of the universe

Success criteria

SC 1: I can use visual representations to show the key events in the first few seconds after the Big Bang.

SC 2: I can describe how gravity caused matter to condense into galaxies.

SC 3: I can describe how gravity caused solar systems to form.

SC 1 I can use visual representations to show the key events in the first few seconds after the Big Bang

Understanding the key events that transpired in the first few seconds after the Big Bang is crucial to comprehending the early history of the universe (Figure 7.4.1).

Representing key events and processes

Following the Big Bang, the temperature of the universe was about 1 thousand million degrees Kelvin. As the universe expanded and cooled, matter began to form and recombine. Recombination was complete about 380 000 years after the Big Bang. Stars and galaxies formed in a pattern determined by the original variations in temperature shown by the cosmic microwave background (Figure 7.4.2).

The timeline in Figure 7.4.3 outlines the processes that were occurring in the early universe after the Big Bang. Note that the times for the first steps are incredibly small. For example, 10^{-12} seconds is equal to 0.000 000 000 001 s.

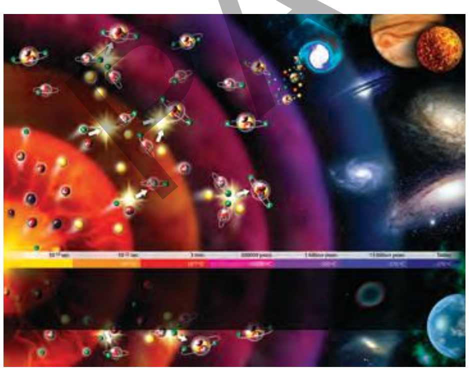

FIGURE 7.4.1 Computer artwork showing the universe's evolution from the Big Bang to the present day

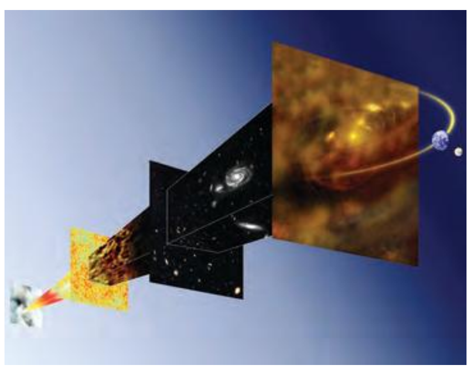

FIGURE 7.4.2 The four stages of the expansion of the universe.

Time	Event	Description
0 seconds	**The Big Bang**	The universe begins with a rapid expansion, where all space, time and matter originate from an infinitely hot and dense point.
10^{-33} seconds	**Inflation**	The universe undergoes a rapid exponential expansion, stretching out from a subatomic scale to a much larger size in an incredibly short time. The theory of **cosmic inflation** was developed during the 1970s and 1980s to explain the even distribution of the cosmic microwave background (CMB) radiation.
10^{-12} seconds	**Formation of quarks**	Quarks, the building blocks of matter start to form as the universe cools down, although it is still too hot for subatomic particles like electrons and protons to form.
10^{-6} seconds	**Formation of nuclei**	Quarks combine to form protons and neutrons.
1 second to 3 minutes	**Nucleosynthesis**	The formation of the first **atomic nuclei** occurs as protons and neutrons combine, leading to the production of hydrogen, helium and trace amounts of lithium. Free electrons form a 'fog' that scatters light and makes the universe opaque.
380 000 years	**Cosmic microwave background forms**	The universe is now cool enough for electrons to combine with atomic nuclei to form atoms. This allowed photons to decouple from matter, traveling without interference: the universe is now transparent. The formation of atoms created the CMB radiation, which is still observable today.
100–500 million years	**First stars ignite**	Gravity causes matter to condense, leading to the ignition of the first stars, marking the end of the cosmic 'dark ages'. Before the first stars were formed, the universe was a 'sea' of light elements (elements with relatively small atoms, such as hydrogen and helium).
700–1000 years	**Formation of galaxies**	As matter accumulates, galaxies begin to take shape, composed of stars.

FIGURE 7.4.3 A timeline showing the development of the early universe after the Big Bang

KEY TERMS

cosmic inflation the theory of the rapid expansion of the early universe

atomic nuclei the centre of an atom that contains protons and neutrons

SC 1 CHECK YOUR UNDERSTANDING

Describe the process of nucleosynthesis that occurred shortly after the Big Bang.

SC 2 I can describe how gravity caused matter to condense into galaxies

Gravity, the invisible force that governs interactions between objects with mass, played an important role in shaping the universe. To understand how the universe developed over billions of years, it is necessary to look at how gravity caused matter to collapse, or condense, into galaxies. This process involved the aggregation (or collection) of gas, dust and **dark matter**, gradually forming massive structures known as galaxies.

The cosmic web: a latticework of galaxies

Imagine the universe as a vast, interconnected web, where galaxies are linked together by invisible threads of gravity. This cosmic web is a spectacular structure that emerged over billions of years, defining the present-day large-scale distribution of galaxies.

Figure 7.4.4 displays an illustration of the cosmic web structure from data which mapped galaxies within 500 million light years of Earth. The three pairs of inset boxes show some individual galaxies (yellow dots).

Current scientific understanding of galaxy formation involves the following key steps.

Cosmic seeds

At the beginning of the universe, tiny fluctuations in the density of matter emerged due to **quantum fluctuations** during inflation. These fluctuations acted as 'cosmic seeds', slightly denser regions in the otherwise uniform distribution of matter.

Gravity at work

Gravity, being a universally attractive force, started to pull matter together in regions where the density was slightly higher. As these regions gathered more mass, their gravitational pull intensified, drawing even more matter towards them.

Collapse and rotation

The matter in these regions continued to collapse under gravity's pull, leading to the formation of **protogalactic clouds**. As these clouds rotated, they formed into spinning disc-like structures.

Star formation

Within these spinning clouds, gas and dust became concentrated at the centre, becoming so dense and hot that **nuclear fusion** reactions were triggered, igniting the first stars (stellar ignition). The stars, along with other celestial objects, grouped together within the protogalactic clouds.

Galactic mergers

Over time, smaller galaxies merged due to gravitational interactions, leading to the formation of the more massive galaxies seen today.

SC 2 CHECK YOUR UNDERSTANDING

Explain the process by which gravity caused matter to condense into galaxies.

KEY TERM

dark matter a form of matter that does not interact with forms of electromagnetic radiation; the existence of dark matter has been inferred from the effect it seems to have on visible matter

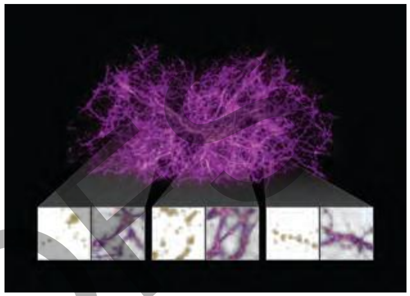

FIGURE 7.4.4 Illustration depicting the cosmic web structure of the universe, generated by a computer algorithm using data from the Sloan Digital Sky Survey

KEY TERMS

quantum fluctuations temporary random changes in a quantum field which can be considered as 'virtual particles' which appear and then rapidly disappear

protogalactic cloud a massive cloud of gas that can form into a galaxy

nuclear fusion the process in which smaller atoms are converted into larger atoms, also producing light and heat

SC 3 I can describe how gravity caused solar systems to form

Solar systems, including the one containing Earth, are celestial structures that emerged from the action of gravitational forces in the cosmos. Understanding the role of gravity in the formation of solar systems helps reveal the nature of these cosmic structures.

The processes of solar system formation

There are several key stages to the development of a solar system (Figure 7.4.5).

FIGURE 7.4.5 Formation of a solar system

Initial conditions

Solar systems begin their journey within vast molecular clouds, consisting of gas and dust, scattered throughout the galaxy. These clouds are remnants of previous star explosions, containing elements crucial for the formation of new stars and planets.

Gravitational collapse

A disturbance, such as a nearby **supernova** or a shockwave from a passing star, triggers a gravitational collapse within the molecular cloud. Gravity pulls the surrounding matter together, causing the cloud to contract and spin.

KEY TERM

supernova a giant explosion that occurs when a star many times larger than the Sun runs out of nuclear fuel

electrostatic force force experienced inside an electric field (also called electric force)

Accretion and protostar formation

As the cloud contracts, it fragments into denser regions known as 'protostellar cores'. In these cores, gas and dust continue to accumulate, forming a central 'protostar'. The protostar grows hotter and denser, eventually igniting nuclear fusion, becoming a young star.

Protoplanetary disc

Surrounding the protostar, a rotating disc of gas and dust, called the 'protoplanetary disc', forms. Gravity and conservation of momentum keep the disc spinning in the same plane as the protostar's rotation.

Planetesimal formation

Within the protoplanetary disc, tiny particles collide and stick together due to **electrostatic forces** that cause attractions between the particles. These collisions gradually form tiny planets called planetesimals, which are between 100 to 1000 metres in size.

Protoplanets and planets

Planetesimals continue to collide and merge, growing larger and forming ‘protoplanets’. As the **solar wind** from the protostar removes remaining gas from the protoplanetary disc, the protoplanets ‘sweep’ their orbits clear of debris, evolving into full-fledged planets.

Gravity is the central force of solar system formation. It causes the molecular cloud’s collapse, leading to the spinning protostar and the protoplanetary disc. Furthermore, gravity enables accretion, the process of particles coming together to form planetesimals and protoplanets.

KEY TERM

solar wind a stream of charged particles, including protons and electrons, from a star’s outer atmosphere

Scifile

Rotating solar systems

The law of the conservation of angular momentum governs the behaviour of the protoplanetary discs. Angular momentum is a measurement based on the mass and the rotational motion of an object. This means that within the protoplanetary disc system, the fact that angular momentum is conserved means that the objects within the system will continue to spin (in the same direction) even as the object themselves change. Therefore, when planets form from a protoplanetary disc they will continue to rotate and orbit around the central star.

SC 3 CHECK YOUR UNDERSTANDING

Name the process by which a solar system forms from a cloud of gas and dust.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1 Compare the conditions of the universe during the inflation period with the conditions during nucleosynthesis.

2 Visual representations can help illustrate the key events after the Big Bang.
- **a** Identify the first event that occurred after the Big Bang.
- **b** Describe the conditions of the universe during this event.
- **c** Create a visual timeline including at least three key events in the first few seconds after the Big Bang.
- **d** Explain the significance of each event on the timeline.

3 Apply the concept of gravitational collapse to describe how a region of space with higher matter density might evolve over time.

4 Gravity is essential in the formation of solar systems.
- **a** Define gravitational collapse.
- **b** Describe the steps involved in the formation of a solar system from a cloud of gas and dust.
- **c** Explain the role of gravity in the formation of the solar system’s central star.
- **d** Compare the role of gravity in solar system formation with its role in galaxy formation.

7.5 Light spectra

Learning intention

To understand what information can be learned about a star from its light spectrum

Success criteria

SC 1: I can explain how the presence of chemical elements can be seen in a star's spectrum.

SC 2: I can explain how a star's spectrum can be used to provide information about other properties including temperature.

KEY TERMS

spectrum a band of colours produced by separation of the components of light

spectrograph an instrument for producing and recording a spectrum of light or other form of electromagnetic radiation

spectroscopy the measurement and analysis of spectra produced by the interaction of electromagnetic radiation, such as light and radio waves, with matter

electromagnetic radiation electromagnetic waves consisting of oscillating electric and magnetic fields travelling at the speed of light

Lesson overview

A light spectrum is a valuable source of data used to analyse and interpret the light emitted by celestial objects. A **spectrum** is the separated components of a particular source of light. By using specialised instruments such as **spectrographs**, scientists can determine the distinct patterns embedded within a star's spectrum (Figure 7.5.1).

In this lesson you will learn about how **spectroscopy** aids in determining the elements that stars are composed of, and the process of identifying a star's temperature and other fundamental properties through its light spectrum.

FIGURE 7.5.1 Star spectra provide information about the elements present in a star and its physical properties

SC 1 I can explain how the presence of chemical elements can be seen in a star's spectrum

The nature of light

Light is a form of **electromagnetic (EM) radiation**, a wave-like and particle-like phenomenon that can travel through space. The EM spectrum (Figure 7.5.2) has a wide range of wavelengths and frequencies, from long radio waves to short gamma rays. Visible light, which includes all the colours of the rainbow, occupies a small portion of the EM spectrum, with wavelengths ranging from approximately 400 to 700 nanometres.

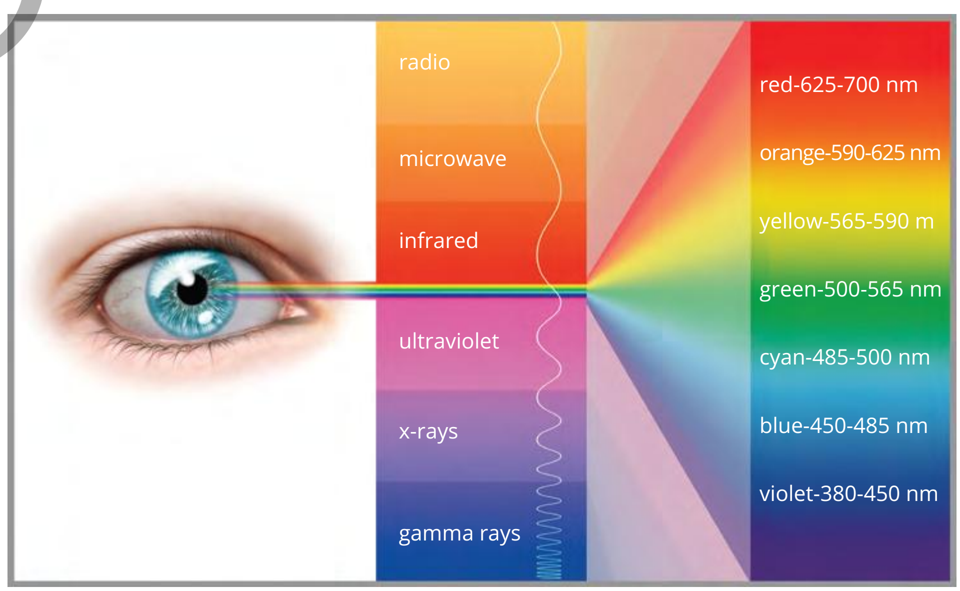

FIGURE 7.5.2 The electromagnetic spectrum. Light is separated into different groups based on specific wavelengths and frequencies.

The structure of atoms

At the centre of an atom lies a nucleus composed of protons and neutrons, while electrons orbit the nucleus in specific energy levels called electron shells. The arrangement of electrons in these shells determines the chemical properties of an element. Electrons can move between different energy levels when they are excited by external an energy source, such as electromagnetic radiation.

Spectra production

When light created in the centre of a star passes through its outer layers, it interacts with the atoms present. This can produce two distinct types of spectra, emission and absorption.

Absorption spectra

As photons of light travel through the outer atmosphere of a star, they encounter atoms. The atom in its unexcited state has electrons held in specific energy levels. When photons of light interact with these electrons, they may absorb the energy of the photon and jump up to a higher energy level (an excited state). These electrons in their excited state are unstable, and will fall back down, re-emitting the absorbed energy as light. This process is outlined in Figure 7.5.3. The re-emitted light goes in all different directions (like fireworks exploding in the sky). So, it is unlikely that the re-emitted light will go in the exact same direction as the original light.

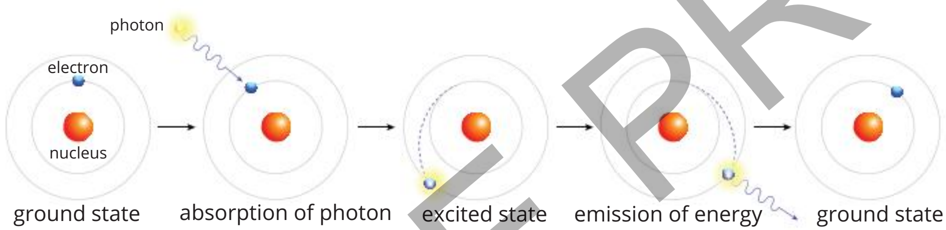

FIGURE 7.5.3 Photons of light can be absorbed by electrons in an atom, causing the re-emission and scattering of light.

Due to the absorption of certain wavelengths of light, some wavelengths (colours) appear to be 'missing' when observing the light from a star. These missing wavelengths create dark lines in the star's spectrum, known as 'absorption lines'. This can be seen in the absorption spectrum of hydrogen in Figure 7.5.4. It is like seeing gaps in a rainbow where certain colours are less bright or even missing. Each element present in the star's atmosphere absorbs specific wavelengths of light, creating a unique set of dark lines in the absorption spectrum, like a chemical fingerprint.

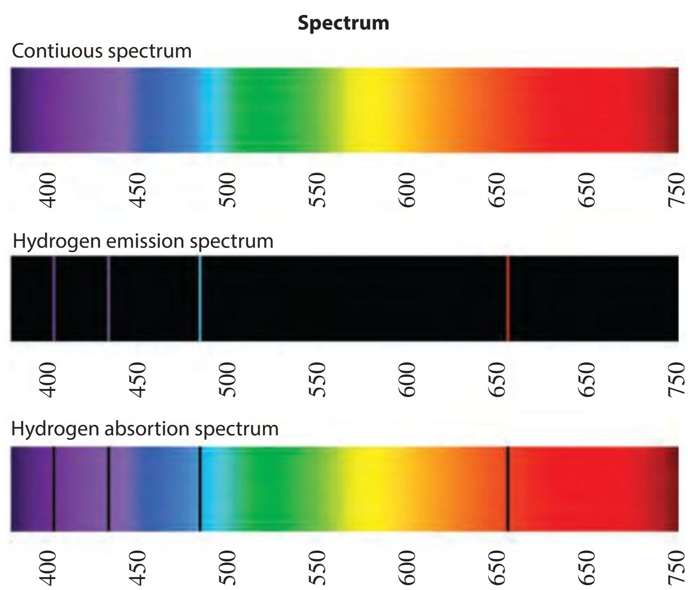

FIGURE 7.5.4 The emission and absorption spectra of hydrogen. In the emission spectrum, only light of certain wavelengths are visible. In the absorption spectrum the same wavelengths are missing and appear as black lines.

Emission spectra

Consider a situation where electrons in an atom have been excited to a higher energy level due to the absorption of energy. The instability that results causes the electrons to return to their unexcited state.

As these electrons return to lower energy levels, they release energy in the form of light. This produces bright emission lines at specific wavelengths in the star's emission spectrum, indicating the presence of certain elements.

Each type of spectrum discussed is shown in Figure 7.5.4. The figure shows a full spectrum of light that has not interacted with any atoms. After interaction with hydrogen atoms, some wavelengths of light are absorbed leaving 'gaps' in the spectrum (the absorption spectrum). The return of the excited electrons to their unexcited state produces the emission spectrum.

Understanding the production of spectra and the specific wavelengths absorbed or emitted by different elements allows astronomers to identify the chemical composition of stars. Analysing the spectra of distant stars through the process of spectroscopy offers valuable insights into the elements that make them up, helping unravel the secrets of the cosmos.

SCIENCE IN SOCIETY

Australian Astronomical Optics

Different light sources produce different spectra due to their unique compositions and processes. For instance, the spectrum of a star will show absorption lines corresponding to the elements in its atmosphere, while the spectrum of a fluorescent light will show emission lines from the gases inside the tube.

The Australian Astronomical Optics (AAO) is a world leading scientific instrumentation, software and research organisation based at Macquarie University. They design and build a variety of groundbreaking spectrograph and optical imagers. AAO are responsible for building the spectrographs for some of the largest and most impactful optical telescopes in the world, including the Anglo Australian Telescope (AAT) located in New South Wales (Figure 7.5.5) and the European Southern Observatory's Very Large Telescope located in Chile.

FIGURE 7.5.5 The inside of the Anglo-Australian telescope, located in the Siding Spring Observatory in Coonabarabran, New South Wales

The analysis of light spectra produced from these spectrographs provides valuable information about the composition and property of different astronomical light sources.

SC 1 CHECK YOUR UNDERSTANDING

Explain how absorption lines in a star's spectrum indicate the presence of specific chemical elements.

SC 2 I can explain how a star's spectrum can be used to provide information about other properties including temperature

A star's spectrum provides a wealth of information beyond its chemical composition. Spectra are typically represented as graphs showing intensity (brightness) plotted against wavelength or frequency. In emission spectra, bright lines appear at specific wavelengths, indicating the emission of light by certain elements. In contrast, absorption spectra exhibit dark lines where specific wavelengths are absorbed by elements in the star's atmosphere.

Temperature radiation

One critical property shown by a star's spectrum is its temperature. All stars emit radiation (light). Their temperature determines the brightness and colour of the light they emit. The emitted light is not a single colour (wavelength) – it is a range of different wavelengths, with some being more intense (brighter) than others. The graph in Figure 7.5.6 shows how this peak (most intense) wavelength changes with temperature. Hotter stars emit more intense radiation with shorter wavelengths, appearing blue or white. Cooler stars emit weaker radiation with longer wavelengths, appearing reddish.

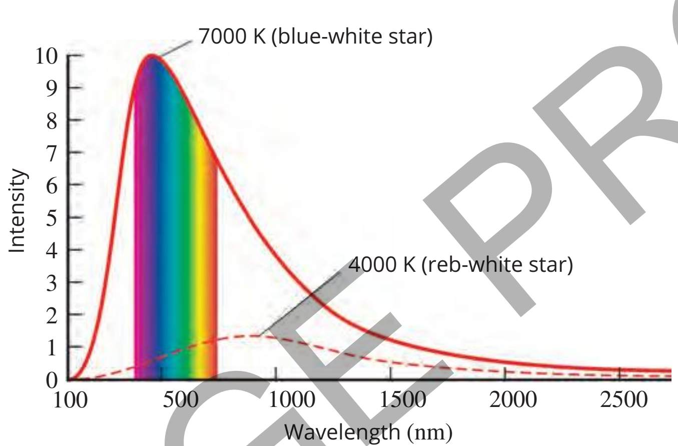

FIGURE 7.5.6 Hotter stars emit more intense radiation with shorter wavelengths and cooler stars emit weaker radiation with longer wavelengths.

Other star properties

Density

The width and shape of spectral lines can reveal information about the density of the star's atmosphere. Broad and shallow lines indicate a denser atmosphere, while narrow and deep lines suggest a sparser atmosphere.

Motion

The Doppler effect observed in a star's spectrum allows astronomers to measure the star's radial velocity (motion toward or away from Earth). The Doppler effect is a change in the wavelength (and hence colour) of light due to the relative motion of the observer (an astronomer on Earth) and the source (the star or other celestial object). This helps determine the star's motion relative to Earth and provides clues about its orbit or rotation.

Magnetic field

In certain stars, magnetic fields cause shifts in spectral lines known as Zeeman splitting. Analysing these shifts helps astronomers study the strength and orientation of the star's magnetic field.

SC 2 CHECK YOUR UNDERSTANDING

Explain how the peak wavelength of a star's spectrum relates to its temperature.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1. Identify the tool used to observe a star's light spectrum.
2. Outline the relationship between a star's temperature and the spectrum that it produces.
3. Compare the spectra of a blue star and a red star to determine their relative temperatures.
4. There are two types of spectra that can be analysed, absorption and emission spectra.
   a. Describe the visible difference in the spectra produced.
   b. Compare how absorption and emission spectra are produced.

Practical investigation

7.6 Using a spectrometer

Introduction

The light from distant stars will vary depending on the elements present in the stars. By analysing this light using spectrometers, scientists can determine the proportions of chemicals in a particular star and even calculate how fast the star or galaxy is moving away from Earth. The spectrometer splits the visible light up into a spectrum, which can be seen as a pattern with the range of colours of light being given off from the light source (Figure 7.6.1).

In this practical investigation you will use a spectroscope, which is a type of spectrometer, to analyse the light from a range of light sources to see how the spectra vary between the sources.

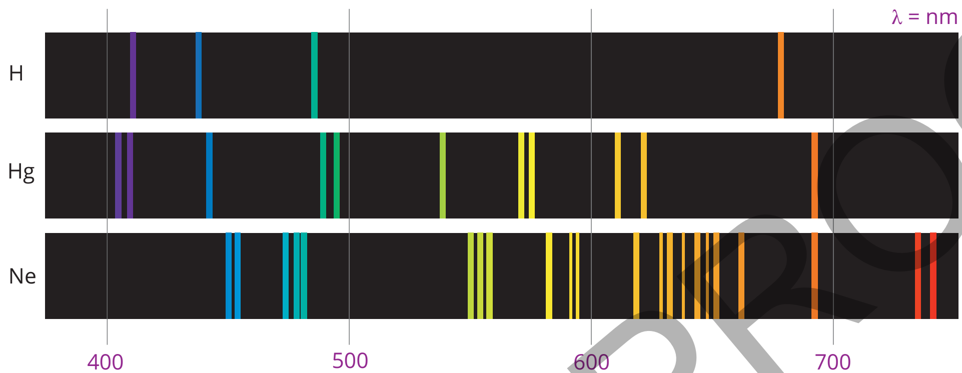

FIGURE 7.6.1 When heated, the elements hydrogen (H), mercury (Hg) and neon (Ne) emit light that produces three different spectra when viewed through a spectrometer.

Learning intention

To be able use a spectroscope to analyse light from a range of sources

Success criteria

SC 1: I can observe and record light spectra using a spectroscope.

SC 2: I can identify and describe differences in spectra from different light sources.

SC 3: I can evaluate how well the experiment models the observation of stars and galaxies.

Background

Spectrometers can be used to analyse the light emitted by stars. By comparing the spectral lines observed in a star's spectrum with known patterns, astronomers can identify the chemical elements present in the star's atmosphere. This method allows them to determine the composition of stars in distant galaxies. Spectrometers that are used to analyse visible light are called spectroscopes.

KEY TERM

spectrometer a device that splits radiation into a spectrum, which can reveal the wavelengths of the various components of the radiation

Aim

To learn how to use a spectroscope and to use it to compare the spectrum of light produced by different sources

Materials

- spectroscope
- lightbulb and coloured filters (a Hodgson's light box or similar would be suitable)
- fluorescent light tube
- coloured pencils

SAFETY NOTE

- Never look directly at the Sun, whether using a spectroscope or not.

Assessment of risk

Ensure you are aware of the risks of this practical investigation and have considered how safety can be improved before carrying out this activity.

Method

1. Aim the slotted end of the spectroscope at the glowing lightbulb.
2. Look through the eyepiece of the spectroscope tube until you see the light spectrum.
3. Use the coloured pencils to sketch this spectrum.
4. Use a red filter to change the colour of the light. Observe and sketch this spectrum.
5. Use a blue filter to change the colour of the light. Observe and sketch this spectrum.
6. Use the spectroscope to study the spectrum of light from a fluorescent tube. Sketch the spectrum from the fluorescent tube, showing the differences between it and the one produced by the lightbulb.
7. Looking through a window, observe and sketch the spectrum of light reflected off the ground or a building. (Never point the spectroscope directly at the Sun.)

HINT

You may need to change the angle that you look into the spectroscope to get the spectrum to appear more clearly.

Results

Sketch the five spectra observed in this experiment.

Conclusion

Compare your observations by describing the spectra observed for:

- light seen through the red filter compared to the light seen through the blue filter
- sunlight compared to the light from a fluorescent tube
- light from a fluorescent tube compared to the light from an incandescent lightbulb.

Evaluation

Evaluate how well the experiment models the observation of stars and galaxies.

7.7 The Doppler effect and redshift

Introduction

Imagine the vastness of space where celestial objects are shining, developing and moving. This inquiry activity focuses on the movement that is associated with cosmic expansion. Much like the changing pitch of an approaching ambulance siren, the light emitted by distant galaxies undergoes a change due to the motion of the galaxies. This change can be analysed to determine the speed and direction of moving galaxies. Much like the changing pitch of an approaching ambulance siren, the light emitted by distant galaxies undergoes a change due to the motion of the galaxies. This change can be analysed to determine the speed and direction of moving galaxies.

In this lesson you will develop a model to illustrate how light from moving objects undergoes this colour change. By the end of this lesson, you will possess the knowledge and skills to explain these cosmic phenomena, allowing you to understand the marvels of the universe's expansion.

Learning intention

To be able to show how redshift relates to the movement of objects in space

Success criteria

SC 1: I can explain how the Doppler effect results in redshift or blueshift.

SC 2: I can develop a model to demonstrate how redshift of light occurs for moving objects in space.

Background

The **Doppler effect** is a phenomenon observed in waves when there is relative motion between the source of the wave and the observer. The Doppler effect occurs when there is an expansion or compression of waves due to the motion of the object making the wave. An everyday example of this is the change in pitch of a soundwave from an ambulance siren. The pitch of the sound depends on the motion of the ambulance and the observer's position (Figure 7.7.1).

FIGURE 7.7.1 The Doppler effect. The sound waves heard by the person on the left are 'stretched' and will have a longer wavelength (and hence lower pitch) than the 'squashed' waves which will sound higher because of the shorter wavelength and higher frequency.

In the context of light, the Doppler effect leads to a shift in the wavelength of light, resulting in either a **redshift** or a **blueshift**. Redshift is a critical concept in cosmology, providing evidence for the expansion of the universe.

KEY TERMS

Doppler effect the expansion or compression of waves due to the motion of the object making the waves

redshift the stretching of light waves due to the motion of an object of away from the observer; redshift makes light from object the appear redder than it would if the object was stationary

blueshift the compression of light waves due to the motion of stars towards Earth; blueshift makes light appear bluer than it should

In this inquiry activity, you will explore how the Doppler effect leads to redshift and blueshift in space.

FIGURE 7.7.2 This graphic shows waves from an object that is moving to the right. It might give you some ideas about your model.

HINT

Your model could be a physical model, a digital simulation or even a mathematical model.

Aim

To create a model that demonstrates the Doppler effect and explains how waves of light can become redshifted

Plan

Collaborate with your classmates and plan how you will create your model to demonstrate the Doppler effect and redshift. Consider how you will represent the source of light, the observer of light, the wavelength of light and the change in wavelength due to the motion of the source.

Conduct

Based on your plan, create the model using the materials you have gathered.

Improve

Consider the accuracy of your model in representing the Doppler effect and redshift.

Evaluate

Reflect on the inquiry question about how we know the universe is expanding. Explain how the concept of redshift, as demonstrated by your model, provides evidence for the universe's expansion.

7.8 Evidence for an expanding universe

Lesson overview

At the start of the twentieth century, knowledge and understanding of the universe was vastly different from today. Before the ground-breaking work of Edwin Hubble, scientists believed that the universe was static and unchanging, with all celestial objects fixed in their orbits. However, Hubble's revolutionary observations challenged this notion and paved the way for a new understanding of the universe and its size.

SC 1	I can describe Hubble's observation that most galaxies are moving away from Earth and that more distant galaxies are moving away more quickly

Edwin Hubble's remarkable observation that most galaxies are moving away from Earth had a transformative impact on understanding the universe's scale and dynamics. This ground-breaking discovery, backed by advancements in observational technology, unveiled a cosmos in constant motion.

Hubble and Slipher's observations

In the early twentieth century, an astronomer called Vesto Slipher used spectrographs to study the light emitted by galaxies. He noticed that the spectra of most galaxies exhibited a redshift, a shift of spectral lines toward longer wavelengths. This indicated that galaxies were moving away from us.

In the 1920s, Edwin Hubble employed the powerful Mount Wilson Observatory telescope to study more galaxies beyond the Milky Way (Figure 7.8.1).

Hubble and Leavitt's observations

Hubble used the data from Slipher and other astronomers in his work to understand and predict the increasing distances between galaxies. These included Henrietta Leavitt, who discovered a way of measuring how far pulsing stars, called Cepheid variables, were away from Earth. Cepheid variables are stars that brighten and dim in regular patterns. These could then be used as reference points to determine distances in space.

Hubble was able to confirm the relationship between a galaxy's distance and its redshift: the farther away a galaxy is, the greater its redshift. Another way to put this is that galaxies further away are moving away faster than closer galaxies! This is due to the light waves emitted by galaxies being stretched as they move away, causing a redshift in their spectra (Figure 7.8.2).

Changing understanding

Hubble's observations led to a stunning revelation: the universe was expanding. Imagine the universe as a balloon being inflated, with galaxies represented by dots on its surface. As the balloon expands, the dots move away from each other, just as galaxies do in the universe. This concept challenged the previous notion that the universe was static and unchanging.

Learning intention

To understand Hubble's observations and what they suggest about the universe

Success criteria

SC 1: I can describe Hubble's observation that most galaxies are moving away from Earth and that more distant galaxies are moving away more quickly.

SC 2: I can explain how Hubble's observations indicate that the universe is expanding.

SC 3: I can explain how Hubble's observations support the big bang theory of the origin of the universe.

FIGURE 7.8.1 Edwin Hubble in his observatory

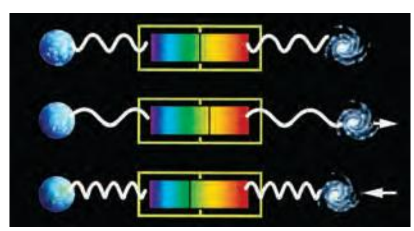

FIGURE 7.8.2 Evidence for an expanding universe includes the redshift observed in light travelling from distance galaxies.

SC 1 CHECK YOUR UNDERSTANDING

Outline Hubble's observation about the movement of galaxies.

SC 2 I can explain how Hubble's observations indicate that the universe is expanding.

Edwin Hubble's observations revolutionised how the expansion of the universe is understood. By studying the spectra of distant galaxies, he uncovered a clear pattern that provided compelling evidence for the continuous expansion of the cosmos.

Spectra and redshift

When light from galaxies is passed through a prism or spectrograph, it breaks into a spectrum of colours, revealing specific lines corresponding to elements present in the source. Hubble's study of these spectra revealed a consistent phenomenon: a redshift in the spectral lines. This redshift indicated that galaxies' light was shifted toward longer wavelengths, signifying their motion away from us.

KEY TERMS

Hubble's law the law that states that a galaxy's velocity moving away from our galaxy is directly proportional to its distance from our galaxy

Hubble constant the number that can be used to predict the velocity of a galaxy based on its distance from Earth; the exact value of the Hubble constant is yet to be confirmed

Hubble's law

Hubble's breakthrough was recognising the correlation between the amount of redshift and a galaxy's distance. He observed that galaxies farther away had greater redshifts, indicating they are receding faster from Earth than those nearest. This relationship, known as **Hubble's law**, provided clear evidence that the universe was expanding uniformly, like an inflating balloon.

This law is expressed by the equation $v = H_0 \times d$.

'v' represents the velocity at which a galaxy is moving away from an observer, 'd' is the galaxy's distance, and 'H_0' is the **Hubble constant**. The Hubble constant quantifies the rate of the universe's expansion (Figure 7.8.3).

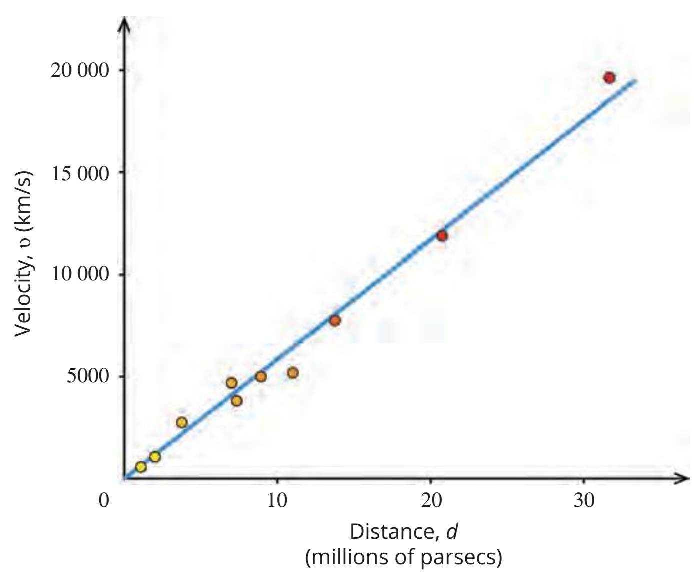

FIGURE 7.8.3 This graph shows data for the velocity of galaxies plotted against the distance to the galaxies. The resulting straight-line graph means the two values are proportional, related by a constant called the Hubble constant, H_0.

Recent observations, like those from the European Space Agency's Planck satellite and the Hubble Space Telescope, have provided refined measurements of the Hubble constant. Current estimates place the Hubble constant at around 67 kilometres per second per megaparsec. This value implies that galaxies situated one megaparsec (approximately 3.26 million light years) away from Earth are moving away at a rate of 67 kilometres per second due to the universe's expansion.

Hubble's law not only substantiates the expanding universe theory but is also the framework for modern cosmological models. Astronomers continue to refine the Hubble constant, by tracing galaxies' motion and measuring their redshifts, thus contributing to knowledge of the universe's past, present and future.

SC 2 CHECK YOUR UNDERSTANDING

Describe what the Hubble constant is and what it measures.

SC 3 I can explain how Hubble's observations support the big bang theory of the origin of the universe

Edwin Hubble's observations reshaped understanding of the universe and provided compelling proof for the predictions of the big bang theory. This process of scientific evidence and refinement continues with further discoveries by astronomers, building upon Hubble's foundation.

Hubble's observations and the Big Bang

Hubble's discovery of galaxies' redshifts, indicating their movement away from us, aligns with the big bang theory. The theory proposes the idea that the universe began as an incredibly dense, hot state and has been expanding ever since. The observed redshifts are consistent with the prediction that galaxies were once much closer together and have been receding due to the expansion of space.

Subsequent discoveries

Since Hubble's pioneering work, several space missions have played important roles in refining the value of the Hubble constant.

The Hubble Space Telescope continues to provide data by observing distant galaxies and Cepheid variable stars, aiding in distance measurements. The Wilkinson Microwave Anisotropy Probe (WMAP) and the Planck satellite have focused on mapping the cosmic microwave background's temperature fluctuations, refining understanding of the universe's geometry, composition and age. The GAIA Space Telescope contributes indirectly by accurately measuring the distances to stars (Figure 7.8.4).

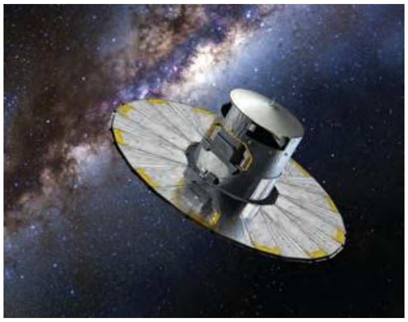

FIGURE 7.8.4 The GAIA mission, launched by the European Space Agency (ESA), aims to map the positions, distances, and velocities of over a billion stars in the Milky Way galaxy and beyond.

Collectively, these missions, combined with advancements in technology, have led to a more precise determination of the Hubble constant, advancing knowledge of the expansion of the universe.

SC 3 CHECK YOUR UNDERSTANDING

Explain how the observation of redshifted galaxies supports the big bang theory.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1 Outline the key observation made by Hubble that led to the conclusion that the universe is expanding.

2 Apply Hubble's Law to calculate the velocity of a galaxy 100 million light years away, given the Hubble constant can be rounded to 67 km/s/Mpc.

3 Apply Hubble's observations to describe how the universe's expansion supports the idea of a singular beginning (the big bang theory).

4 Compare the implications of Hubble's observations with those of the steady state theory regarding the expansion of the universe.

7.9 The life cycle of stars

Lesson overview

Consider the journey of stars as they evolve over time. Stars, those twinkling celestial objects in the night sky, have fascinating life stories. Just like humans, stars go through different stages in their lives, each with unique characteristics.

Over time, stars change. Some, like red giants, expand and cool as they run out of fuel, while others burn bright and fast. Supernovae, incredibly powerful explosions, mark the end of massive stars. What remains can become a white dwarf, neutron star, or even collapse into a mysterious entity called a black hole.

In this lesson, you will learn about the life cycle of stars, from their birth in nebulae to their dazzling lives as main sequence stars, and their transformations into giants, and more.

NGC 3324 lies about 7500 light years from Earth. Image obtained by the Near-Infrared Camera (NIRCam).

Learning intention

To understand the life cycles of stars

Success criteria

SC 1: I can describe the key stages in the life cycle of a star.

SC 2: I can describe and compare different types of stars including white dwarf, red giant, blue giant and neutron star.

SC 3: I can explain the formation and characteristics of a black hole.

SC 1 I can describe the key stages in the life cycle of a star

Stars have captivating life stories filled with dramatic transformations. Understanding the key stages in a star's life cycle involves exploring the processes and forces that shape its formation and development.

Formation of a star

Stars begin their journey as colossal clouds of gas and dust called **nebulae** (figure 7.9.1). Gravity's gentle tug starts the process of collapse, as particles within the nebulae come closer together. This gradual gathering of material leads to the formation of a **protostar** – a baby star in its infancy.

Main sequence

As the protostar continues to accumulate matter, it heats up. The tremendous pressure and temperature at its core initiate nuclear fusion – a process where hydrogen atoms combine to form helium, releasing an enormous amount of energy in the form of light and heat. This phase is known as the main sequence, characterised by a star's stable state. Gravity pulls inward and the energy from fusion pushes outward, maintaining equilibrium.

Evolution and end stage

Depending on a star's mass, it takes a distinct path in its evolution. Smaller stars like the Sun will gradually swell into **red giants** as their hydrogen fuel depletes. The balance between gravity's pull and the pressure from fusion-generated energy shifts, leading to a star's expansion. When all of the fuel is used, a red giant collapses into a white dwarf. This white dwarf, a dense compact core of the former star, is left to radiate energy as it cools.

KEY TERMS

nebula a cloud of gas found in the empty space between stars; birthplace of new stars

protostar a collapsing cloud of gas that will eventually become a star

red giant a star produced when the core of a sun-sized star runs of hydrogen

FIGURE 7.9.1 James Webb Space Telescope (JWST) image of the open star cluster NGC 3324 in the Carina Nebula. At top is part of a gigantic gaseous cavity where extremely massive hot young stars are forming.

KEY TERM

neutron star remnant of a supernova, consisting entirely of neutrons

Massive stars, on the other hand, experience more spectacular endings. When they exhaust their nuclear fuel, gravity triumphs over pressure, causing a violent explosion called a supernova. This explosive event scatters heavy elements into space and can create **neutron stars** or even black holes, where gravity is so intense that nothing – not even light – can escape.

Figure 7.9.2 illustrates how the life cycle of a star takes different paths depending on the initial mass.

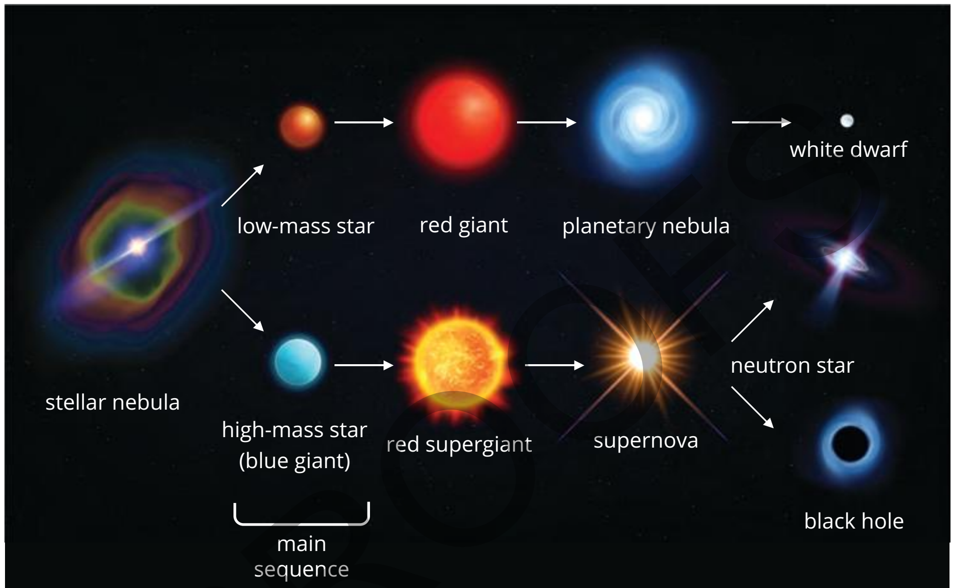

FIGURE 7.9.2 Illustration of the life cycle of a star showing different paths, depending on the initial mass of the star

SC 1 CHECK YOUR UNDERSTANDING

Describe the processes that enable a nebula to form a main-sequence star.

SC 2 I can describe and compare different types of stars including white dwarf, red giant, blue giant and neutron star

Life cycles of high-mass and low-mass stars

Stars transform from one type to another across their life. The type of stars they will transform into at the end of their life cycle, depends on their mass, as shown in Figure 7.9.3.

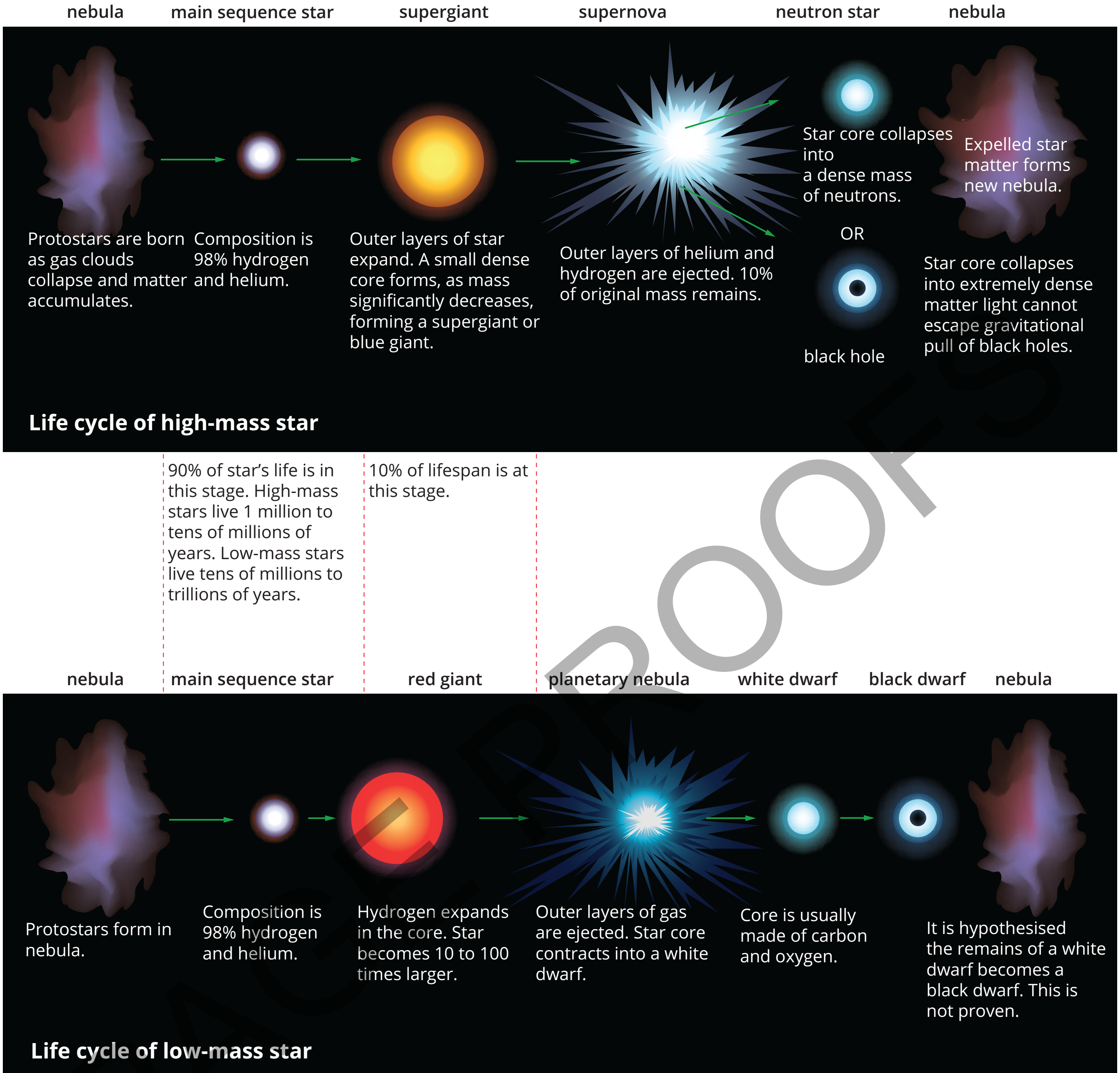

FIGURE 7.9.3 Stars follow different lifecycles depending on their initial mass

Types of stars

Stars exhibit a fascinating array of properties that offer insight into their nature and life cycles. When comparing stars like white dwarfs, red giants, blue giants and neutron stars, several key properties stand out: mass, temperature and composition (Table 7.9.1).

TABLE 7.9.1 The properties of stars as they progress through different stages of their life

Stage	Mass	Temperature	Composition
main sequence star	varies from 0.1 to 10 times the mass of the Sun	smaller stars: ~5500°C larger stars: higher temperatures.	primarily hydrogen, undergoing nuclear fusion to form helium
red giants	10 to 100 times the size of their main sequence counterpart	cooler than main sequence stars: 2500°C to 4000°C	heavier elements produced in earlier stages enrich their outer layers
blue giants	often tens of times the mass of the sun, relatively short-lived	surface temperatures exceed 10,000°c, much hotter than others	primarily hydrogen, actively fusing hydrogen into helium
white dwarfs	comparable to the sun in mass, but much smaller (size of Earth)	cooling state, temperature ranges from 5000°C to 30 000°C	primarily carbon and oxygen, remnants of earlier stages
neutron stars	masses larger than the Sun compressed into very small spheres	extremely hot, temperatures can exceed 1 million °C	primarily neutrons, formed from supernova remnants of massive stars

The Sun

The Sun is a low-mass main sequence star. It will stay like this for another 5 billion years, before it enlarges to become a red giant, engulfing the inner solar system. When all its fuel is used, the Sun will collapse and become a white dwarf (Figure 7.9.4).

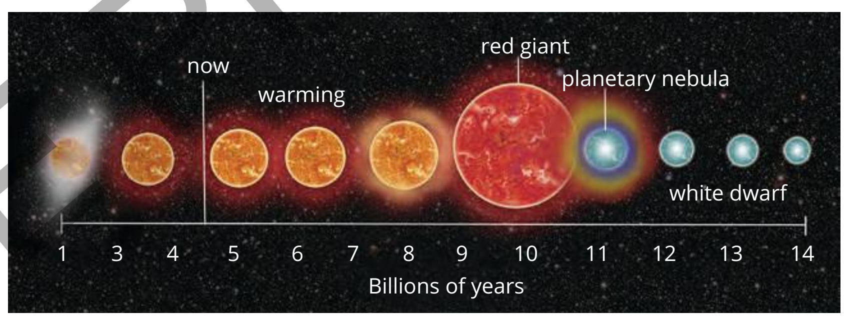

FIGURE 7.9.4 The life cycle of the Sun, a low-mass main sequence star

SC 2 CHECK YOUR UNDERSTANDING

Compare the life cycles of a neutron star and a white dwarf, focusing on their formation and end stages.

SC 3 I can explain the formation and characteristics of a black hole

KEY TERM

black hole a collapsed star so massive that not even light can escape from its gravitational field; also known as a singularity

Prepare to journey into the realm of cosmic mysteries while exploring **black holes**. A black hole is an incredibly dense region in space where the gravitational pull is so intense that nothing, not even light, can escape its grasp. To understand the formation and unique properties of black holes, it is helpful to connect them to the stages and processes previously discussed.

Formation of a black hole

Black holes are formed from the remnants of massive stars that undergo a dramatic process called a supernova. When a high-mass star exhausts its nuclear fuel, gravity causes its core to collapse inwards. The core can collapse to an object of huge density, the black hole. The black hole is surrounded by an event horizon—the boundary beyond which escape of anything, including light, is impossible because the pull of gravity is so strong.

Stellar evolution

Black holes signify the end of massive star evolution. Their life cycle involves stages like main sequence, red supergiant and supernova before collapsing into a black hole.

Gravity's triumph

The force that created main sequence stars also gives rise to black holes, although in a dramatically different manner. It is gravity that maintains the stability of stars during their life, and it can cause their collapse into a black hole at the end of their lives.

Black holes and singularities

Singularities can be defined as points where there is a breakdown in **spacetime**. They are a theoretical concept based on predictions from Einstein's general theory of relativity. At the centre of a black hole is a singularity, but singularities remain a subject of mathematical and scientific exploration.

Unique characteristics and conundrums

Black holes are interesting due to their exceptional properties, but they have also sparked intriguing debates in the scientific community. One of the most perplexing aspects is the concept of Hawking radiation, theorised by physicist Stephen Hawking. This phenomenon suggests that black holes might emit a faint form of radiation and eventually evaporate, posing a challenge to the traditional idea that nothing can escape a black hole's grasp.

Additionally, the information loss debate questions whether information that falls into a black hole is truly lost forever, defying fundamental principles of **quantum mechanics**.

Examples of black holes

Cygnus X-1

An X-ray binary star system containing a black hole with a mass about 15 times that of the Sun. This system is made up of a normal star and a collapsed star orbiting around each other, which emit X-rays (Figure 7.9.5).

KEY TERMS

spacetime a mathematical model that combines the three dimensions of space and the dimension of time

quantum mechanics a branch of science that explores the motion and interaction of subatomic particles, including the ideas that energy exists in small 'packets' and extremely small particles can display the characteristics of particles and waves

Scifile

Black holes

When a massive star collapses under its own gravity, it can form a black hole, an object with gravity so strong that not even light can escape it. Astronomers cannot observe black holes directly due to the lack of light. Therefore, they observe them indirectly by studying the effect that the increased gravity has on surrounding matter, such as the orbits of other stars.

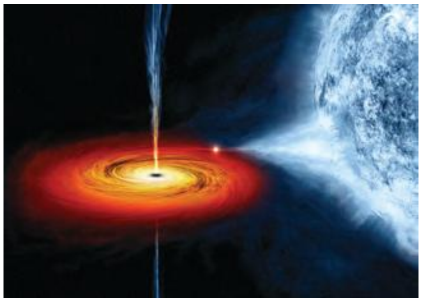

FIGURE 7.9.5 This illustration depicts what astronomers think is happening within the Cygnus X-1 system.

Sagittarius A*

A **supermassive black hole** at the centre of the Milky Way galaxy, with a mass equivalent to about 4 million Suns (Figure 7.8.6). The black hole lies 26 000 light years away from Earth. Despite the black hole itself being completely dark, the image shows its shadow surrounded by a ring of glowing gas warped by the hole's own gravity.

KEY TERM

supermassive black hole a black hole millions or billions of times the mass of the Sun found at the centre of a galaxy

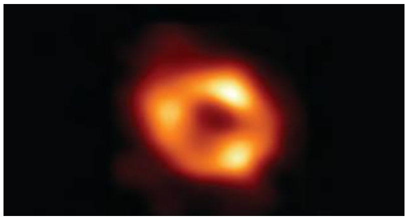

FIGURE 7.9.6 Event Horizon Telescope (EHT) collaboration image of Sagittarius A*, the supermassive black hole at the centre of the Milky Way. Image taken using 2017 observations from the Event Horizon Telescope (EHT), a global network of radio telescopes.

V404 Cygni

This is a binary star system containing a black hole located about 7800 light-years away from Earth. A binary star system is one where there are two stars orbiting around a central point of mass. V404 Cygni gained attention in 2015 when it became one of the brightest sources of X-ray radiation due to its high activity. The black hole in this system has a mass estimated to be about nine times that of the Sun (Figure 7.8.7).

FIGURE 7.9.7 Composite X-ray (light blue) and optical image of rings around a black hole in V404 Cygni. In 2015, X-ray flares were detected from the black hole producing high energy rings known as light echoes. The light echoes were created when light reflected off dust clouds between V404 Cygni and Earth, forming the concentric rings.

M87's Supermassive Black Hole (Messier 87)

This supermassive black hole lies at the heart of the giant elliptical galaxy M87, located in the Virgo galaxy cluster. In 2019, the Event Horizon Telescope captured the first-ever image of this black hole's event horizon, providing visual confirmation of its existence. The black hole in M87 has a mass equivalent to about 6.5 billion Suns, making it one of the most massive known black holes (Figure 7.8.8).

FIGURE 7.9.8 This is the first direct visual evidence of the supermassive black hole in the centre of the galaxy Messier 87 and its shadow. The shadow of a black hole is the closest it is possible to come to an image of the black hole itself, as it is a completely dark object from which light cannot escape.

SC 3 CHECK YOUR UNDERSTANDING

Define the term black hole.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1 Outline how a black hole forms.

2 Explain how a red giant differs from a blue giant.

3 Consider the life cycle of a star.

  a Describe the characteristics of a star in its main sequence stage.

  b Explain the equilibrium of forces that exist for a star in their main sequence.

4 Describe what happens to a star like the Sun after it exhausts its hydrogen fuel.

5 Compare a black hole to a neutron star in terms of their formation and characteristics.

7.10 Modelling the formation of a neutron star

Learning intention

To be able to construct appropriate representations to process data and information

Success criteria

SC 1: I can use measurements to calculate the volume and density of a neutron star model.

SC 2: I can analyse how the volume, mass and density changes as the model collapses.

SC 3: I can evaluate the effectiveness of a model that represents a collapsing star.

Introduction

Neutron stars are formed by the collapse of the core of a massive star after a supernova (Figure 7.9.1). Neutron stars are extremely dense, with one to two times the mass of the Sun being formed into an object the size of a small city. That's a lot of mass in a very small space. With this high density, even the properties of atoms are changed, with electrons and protons combining to form neutrons, hence the name neutron star. All the space within atoms in the star has basically been filled up as the subatomic particles are forced together due to the immense power of gravity.

If the star that is collapsing has enough mass, a black hole will be formed instead of a neutron star.

In this practical investigation you will use a balloon to model the collapse of a star as it forms a neutron star.

Background

Neutron stars are formed because of the collapse of stars that have a mass of 10 times or more the mass of the Sun (Figure 7.10.1). The Sun will form a white dwarf, as the effect of gravity will not be strong enough to create a neutron star, or a black hole.

This model uses an inflated balloon to represent a star during its stable state, or main sequence as it can be described. Air is removed to represent the collapsing of the star.

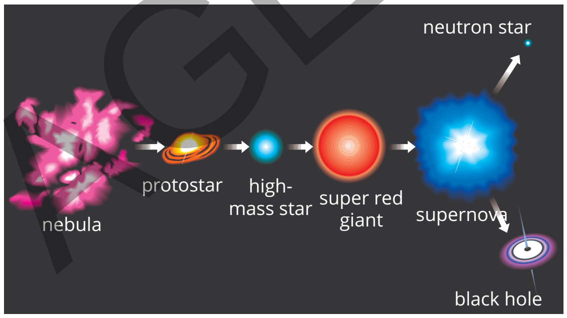

FIGURE 7.10.1 A neutron star is produced at the end of a life cycle of a large star

Aim

To model the change in density that occurs when a star collapses to form a neutron star

Materials

- 2–3 m of aluminium foil
- round balloon
- tape
- electronic balance
- metre rule
- pin

Method

1 Inflate the balloon to a diameter of about 15 cm. Tie the balloon so it remains inflated.

2 Cover the outside of the balloon with aluminium foil. Leave no gaps. Use tape to fix the foil to the balloon if necessary. This model represents the original star.

3 Measure the diameter of the model with the ruler. Halve this measurement to get the radius, r. Record this measurement in your results table.

4 Measure the mass of the foil covered balloon in grams with the electronic balance. Record this in your table.

5 Prick the balloon with a pin so that it bursts. Crumple the foil into a very loose ball. This model represents the star as it starts to collapse. Repeat steps 3 and 4 for this loose ball of foil.

6 Crush the foil into the smallest ball possible. This model represents the neutron star. Repeat the measurements of mass and radius for this tightly packed star.

7 Calculate the volume and density of each model using these relationships:

For a sphere, volume $= \frac{4}{3} \times \pi \times r^2$

where

r is the radius of the balloon

π is 3.142

density $= \frac{\text{mass}}{\text{volume}}$

Results

Copy the table below into your workbook. Record your measurements and calculated results.

Model	Mass (g)	Radius (cm)	Volume (cm^3)	Density (g/cm^3)
original star				
collapsing star				
neutron star				

Conclusion

Discuss the changes (if any) in the following quantities as the ‘star’ collapses:

- mass
- volume
- density.

Evaluation

Evaluate how well the experiment models the collapsing of a star to form a neutron star.

7.11 Current understandings and futures for the universe

Learning intention

To understand the significance of recent cosmological observations and associated theories

Success criteria

SC 1: I can explain how evidence about the motion of stars suggests the existence of dark matter and dark energy.

SC 2: I can explain how gravitational waves can be described as a variation in spacetime which can provide new ways to observe the universe.

SC 3: I can describe examples of the contribution of Australian science to current understandings and possible futures of the universe.

Lesson overview

Did you know that scientists do not know what most of the universe is made of? There are very good reasons for *thinking* that most of the universe is dark matter and dark energy (that influence the behaviour of galaxies) and that these cosmic components hold the key to explaining the universe's dynamic nature. However, no one knows what they actually are!

What about the fabric of space and time itself? The recent discovery of gravitational waves – ripples in spacetime caused by massive cosmic events – offers new ways to observe the universe.

From cutting-edge observatories to groundbreaking research, Australian scientists have played a significant role in advancing cosmic understanding and the evolving story of the universe.

In this lesson, you will learn about how the motion of stars suggests that dark matter and dark energy exist, how gravitational waves offer new ways to observe the universe and examples of Australian science shaping understanding of the universe's current state and potential futures.

SC 1	I can explain how evidence about the motion of stars suggests the existence of dark matter and dark energy

In the vast expanse of the universe, mysteries lurk beyond what meets the eye. Among these puzzles are dark matter and dark energy—two cosmic components that challenge understanding of the cosmos.

The mystery of dark matter

Dark matter, a mysterious substance, is believed to make up about 27% of the universe's total mass-energy content. Unlike ordinary matter that emits light and interacts with electromagnetic forces, dark matter remains elusive, interacting only through gravity. Its presence was first hypothesised to explain the unexpected motion of stars within galaxies, as observed by astronomers like Vera Rubin.

Vera Rubin

Vera Rubin's (Figure 7.11.1) ground-breaking work in the 1970s played a pivotal role in uncovering the existence of dark matter. Her work centred on rotational motion of galaxies and observing stars' velocities at varying distances from the galactic centre. According to classical physics, stars should slow down as they move away from the centre due to weaker gravitational forces. However, Rubin's observations defied expectations – stars maintained high speeds at larger distances, indicating the presence of hidden mass, later named as dark matter.

While the nature of dark matter is still being explored by scientists, some proposed explanations include objects known as weakly interacting massive particles (WIMPs). Axions, another type of hypothetical particle, are also being considered as a potential part of the explanation of the current mystery of dark matter.

FIGURE 7.11.1 Vera Rubin, American astronomer

The puzzle of dark energy

Dark energy, accounting for roughly 68% of the universe's energy, presents an even more perplexing puzzle (Figure 7.11.2). In the late twentieth century astrophysicist Brian Schmidt and his team embarked on a journey to measure the universe's expansion rate using distant supernovae as markers. They found that the universe's expansion was not slowing down but accelerating. This unexpected result hinted at the existence of a repulsive force – dark energy – counteracting gravity's pull and driving the universe's expansion. The nature of dark energy remains one of the most significant unanswered questions in cosmology.

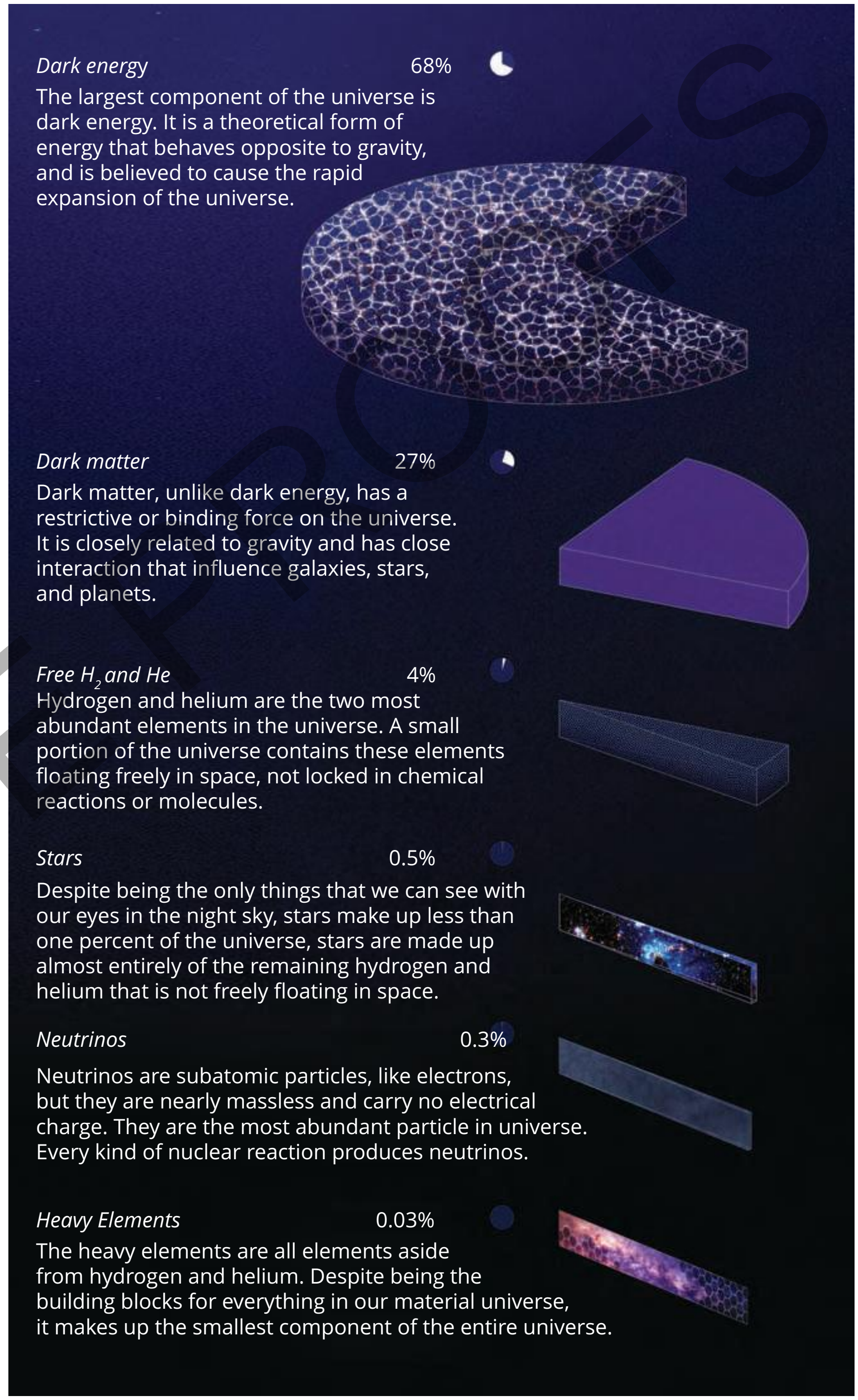

FIGURE 7.11.2 Infographic illustration depicting the contents of the universe. Data based on measurements by the European Space Agency and the Brookhaven National Observatory.

SC 1 CHECK YOUR UNDERSTANDING

Define dark matter.

SC 2 I can explain how gravitational waves can be described as a variation in spacetime which can provide new ways to observe the universe

Understanding gravitational waves

Gravitational waves are ripples in spacetime. These ripples in the 'fabric' of spacetime are created by violent and energetic processes in the universe, such as black hole or neutron star collisions (Figure 7.11.3). These waves were first predicted in 1916 by Albert Einstein. According to Einstein's theory of **general relativity**, massive objects like planets, stars and galaxies create distortions in spacetime due to their gravitational pull. When these objects move or interact, they send ripples – gravitational waves – moving through spacetime, similar to how dropping a stone creates ripples in a pond.

KEY TERMS

gravitational wave ripple in spacetime that travels at the speed of light, caused by major disruptions of spacetime

general relativity the theory that explains gravity as a curving or warping of space

FIGURE 7.11.3 Illustration of two black holes orbiting each other, emitting gravitational waves.

Detecting gravitational waves

Nearly a century after their prediction, the first historic detection of gravitational waves occurred on September 14, 2015, at the LIGO observatories in the United States of America (Figure 7.11.4). This detected event was the collision of two black holes, about 1.3 billion light-years away, creating a bigger black hole and releasing an enormous amount of energy. This monumental discovery not only confirmed Einstein's general theory of relativity but also unveiled a new era in observational astronomy. Further gravitational wave detections have since been made by LIGO and other observatories including Virgo in Italy and KAGRA in Japan.

FIGURE 7.11.4 Gravitational wave detection: perpendicular ultra-high vacuum tubes are used to detect gravitational waves. Gravitational waves will cause extremely small changes in the lasers (red and blue lines) moving through the tubes which can be detected.

New discoveries

Among the remarkable discoveries is the observation of gravitational waves from a binary neutron star merger on August 17, 2017 (Figure 7.11.5). This event, witnessed across the electromagnetic spectrum from radio to gamma rays, provided a wealth of information about the universe's expansion rate, neutron star properties and the origin of heavy elements.

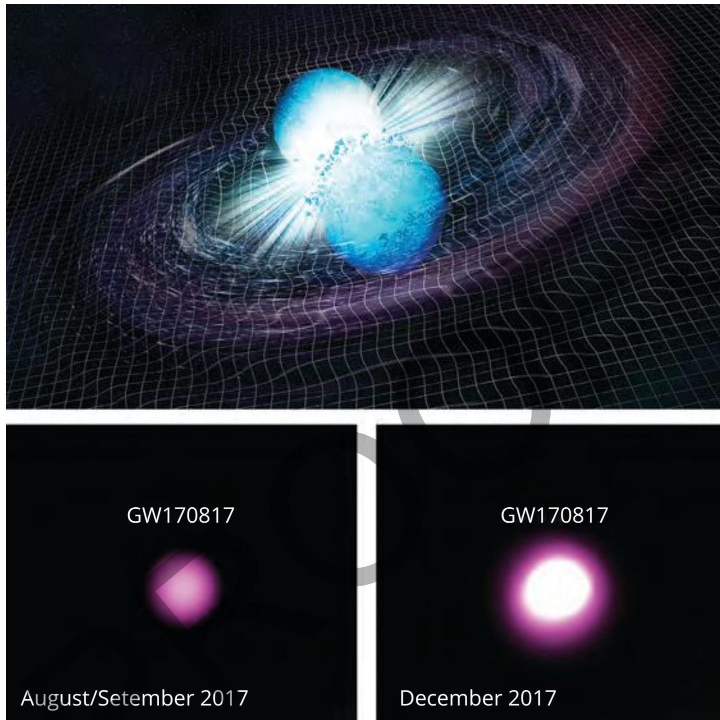

FIGURE 7.11.5 Neutron star merger. Two separate stars underwent supernova explosions, leaving behind two ultra-dense cores (neutron stars) that eventually collided (top). Gravitational wave radiation (observed by the LIGO and Virgo detectors) is shown rippling outwards from the merger. The result was a black hole.

SCIENCE IN SOCIETY

ARC Centre of Excellence for Gravitational Wave Discovery

The ARC Centre of Excellence for Gravitational Wave Discovery (OzGrav) is an Australian organisation that is dedicated to understanding the extreme physics of black holes. The organisation brings together the Australian Pulsar and gravitational wave communities from a variety of Australian universities, with the goal to contribute to and collaborate on research and development.

These projects include works on improving instrumentation for gravitational wave detectors, using detection algorithms and other research to discover new gravitational wave events as well as modelling and simulating results currently accessible to better understand the nature of gravity and extreme matter.

Gravitational waves offer a unique perspective on the universe and provide valuable information about extreme cosmic events.

Future frontiers

As of January 2022, LIGO had completed multiple observing runs, detecting 90 gravitational wave signals from different sources. Collaborations with Virgo and KAGRA continue to enhance the precision of these detections. Future gravitational wave observatories, such as LISA and Einstein Telescope, are planned, promising deeper insights into the universe.

Gravitational wave astronomy stands at the crossroads of scientific theories and technology, offering a new lens through which to view the universe's most energetic events. This growing field is expected to provide advances in cosmology (measuring fundamental parameters), astrophysics and nuclear physics (the origin of heavy elements) for many years to come.

SC 2 CHECK YOUR UNDERSTANDING

Explain how the detection of gravitational waves supports Einstein's general theory of relativity.

SC 3 I can describe examples of the contribution of Australian science to current understandings and possible futures of the universe

Australia is at the forefront of expanding knowledge of the universe, making significant contributions to the field of astronomy.

Australia's geographical advantages

Australia's unique geographical location provides advantages to its astronomers. It gives an unparalleled view of celestial phenomena that are not visible to observers in other parts of the world. Additionally, Australia's pristine skies offer optimal conditions for stargazing, with regions like the Murchison Radio-astronomy Observatory in Western Australia providing quiet zones free from radio interference. These radio-quiet zones enable the precise observation of cosmic radio emissions.

A history of contributions

Australian astronomers and scientists have made a range of significant contributions to astronomy and space science, including fields such as **radio astronomy** and satellite technology.

Some specific examples include:

The October 1945 observations of the Sun using a World War II radar (located at Collaroy Plateau) by scientists at the CSIR (later to become the CSIRO). This was the start of radio astronomy in Australia, a field in which Australia remains a world leader.

The 2df instrument at the Anglo-Australian Telescope in NSW (Figure 7.11.6) has measured spectra and redshifts for around 250 000 galaxies which contributed to a better estimate of mass density in the universe and measurement of the Hubble constant.

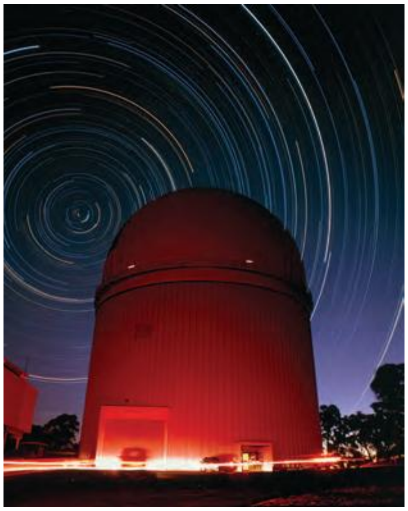

FIGURE 7.11.6 Time-lapse image of the Anglo-Australian Telescope

KEY TERM

pulsar a rotating neutron star that gives of pulses of radiation at regular intervals

The Parkes Radio Telescope has been a leading observatory for pulsar research since the late 1960s and has found over half of all currently-known **pulsars** (approximately 3000 total).

The Square Kilometre Array (SKA) telescope

Australia and South Africa are co-hosts of the Square Kilometre Array (SKA) telescope, a cutting-edge project that may revolutionise cosmic exploration. Australia will host the SKA's low-frequency aperture array. This array of antennas, spread across a vast area, will detect radio signals from distant celestial objects. The SKA will investigate the mysteries of cosmic phenomena, including the evolution of galaxies, the birth and death of stars and the nature of black holes. The amount of data that the SKA will produce is going to require new supercomputers and data processing techniques, and so will provide advances in many areas in addition to the astronomical breakthroughs.

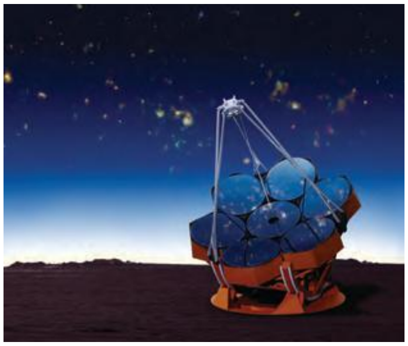

FIGURE 7.11.7 Artwork of the Giant Magellan Telescope (GMT), an optical telescope comprising seven primary mirrors, each with a diameter of 8.4 metres

The Giant Magellan Telescope

This telescope (Figure 7.11.7) being constructed in Chile will be significantly larger than any current telescope. Three of its instruments are being designed in Australia. These instruments include an optics system to reduce atmospheric blurring, and a spectrograph that will collect detailed spectra from the telescope's entire field of view at once.

The Very Large Telescope

Australia is a partner in the European Southern Observatory. Two Australian universities are designing the MAVIS instrument which will be used on the Very Large Telescope (VLT) in Chile, to explore stellar evolution and formation and many other astrophysical questions. The VLT is the second-most productive telescope in the world (behind the Hubble Telescope) in terms of the number of scientific papers relating to visible-light astronomy.

SC 3 CHECK YOUR UNDERSTANDING

Compare the contributions of Australian facilities like the Parkes Observatory and the Australian Square Kilometre Array telescope (SKA) to cosmological research.

Lesson review

Use these questions to check whether you have met the learning intention for this lesson.

1 Explain how the motion of stars in galaxies suggests the existence of dark matter.

2 Explain how the Parkes Observatory has contributed to understanding of the universe.

3 Apply your understanding to describe how Australian scientists have contributed to the study of dark energy.

4 Gravitational waves provide new ways to observe the universe.

a Explain what gravity waves are.

b Explain how gravitational waves are detected.

c Describe one astronomical event that could produce gravitational waves.

d Compare the information provided by gravitational waves with that provided by electromagnetic waves.

7 Big bang theory and the evolution of the universe

Topic summary

The key concepts included in this topic are:

- New scientific discoveries can disprove and develop scientific models of the time.
- Distances in space are vast and are measured in light years, which equates to approximately 9.46 trillion kilometres.
- Distances to celestial objects can be calculated using stellar parallax.
- The accepted model for the beginning of the universe is the big bang theory, where the universe began 14.6 billion years ago as an extremely hot, infinitely dense point and it has been expanding ever since.
- The cosmic microwave background radiation is permeating low frequency microwaves that are evidence for the Big Bang.
- Stars produce a specific light spectrum. These spectra can indicate the size, temperature and chemical makeup of the star. These spectra are analysed using spectrometers.
- Hubble's observations were that all galaxies are accelerating away from ours, with further galaxies accelerating faster. This indicates that the universe is expanding.
- Redshift is the lowering of frequency of waves produced by galaxies. This occurs as galaxies move away from Earth and is evidence of the expanding universe due to the Big Bang.
- Stars go through different life cycles based on their size. The two forces that control the life cycle of a star are gravity and nuclear fusion of material in the stars core.
- Australia plays a crucial role in Astronomical discoveries, most notably with new research on Gravity waves, black holes, dark energy and matter.

Review questions

The following questions will assess your success in achieving the learning intentions for this topic.

Remember

1 Describe the cosmic microwave background radiation.

2 State many kilometres there are in one light year.

Understand

3 Explain how the heliocentric model proposed by Copernicus differed from the geocentric model.

4 Explain how gravity waves provide new ways to observe the universe.

5 Explain how the volume, mass, and density of a neutron star change as it collapses.

Apply

6 Compare the life cycles of a low-mass star and a high-mass star.

7 Use Hubble's observations to explain the relationship between the distance of a galaxy and its velocity.

8 Use a visual representation to show the key events in the first few seconds after the Big Bang.

9 Design a simple experiment to measure the distance to a nearby tree using parallax.

Analyse

10 Stars and Galaxies are celestial objects that continue to be observed and researched.

- **a** Describe the process of galaxy formation after the Big Bang.
- **b** Describe the role gravity plays in the formation of galaxies.
- **c** Describe how the presence of chemical elements can be identified in a star's spectrum.
- **d** Explain how the study of star spectra has contributed to understanding stellar composition.

11 Stellar parallax and the redshift measurements are used by astronomers to map the position and movement of celestial objects.

- **a** How is stellar parallax used to measure the distance of objects from Earth?
- **b** What are the limitations of using stellar parallax for measuring distances?
- **c** Explain how the Doppler effect results in redshift.
- **d** Explain how redshift measurements can been used to map the expansion of the universe.

Extension

12 Australia is at the forefront of astronomical discoveries. Research why Australia is a suitable location for a number of astronomical activities and create a presentation on an organisation that is currently operating in the astronomical field in Australia. Describe what that organisation does and what projects they are working on.

Topic reflection

The learning intentions for this topic are given in each lesson and at the beginning of the topic. Consider how well you have achieved them. Note down any particular areas that you are confident in, and others where you are not so sure.

7 Glossary

astronomer scientist who studies the stars, planets and other celestial objects

astronomy the study of space

atomic nuclei the centre of an atom that contains protons and neutrons

Big Bang the sudden expansion of space from a point of dense energy which occurred at the start of the universe

big bang theory theory that states that the universe began as a very hot and infinitely dense point and has been expanding ever since

black hole a collapsed star so massive that not even light can escape from its gravitational field; also known as a singularity

blueshift the compression of light waves due to the motion of stars towards Earth; blueshift makes light appear bluer than it should

constellation a group of stars which form a recognisable pattern in the night sky

cosmic inflation the theory of the rapid expansion of the early universe

cosmic microwave background radiation the afterglow of the Big Bang; low-frequency radiation that fills the universe

dark matter a form of matter that does not interact with forms of electromagnetic radiation; the existence of dark matter has been inferred from the effect it seems to have on visible matter

Doppler effect the expansion or compression of waves due to the motion of the object making the waves

electromagnetic radiation electromagnetic waves consisting of oscillating electric and magnetic fields travelling at the speed of light

electron a subatomic particle with a negative electric charge, located around the nucleus of an atom

electrostatic force force experienced inside an electric field (also called electric force)

elliptical something that has the shape of an ellipse

galaxy a large group of stars attracted to one another by gravity

general relativity the theory that explains gravity as a curving or warping of space

geocentric model model of the universe with Earth at its centre

gravitational wave ripple in spacetime that travel at the speed of light, caused by major disruptions of spacetime

heliocentric model a model of the solar system with the Sun at the centre

Hubble constant the number that can be used to predict the velocity of a galaxy based on its distance from Earth; the exact value of the Hubble constant is yet to be confirmed

Hubble's law the law that states that a galaxy's velocity moving away from our galaxy is directly proportional to its distance from our galaxy

Kelvin a temperature scale based on absolute zero, which is the coldest possible temperature. Zero kelvin is equal to −273.15°C, and a change of one kelvin is the same as 1 degree Celsius

light energy that allows the human eye to see objects

light year the distance light travels in one year through space, approximately 9 500 000 000 000 km

lunar eclipse when Earth blocks sunlight from reaching the Moon

nebula a cloud of gas found in the empty space between stars; birthplace of new stars

neutron star remnant of a supernova, consisting entirely of neutrons

nuclear fusion the process in which smaller atoms are converted into larger atoms, also producing light and heat

parsec an astronomical unit of length equal to 3.26 light years

photon a particle without mass that carries a specific amount of energy representing a minute quantity of light or other electromagnetic radiation

protogalactic cloud a massive cloud of gas that can form into a galaxy

proton a subatomic particle with a positive electric charge, located in the nucleus of an atom

protostar a collapsing cloud of gas that will eventually become a star

pulsar a rotating neutron star that gives of pulses of radiation at regular intervals

quantum fluctuations temporary random changes in a quantum field which can be considered as 'virtual particles' which appear and then rapidly disappear

quantum mechanics a branch of science that explores the motion and interaction of subatomic particles, including the ideas that energy exists in small 'packets' and extremely small particles can display the characteristics of particles and waves

radio astronomy a field of astronomy that uses radio waves produced form objects in space to explore features of the universe

red giant a star produced when the core of a sun-sized star runs of hydrogen

redshift the stretching of light waves due to the motion of an object of away from the observer; redshift makes light from object the appear redder than it would if the object was stationary

solar eclipse when the Moon blocks sunlight from reaching Earth

solar system the Sun and all the planets, satellites, asteroids, comets and other bodies revolving around it

solar wind a stream of charged particles, including protons and electrons, from a star's outer atmosphere

spacetime a mathematical model that combines the three dimensions of space and the dimension of time

spectrograph an instrument for producing and recording a spectrum of light or other form of electromagnetic radiation

spectroscope a device that splits radiation into a spectrum, which can reveal the wavelengths of the various components of the radiation

spectroscopy the measurement and analysis of spectra produced by the interaction of electromagnetic radiation, such as light and radio waves, with matter

spectrum a band of colours produced by separation of the components of light

star a celestial body consisting of gas and undergoing nuclear reactions in the interior

steady state theory now discounted theory that the universe has always existed in the form that it is in today; also known as the 'infinite universe' theory

stellar parallax the apparent change in the position of a star throughout the year due to Earth's motion around the Sun

supermassive black hole a black hole millions or billions of times the mass of the Sun found at the centre of a galaxy

supernova a giant explosion that occurs when a star many times larger than the Sun runs out of nuclear fuel

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