CHAPTER 15 Is there life beyond our solar system?

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Observations from ALMA, the Atacama Large Millimeter/submillimeter Array, reveal extraordinarily fine detail that has never been seen before in the planet-forming disc around a young star.

**REMEMBER**

Before beginning this chapter, you should be able to:

- explain the arrangement and properties of the particles that make up an atom
- describe simple relationships between distance, velocity, acceleration and time
- recall that all objects with mass exert a gravitational force on other masses
- recognise that light is modelled as a wave as part of the electromagnetic spectrum
- recall that light is produced when electrons transition between energy levels in an atom.
KEY IDEAS

After completing this chapter, you should be able to:

- describe how light is modelled as a wave
- recognise the relationship between an object’s temperature and the light it emits
- use atomic absorption and light emission spectra to describe how astronomers identify chemicals in the universe
- understand how an object’s motion can cause a Doppler shift in its spectrum
- evaluate the methods used to search for extrasolar planets
- recognise the importance of liquid water in the search for life outside the solar system
- examine the use of the radio section of the spectrum in SETI.

The key is in the light

Understanding how life could exist in our universe is the ultimate quest for astronomy. The investigation of our solar system using spacecraft has revealed much new information and stimulated extensive debate on the origins of life on Earth and beyond. But how do we look outside our solar system? How can we discover the make-up and origin of other planets and stars when they are too far away to physically visit?

In earlier science studies, you may have discovered that visible light is just a small part of a much bigger electromagnetic spectrum. This spectrum identifies light through different wavelengths and frequencies, that is, light modelled as a wave. This model of light is the key to our understanding of the universe, so it is important to look at what the model tells us.

Dispersion: Producing colour from white light

White light can be separated into colours using a narrow beam of light and a glass triangular prism. This phenomenon is called dispersion. It was first analysed by Isaac Newton in 1666, although René Descartes had sought an explanation for rainbows in 1637 by working with a spherical glass flask filled with water.

As light enters a triangular glass prism, it is bent. It then travels through the prism to the other side where it is bent again.

The colours in white light separate as they enter the glass and separate even more when they leave. At each edge, violet light is deflected more than red light.
The colours spread as they enter the glass and travel on different paths through the triangular prism. They are spread even more as they leave the glass. Violet light is bent the most and red the least. The order of the colours, from the colour that bends least to the colour that bends most, is: red, orange, yellow, green, blue, indigo, violet. You would know these colours as the colours of a rainbow. They are also known as the visible spectrum.

A spectrum of colours is produced when white light is passed through a prism. The red light is deflected the least and each colour in the spectrum is deflected progressively more.

By analysing the different spectra of light from distant stars we can determine their temperature, chemical make-up and age. We can tell how fast they are moving and whether they have planets. This process of examining the spectra of light is called spectroscopy.
The solar spectrum

Isaac Newton (1642–1727) published his book *Opticks* in 1704. In the first volume he demonstrated that light from the Sun can be dispersed into its constituent colours. Other theories about why rainbows formed, why prisms of glass produced a spectrum of colours and why soap bubbles appeared coloured involved the prism, raindrop or bubble altering the light. However, as Newton demonstrated, the prism, raindrop or bubble simply disperse the light according to its colour (wavelength), revealing information about the Sun. Newton’s prisms showed the colour spectrum from the Sun to contain red, orange, yellow, green, blue, indigo and violet.
In 1802, William Wollaston (1766–1828) invented the spectroscope in an effort to explore the spectrum in more detail. He found the solar spectrum was not continuous but was crossed by a number of black lines. In 1814, Joseph von Fraunhofer (1787–1826) mapped the spectrum in much greater detail, finding 576 black lines. These have become known as Fraunhofer lines.

John Herschel (1792–1871), and W H Fox Talbot (1800–1877), a pioneer in photography, found that when chemical substances were heated in a flame and observed through a spectroscope, each chemical had a distinctive set of bright bands of colour forming its spectrum. This meant that scientists could identify chemicals simply by observing their spectra. Other scientists found that when sunlight is passed through gas before entering the spectroscope, it had extra black lines through its spectrum. This suggested that the black lines in the solar spectrum were due to light passing through gases in the Sun. These scientists had identified a method for determining the elements in stars.

The absorption spectrum for hydrogen

In 1859, Gustav Kirchhoff (1824–1887) with his friend Robert Bunsen (1811–1899) used Bunsen’s burner to burn elements and clearly describe the cause of these spectral lines. They found that:

- a continuous colour spectrum is produced by glowing solids or dense gaseous bodies like the Sun
- if a gas is between the light source and the spectroscope, light is absorbed from the continuous spectrum at wavelengths or colours characteristic of the chemical components of the gas
- a glowing gas produces bright lines on a dark background at wavelengths or colours characteristic of the chemical components of the gas.

One of the first successes with this new tool of astrophysics was the spectroscopic analysis of planetary nebulae by William Huggins (1824–1910). Working in London in 1864, he found that these nebulae produced the bright line spectra of glowing gas, showing that they were clouds of gas rather than groups of very distant stars (see table 15.1). Some of the nebulae documented by Herschel, however, showed that they were collections of stars, as they emitted continuous spectra interrupted by black lines. Huggins’s investigations also provided very convincing evidence that the stars in the sky really are distant suns.

<table>
<thead>
<tr>
<th>Type of spectrum</th>
<th>Generally produced by:</th>
<th>Celestially produced by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous</td>
<td>Hot solids, liquids, gases under pressure</td>
<td>Galaxies, inner layers of stars</td>
</tr>
<tr>
<td>Emission</td>
<td>Incandescent low-density gases</td>
<td>Emission nebulae, quasars</td>
</tr>
<tr>
<td>Absorption</td>
<td>Cool gases in front of continuous spectrum</td>
<td>The atmospheres of stars</td>
</tr>
</tbody>
</table>

Helium

In 1868, Joseph Norman Lockyer (1836–1920), Used the spectroscope to detect some Fraunhofer lines in the solar spectrum that did not correspond with any known element on Earth. He predicted that there must be an as yet undiscovered element in the Sun and called it helium, after the Greek helios, meaning Sun. William Ramsay (1852–1916) confirmed this in 1895, when he isolated the gas helium in the laboratory. Although the second most common element in the universe, helium is rare on Earth because it has so little mass that, even at normal temperatures, it has sufficient energy to escape the atmosphere, a property that makes it useful in blimps and party balloons. Helium is also extremely unreactive with other chemicals so it forms few compounds, unlike hydrogen which is even less massive but occurs in many compounds on Earth, including water and organic compounds.
Composition of the Sun

Early in the twentieth century, no one understood what could power the Sun. Chemical reactions did not produce sufficient energy. Scientists considered that maybe it was some form of nuclear reaction that could release some of the Sun’s mass in the form of energy, as Einstein described in 1905 in the equation $E = mc^2$. However, scientists thought the Sun was made largely of iron, the most stable nucleus of all. This conclusion was based on measurements of tidal effects on the Earth that showed that the Earth was mostly made of iron, and on analysis of meteorites from space that showed that they too were composed largely of iron.

Spectroscopic results seemed to confirm the iron content of the Sun. However, reading spectrographs of the Sun is not easy as many spectra of different elements overlap. In 1925, a young astrophysicist named Cecilia Payne (1900–1979) wrote one of the most highly regarded PhD theses in astronomy on the spectra of stars. In fact, what she did not write, under the advice of her supervisor, was just as interesting as what she did write. She interpreted the spectra as showing that the Sun was mostly hydrogen, not iron at all. The scientists had all been reading the Fraunhofer lines incorrectly, which is easy to do when the lines of so many elements overlap. It was not long before the scientific community believed that hydrogen was the main element found in the Sun. Hydrogen not only fitted the spectra, it explained the Sun’s energy, unlike iron.

**SAMPLE PROBLEM 15.1**

Describe how astronomers can determine the elements that are present in the Sun.

**Solution:**

Astronomers observe the Sun’s light through a spectroscope. The solar spectrum contains absorption lines that are characteristic of the elements found in the Sun’s atmosphere.

**REVISION QUESTION 15.1**

The Sun is a hot ball of gas. Explain why it does not produce an emission spectrum.

Explaining the light of hot objects

It is important to understand why objects emit light. Think about the sources of light you come into contact with everyday. Can you explain why they make light?

Electromagnetic radiation is produced when charged particles accelerate. When an object gets hot, the particles that make up the object gain kinetic energy; that is, they move about. When an object gets really hot, charged particles such as electrons start to move so much they can oscillate very quickly and sometimes collide with nuclei or other charged particles around them. Thus we have charged particles experiencing acceleration, and so we have light! The hotter the object, the more kinetic energy and the more energetic movement of the charge, resulting in higher energy light emissions. This is how an **incandescent** source emits light.
a) Incandescent light sources use heat (through electrical resistance) to create light. b) Fluorescent light sources use electrical energy to stimulate transitions of electrons within the energy levels of an atom. Both involve the excitement of charged particles within a material.

Heat and temperature

If you have ever heated a piece of metal in a fire, you would know that the metal glows as it heats up. As it gets even hotter it gets brighter, but something else also happens: it changes colour.

When iron such as this iron pipe is heated, the hottest section is the brightest and is also yellow in colour. The cooler sections are less bright and red.
The changing brightness and colour are both explained by our understanding of the kinetic motion of charged particles and their interactions. All incandescent sources produce a **continuous spectrum**. This is because the interactions and collisions between charged particles are random. This means any size collision is possible and can occur, from a very small glancing bump to a head-on smash! The size of the acceleration (or deceleration) results in different types of electromagnetic emissions or wavelengths produced. Cooler objects tend to be red in colour as red wavelengths represent lower energy emissions. As objects get hotter, their charged particles experience more frequent, higher energy collisions resulting in higher energy emission and the colours we see move toward yellow, white and then to blue. The intensity or brightness of light increases because there are many more collisions as the object gets hotter, which in turn means more electromagnetic radiation is emitted.

The relationship between heat and the electromagnetic emission of an object is often represented as a blackbody curve. This curve enables us to examine the spread of an object's spectrum as well as how intense (bright) different parts of the spectrum are.

![Blackbody Curve](image)

The blackbody curve shows that as temperature increases, the shape of the curve tends to ultraviolet and gets more peaked. You can see how the wavelength of maximum brightness moves up and toward the purple end of the visible spectrum. Remember all the other parts of the spectrum are still being produced, this is why the curve slopes down on both sides.

**The temperature of stars**

In the 1920s, astronomers like Cecilia Payne determined how stellar temperatures related to their spectrum. The spectrum of a star is not of equal intensity for all colours. They found that hot stars radiate more energy at short wavelengths than cooler stars. Short wavelengths correspond to the blue end of the visible spectrum, while longer wavelengths correspond to the red end of the spectrum.

We are all familiar with this relationship between colour and temperature. In the school laboratory you have probably used a Bunsen burner. These burners have two settings, one a cool, yellow flame and the other a hot, blue flame. The flames emit more than just the colours we see. If you hold your hand in the air about 30 cm from the flame you can feel heat, indicating that the flame is emitting infra-red radiation that we can feel but cannot see.

Astronomers generally like to use the Kelvin temperature scale. Every degree in temperature difference is the same as the Celsius scale, but 0 K is set at the coldest possible temperature, which corresponds to −273.15°C. This means that 0°C is 273.15 K.

On a clear night it is possible to see some variation in the colour of stars, but the rods in the retinas of our eyes that are responsible for distinguishing colours are not very sensitive to dim light. A photograph will show the
colours much more clearly. We notice that some stars are red and some are white or blue. The Sun is a yellow star, indicating that it is neither particularly hot nor cool in the range of star temperatures. The colour of a star indicates the area of the spectrum of the star that is most intense. Some stars are so hot that they emit most of their radiation at very short wavelengths of ultraviolet light, making them invisible from Earth. They must be observed using UV telescopes in orbit because the atmosphere absorbs most UV radiation, preventing it from reaching ground-based telescopes.

The temperature of a star’s outer layers determines its colour. The core of the star is much hotter than the outer layers, due to fusion reactions and gravitational energy.

![Emission at different wavelengths for objects of different temperatures](image)

A portion of the night sky including the constellation of Orion. Four of the brightest stars in the sky can be seen. Notice the different colours: Betelgeuse is a red supergiant, Rigel is a blue supergiant, Sirius and Procyon are white main sequence stars.
SAMPLE PROBLEM 15.2

Describe what happens to the wavelength and intensity of light from a star as its temperature increases.

Solution:
The wavelength of the light emitted becomes shorter and the intensity increases.

REVISION QUESTION 15.2

Describe how astronomers can determine the surface temperature of a star.

Spectral type

When the spectra of stars were first observed in detail in the nineteenth century, it seemed that the spectrum of every star was different. Gradually, some sense was made of the multitude of lines that crossed the spectra and stars were classified into spectral types. The system developed by Annie Jump Cannon (1863–1941) has been used since 1910. It classes stars as O, B, A, F, G, K or M according to the relative intensity of various absorption lines in their spectra. For example, for type A stars the lines of the hydrogen spectrum are very clear. The spectral classes are arranged in order of temperature from O, the hottest with a spectrum peaking in the ultraviolet, to M, the coolest with a spectrum peaking in the infra-red. The Sun is a type G star and these are yellow. A full description of the spectral classes is given in table 15.2.

Table 15.2 Spectral classifications and their corresponding features. Note that in astronomy the term ‘metal’ refers to any element other than hydrogen or helium

<table>
<thead>
<tr>
<th>Spectral class</th>
<th>Surface temperature (K)</th>
<th>Colour</th>
<th>Spectral features</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>28 000–50 000</td>
<td>Blue</td>
<td>Ionised helium lines Strong UV component</td>
</tr>
<tr>
<td>B</td>
<td>10 000–28 000</td>
<td>Blue</td>
<td>Neutral helium lines</td>
</tr>
<tr>
<td>A</td>
<td>7500–10 000</td>
<td>Blue-white</td>
<td>Strong hydrogen lines Ionised metal lines</td>
</tr>
<tr>
<td>F</td>
<td>6000–7500</td>
<td>White</td>
<td>Strong metal lines Weak hydrogen lines</td>
</tr>
<tr>
<td>G</td>
<td>5000–6000</td>
<td>Yellow</td>
<td>Ionised calcium lines Metal lines present</td>
</tr>
<tr>
<td>K</td>
<td>3500–5000</td>
<td>Orange</td>
<td>Neutral metals dominate Strong molecular lines</td>
</tr>
<tr>
<td>M</td>
<td>2500–3500</td>
<td>Red</td>
<td>Molecular lines dominate Strong neutral metals</td>
</tr>
</tbody>
</table>

REVISION QUESTION 15.3

The Sun is a yellow star. Estimate its surface temperature and give its spectral class.

Using the properties of light, astronomers are able to investigate the temperature and chemical make-up of stars. There is one more important tool that is used to investigate the universe. This relates to the way we model light as a wave.
Waves — energy transfer without matter transfer

A wave is a disturbance that travels through a medium from the source to the detector without any movement of matter. Waves therefore transfer energy without any net movement of particles. Periodic waves are disturbances that repeat themselves at regular intervals. Periodic waves propagate by the disturbance in part of a medium being passed on to its neighbours. In this way the disturbance travels, but the medium stays where it is.

### TABLE 15.3 Some examples of waves

<table>
<thead>
<tr>
<th>Wave</th>
<th>Source</th>
<th>Medium</th>
<th>Detector</th>
<th>Disturbance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound</td>
<td>Push/pull of a loud-speaker</td>
<td>Air</td>
<td>Ear</td>
<td>Increase and decrease in air pressure</td>
</tr>
<tr>
<td>Rope</td>
<td>Upward flick of hand</td>
<td>Rope</td>
<td>Person at other end</td>
<td>Section of rope is lifted and falls back</td>
</tr>
<tr>
<td>Stretched spring</td>
<td>Push of hand</td>
<td>Coils in the spring</td>
<td>Person at other end</td>
<td>Bunching of coils</td>
</tr>
<tr>
<td>Water</td>
<td>Dropped stone</td>
<td>Water</td>
<td>Bobbing cork</td>
<td>Water surface is lifted and drops back</td>
</tr>
</tbody>
</table>

Looking at the examples in the table, two different types of waves can be identified. For the pulse on the rope and the ripples on the water surface, the disturbance is at right angles to the direction the wave is travelling. These types of waves are called transverse waves.

In the examples of the sound wave travelling through air and the compression moving along the spring, the disturbance is parallel to the direction the wave is travelling. These types of waves are called longitudinal waves.

**Properties of waves**

The frequency of a periodic wave is the number of times that it repeats itself every second. Frequency is measured in hertz (Hz) and \(1 \text{ Hz} = 1 \text{ s}^{-1}\). Frequency can be represented by the symbol \(f\).

The period of a periodic wave is the time it takes a source to produce a complete wave. This is the same as the time taken for a complete wave to pass a given point. The period is measured in seconds and is represented by the symbol \(T\).
The period of a wave is the reciprocal of its frequency. For example, if five complete waves pass every second, that is, \( f = 5.0 \text{ Hz} \), then the period (the time for one complete wavelength to pass) is \( \frac{1}{5.0} = 0.2 \text{ seconds} \). In other words, \( f = \frac{1}{T} \). It follows that \( T = \frac{1}{f} \).

The **amplitude** of a wave is the size of the maximum disturbance of the medium from its normal state. The units of amplitude vary from wave to wave. For example, in sound waves the amplitude is measured in units of pressure, while the amplitude of a water wave would normally be measured in centimetres or metres.

The **wavelength** is the distance between successive corresponding parts of a periodic wave. The wavelength is also the distance travelled by a periodic wave during a time interval of one period. For transverse periodic waves, the wavelength is equal to the distance between successive crests (or troughs). For longitudinal periodic waves, the wavelength is equal to the distance between two successive compressions (regions where particles are closest together) or rarefactions (regions where particles are furthest apart). Wavelength is represented by the symbol \( \lambda \) (lambda).

Transverse periodic waves in a piece of string

The speed, \( v \), of a periodic wave is related to the frequency and period. In a time interval of one period, \( T \), the wave travels a distance of one wavelength, \( \lambda \). Thus:

\[
\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{\lambda}{T} = \frac{\lambda}{\frac{1}{f}} = f \lambda
\]

This relationship \( v = \frac{\lambda}{T} \) is sometimes referred to as the universal wave equation.

The frequency of a periodic wave is determined by the source of the wave. The speed of a periodic wave is determined by the medium through which it is travelling. Because the wavelength is a measure of how far a wave travels during a period, if it can’t be measured, it can be calculated using the formula:

\[
\lambda = \frac{v}{f}
\]

**Speed of light**

The gap we experience between seeing lightning and hearing thunder shows that sound travels relatively slowly. Light seems to travel so fast that to our experience its speed seems infinite; that is, we seem to observe events at the instant they happen.

Galileo Galilei (1564–1642) was not convinced of this. He attempted to determine the speed of light by measuring the time delay between the flash of
his lamp to an assistant on a distant mountain and the return flash from his assistant’s lamp. No detectable delay was observed and Galileo concluded that the speed of light was very high. A longer distance was needed.

Olaus Roemer was a Danish astronomer born two years after Galileo’s death. He observed that the time between eclipses of Jupiter’s moons by Jupiter decreased as the Earth moved closer to Jupiter and increased as the Earth moved away. Roemer reasoned that this was because the distance the light travelled from Jupiter to Earth became greater as the Earth’s orbit took it further from Jupiter (see figure). Roemer used this time and the known diameter of the Earth’s orbit about the Sun to estimate the speed of light. The value he obtained was $2.7 \times 10^8$ m s$^{-1}$.

Eventually, in the nineteenth century, with stronger light sources and more precise timing devices, Galileo’s method could be revisited, but the assistant was replaced by a mirror. The values obtained then for the speed of light were about $3.0 \times 10^8$ m s$^{-1}$.

Early in the twentieth century, the American scientist Albert A Michelson (1852–1931) used a rapidly rotating eight-sided mirror. The light was reflected to a distant mirror about 35 kilometres away then reflected back to the rotating mirror. For some particular rotation rates, this light was reflected by one of the sides of the rotating mirror directly to the observer. The rotation rate was used to calculate the speed of light. The value Michelson obtained was $2.997\,96 \times 10^8$ m s$^{-1}$. He actually measured the distance of 35 km to an accuracy of 2.5 cm.

In 1973, a laser beam was used to measure the speed of light at $299\,792.4574 \pm 0.001$ km s$^{-1}$. In 1983, the value was set internationally at $299\,792.458$ km s$^{-1}$ and used to define the length of a metre. (We rounded it off to $300\,000$ km s$^{-1}$ for calculation purposes.)

Light from the source reflects off one of the sides of the rotating mirror towards a mirror 35 km away. The returning beam hits the rotating mirror. If one side of the mirror is in the right position, the light enters the eyepiece and can be seen by the observer. By measuring the speed of rotation when the beam enters the eyepiece, the speed of light can be calculated.
Frequency of light

The periodic wave model can be applied to light, with each colour corresponding to a particular frequency. Table 15.4 shows the value of the frequency and wavelength for the colours of the spectrum. In fact, the frequency and wavelength steadily change across the spectrum but the eye and brain divide up the spectrum into separate colours. The values shown are typical values only.

**Table 15.4 Frequency and wavelength of colours**

<table>
<thead>
<tr>
<th>Colour</th>
<th>Red</th>
<th>Orange</th>
<th>Yellow</th>
<th>Green</th>
<th>Blue</th>
<th>Violet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency ($\times 10^{12}$ hertz)</td>
<td>430</td>
<td>480</td>
<td>520</td>
<td>570</td>
<td>650</td>
<td>730</td>
</tr>
<tr>
<td>Wavelength (nanometres)</td>
<td>700</td>
<td>625</td>
<td>580</td>
<td>525</td>
<td>460</td>
<td>410</td>
</tr>
</tbody>
</table>

**SAMPLE PROBLEM 15.3**

When light with a frequency of $5.6 \times 10^{14}$ Hz travels through a vacuum, what is its:

a. period
b. wavelength (in nanometres)?

The speed of light in a vacuum is $3.0 \times 10^8$ m s$^{-1}$.

**Solution:**

(a) $T = \frac{1}{f} = \frac{1}{5.6 \times 10^{14}} = 1.8 \times 10^{-15}$ s

The period of the light is $1.8 \times 10^{-15}$ seconds.

(b) $\lambda = \frac{v}{f} = \frac{3.0 \times 10^8}{5.6 \times 10^{14}} = 5.4 \times 10^{-7}$ m

The wavelength of visible light is usually expressed in nanometres (nm).

1 nm = $1 \times 10^{-9}$ m

$\lambda = 5.4 \times 10^{7}$ nm

The wavelength of the light is 540 nanometres.
REVISION QUESTION 15.4

Find the frequency and period of light with a wavelength of 450 nm.

The frequency of a light ray is determined by the source (that is, what produces the light). The speed of the light is determined by the material the light is passing through. This means that, when light passes from air into water the frequency stays the same, the speed decreases and the wavelength must also decrease.

When you are under water and look around, the objects you see still have the same colour. This means that your eye is responding to the frequency of the light ray and not to its wavelength. The world would be a strange place if the eye’s response was the other way round.

This raises the question — what is actually waving? Towards the end of the nineteenth century, it was proposed by James Maxwell (a British scientist) and verified by Heinrich Hertz (a German physicist) that visible light is one form of electromagnetic radiation. Other forms of electromagnetic radiation, such as radio waves, infra-red, ultraviolet and X-rays, have different frequencies and wavelengths to which our eyes do not respond. Radio waves produced from an antenna, for example, have a wavelength in the range of hundreds of metres, whereas gamma rays have wavelengths in the range of millionths of a metre. However, all the different forms travel at the speed of light.

Forms of radiation and their place in the electromagnetic spectrum. The visible portion of the spectrum is shown enlarged in the upper part of the diagram.

The electromagnetic model of light has oscillating electric and magnetic fields at right angles to each other and also at right angles to the direction of the light (as shown in the diagram). This is a transverse wave model.

A result of light being modelled as a wave is that we can use wave properties to investigate the light from stars. One crucial property that we use to explore our universe is the Doppler effect.
The Doppler effect

On the surface of the Earth, when fast moving objects go by, the sound they make drops in pitch. You can hear this when trains, fire engines or racing cars speed past you. This is known as the Doppler effect, after Christian Doppler, who predicted its existence in 1842, before it had been observed. As a result of the Doppler effect, the pitch of the sounds that we hear depends on the motion of the sound source and the observer. For example, a siren that has a frequency of 500 Hz will have a frequency higher than 500 Hz when it is approaching you, and a pitch lower than 500 Hz when it is moving away from you.

Sound travels as a wave made up of a series of compressions and rarefactions. The distance between one compression and the next is the wavelength of the sound. In still air, a sound wave travels at a constant speed that is independent of the speed of the source. However, if the source is moving towards the listener, the distance between one compression and the next will be shorter than if the source is at rest, making the wavelength of the sound shorter. The number of compressions that the listener hears per second will be greater than if the source was at rest and this higher frequency will be heard as a higher pitch. Similarly, if the source is moving away from the listener, the motion of the source increases the distance between compressions. This results in a lower frequency and a lower pitch being heard.

Doppler realised that, as light behaved like a wave, it should also experience a Doppler effect. While with sound the frequency of the wave determines the pitch, with light the frequency determines the colour. The higher frequencies of light are associated with the blue and violet end of the spectrum and the lower frequencies correspond to the red end of the spectrum. In 1868, William Huggins (1824–1910) detected the red shift of light by noticing that the position of Fraunhofer spectral lines had shifted along the continuous spectrum. Huggins measured the red shift of Sirius, the brightest star in the sky, and found that it is moving away from us at about 32 km s⁻¹. Herschel had been able to measure the transverse (left to right, or up and down) velocities of nearby stars, but the Doppler method using spectroscopy enabled the radial (toward or away) velocity to be measured.
REMEMBER THIS

The visible spectrum of light contains red, orange, yellow, green, blue, indigo and violet. The spectrum continues into invisible forms of radiation, including infra-red at lower frequencies than red and ultraviolet at higher frequencies than violet.

A star with only tangential motion would not change its distance from the Earth. The radial component of its motion will move the star toward or away from Earth.

The search for exoplanets

So how can we use this understanding of light to detect life in our universe? Our quest starts with looking for other planets: extrasolar planets or exoplanets.
Kepler-444 is a recently discovered star with at least five Earth-size planets. The system is 11.2 billion years old.

The detection of extrasolar planets or exoplanets has long been heralded as a way to justify the likelihood that life is not unique to Earth. Since 1995, ground- and satellite-based surveys have detected many planets orbiting other suns. To date, over 1900 planets have been confirmed with more than 4000 candidates pending — none an Earth analogue. The planets that have been detected range considerably in orbits and size.

Finding exoplanets is very difficult. They are near impossible to observe directly due to the fact that they are tens of thousands of times fainter than the stars they orbit. The three restricting factors to direct observation are:

1. Planets do not make their own light; they reflect their star’s light.
2. The star they orbit is so bright the planet cannot be seen through the star’s glare.
3. They are very, very far away.

Very early on astronomers realised that directly observing exoplanets was unlikely to give results. Other methods of detecting needed to be considered using our understanding of how planetary systems behave. Astronomers used the fact that the gravity of planets orbiting their star would cause the star to wobble.

Why does a star wobble?

In our solar system, the planets orbit the Sun at different orbits and different rates. The reason they maintain their orbits is due to the gravitational force between the Sun and the planets. This force acts on both objects. This gravitational force means that a planet’s motion around a star pulls the star slightly from the centre of the system; as the planets rotate around the star, the star is pulled ever so slightly toward the planets.
The orbit of a planet about a star causes the star to wobble because both objects assert a gravitational force on each other.

The above diagram illustrates a single planetary system. This creates a very regular, simple wobble in the star. Our solar system, with its eight planets and many other orbiting bodies, has a much more complicated wobble. However, the shape and size of the wobble is a direct result of the many and varied orbits of bodies in our planetary system. Knowing this, we can use mathematical processes to breakdown a complicated wobble to infer the size and orbits of the bodies around a star.

Knowing that a star wobbles is only half the process; the biggest hurdle is detecting the wobble. Observing this wobble directly is very difficult. This process, known as astrometric measurement, attempts to identify the wobble of a star by measuring tiny variations in the star’s position over time. This process relies on very accurate instruments and to date no exoplanet has been identified using this method. This is not to say that planets cannot be detected this way. In the future, with very large telescopes like the Keck telescopes in Hawaii or proposed space projects such as NASA’s Space Interferometry Mission (SIM), exoplanets may be identified with this method.

Measuring radial velocity

As we have seen, when an object emitting waves is in motion, the Doppler effect causes a change in the detected frequency and wavelength. When a star wobbles due to a planetary system, we can observe the wobble as a red shift (as the star moves away from us) or a blue shift (as the star moves toward us) of the star’s light. Bigger shifts indicate larger movements of the star.

Variations in the wavelength of a star’s light over a period have enabled the identification of planetary systems. This form of exoplanet detection is known as the radial velocity method and is named due to the fact that to observe the change in wavelength the observer must be parallel to the motion, or the line of sight is along the radius connecting Earth to the star. The size and complexity of the Doppler shift can indicate the size of single or multiple planet orbits about a star.
Michel Mayor and Didier Queloz of the Geneva Observatory in Switzerland made the first exoplanet discovery in 1995 using the radial velocity method. They found a planet orbiting the star 51 Pegasi, 47.9 light-years from us in the constellation Pegasus. Since then, thousands of stars have been identified as having planetary systems.

Data from multiple RV readings of 51 Pegasi illustrated the telltale sine graph indicating a close orbiting body. With a period of 4.231 days and a mass of just less than half that of Jupiter, it was the first verified exoplanet to be found.

The speed at which a star wobbles can be determined by the shift in wavelength from a known (stationary) spectrum. The wave equation applied to light can be used to determine how fast an object is moving if we know the change in wavelength:

$$\frac{\Delta \lambda}{\lambda_0} = \frac{v}{c}$$

where $\Delta \lambda =$ change in wavelength,  
$\lambda_0 =$ stationary wavelength,  
$v =$ velocity of moving object  
$c =$ speed of light

The visible spectrum of hydrogen. The positions of the spectral lines are known to high precision, which enables astronomers to compare them to starlight to identify any shift in the spectrum.

Astronomers use the lines of the hydrogen spectrum to compare spectra from different stars. This is because hydrogen is the most common element in the universe and is the main constituent of stars. The hydrogen spectrum measured in a laboratory on Earth is compared to that observed from a star. The shift is measured and then the above relationship is used to determine the speed of the moving object.
SAMPLE PROBLEM 15.4

A star is observed to have a wavelength of $\lambda_{\text{H}} = 656.280\,\text{07 nm}$, the known $\lambda_{\text{H}}$ for a stationary source is $656.280\,\text{10 nm}$. Determine the radial velocity at which the star is moving relative to Earth.

Solution:

\[
\Delta \lambda = \lambda - \lambda_{\text{H}} = 656.280\,\text{07} - 656.280\,\text{10} \,\text{nm} = -0.00003\times10^{-9} \,\text{m}
\]

Rearrange for $v$:

\[
\frac{\Delta \lambda}{\lambda_{\text{H}}} = \frac{v}{c}
\]

\[
v = \frac{\Delta \lambda c}{\lambda_{\text{H}}} = \frac{-0.00003\times10^{-9} \times 3.0 \times 10^{8}}{656.2810\times10^{-9}} = -13.7 \,\text{m/s}
\]

The negative indicates the shift was to a shorter wavelength, that is, a blue shift, suggesting the star is moving toward Earth.

The beauty of the radial velocity method is that the shift in the spectrum of a star due to its wobble is the same no matter how far away that star is from us. However, the changes in wavelength are very small because the movements due to planetary systems are small. The Sun moves at about $12.5 \,\text{m s}^{-1}$ around the solar system’s centre. If we observed this change in speed on a spectrum, it would give a shift in wavelength of about $2.6 \times 10^{-5} \,\text{nm}$. This change accounts for our entire solar system, not an Earth-sized planet on its own. If the Earth were the only planet in our system, the Sun would only move by about $9 \,\text{cm s}^{-1}$. This means that to detect an Earth-like planet, we need to be able to make detections within $1 \,\text{cm s}^{-1}$. This is a very high level of precision. The best ground-based telescopes are currently able to achieve a precision of about $1 \,\text{m s}^{-1}$.

The radial velocity (RV) method has been the most successful Earth-based technique to date but it does have several drawbacks. To identify the variation in the speed of a star, the system is best observed ‘edge on’. Of course, not all systems are in this position relative to Earth; however, a radial velocity component will be detected unless a system is ‘flat on’ or perfectly perpendicular to the Earth. This problem means that the RV method can’t identify an accurate mass of the planets under observation. The RV method can only give a minimum mass value. This leads to errors where possible planets could in fact be a binary star system. In general, planets discovered using the RV method tend to be ‘hot Jupiters’ — named because they are large gas planets that orbit very close to their star — because these types of planets have a greater gravitational effect on their star, and thus cause a larger wobble.
The radial velocity method uses Doppler shift to detect the wobble of a star caused by a planetary system. The size and variation of the shifts over time indicates the size and number of planets in a system.

Precision of Earth-based telescopes is another limit of the RV method. The quest for radial velocity precision significantly less than 1 m s\(^{-1}\) is being made with the development of the Next Generation Adaptive Optics (NGAO) system at the WM Keck Observatory and the Echelle SPectrograph for Rocky Exoplanet and Stable Spectroscopic Observations (ESPRESSO) at the Very Large Telescope (VLT) in Cerro Paranal, Chile, run through the European Space Agency. Both projects are hoping to achieve precisions to a few cm s\(^{-1}\).

A dip in the starlight

Transit photometry, commonly known as the transit method, is the most successful technique for discovering exoplanets. This method involves detecting the small variation in brightness when an exoplanet passes in front of its star. This technique is usually used in conjunction with the RV method to verify any discovery. This is because the dimming effect observed could also be caused by other factors. The most significant contributor to the transit method of detecting exoplanets is the Kepler space telescope — launched in 2009, it has found over 5000 planet candidates. Most detections from Kepler are termed ‘candidates’ until they are verified by ground-based observations. The Kepler data is double-checked through a Follow-up Observation Program (FOP) using the Lick, Las Cumbres and Keck observatories. In addition, an online project known as Planet Hunters enables thousands of online users to assist in identifying possible exoplanet transits from the thousands of star candidates identified by Kepler.
When a planet travels in front of a star it is called a transit. As the planet obscures a small amount of light coming from the star, this can be measured as a very slight variation in brightness. Not only does this method enable the detection of a planet but also it enables information such as size, atmospheric composition and surface temperature to be determined.

Not only is the transit method useful in exoplanet detecting, but this technique also gives a much better picture of the exoplanet. As the planet transits the star, the degree to which the star’s visible light is diminished can give an indication of the planet’s diameter. During an exoplanet’s transit, additional absorption lines due to starlight travelling through the planet’s atmosphere can be detected to identify an atmosphere and its make-up. When the planet moves behind the star, a drop in infrared light can be used to determine the temperature of the planet. Space-based transit method observations have revealed broader and more detailed data on exoplanet properties as technologies improve.

The transit method does have drawbacks. The most significant is that for us to see a transit, the system must be very close to edge on from our point of view. This means the transits we observe represent a very small number of the total systems in our universe. A second difficulty is that the time of a transit is only a very small fraction of the total orbit time of an exoplanet. This means that the likelihood of observing the transit at all is very low. In addition, multiple transits need to be observed to verify a sighting. Finally, the transit method can produce false readings where a binary system can be mistaken for a planetary system.
In order to find transits, our telescopes need to be continually observing the sky. This is achieved by using both space-based and ground-based telescopes. In addition to Kepler, the Spitzer space telescope, launched in 2003, uses the transit method to gather detailed spectra in the infra-red and has sensitivity three orders of magnitude greater than any other infra-red observatory. Spitzer's replacement, the James Webb Space Telescope (JWST), which is also the optical replacement for the Hubble space telescope, has suffered delays and funding concerns and is working toward a 2018 launch date.

**Using Einstein's relativity**

In 1915 Einstein's General Theory of Relativity described how light would be affected by gravity. Einstein's theory predicted that gravitational effects of large bodies such as stars would cause light to bend around them. Astronomers realised that they could use Einstein's theory and the variations of gravity caused by a planetary system on a star to identify exoplanets.

Stars in our sky move relative to each other, with closer stars appearing to move faster than more distant background stars. When the light from a distant star travels past a closer star, some of its light is bent around the closer star, causing the distant light to appear brighter than it actually is. This phenomenon is called microlensing as the foreground star (known as the lens star) bends the light in the same way a magnifying glass does. If the lens star has a planetary system, it changes the effects of the lensing in a mathematically predictable way. This method was first proposed to discover binary star systems in 1992. The first successful exoplanet discovery using microlensing was made in 2002.

As the lens star and planet move in between Earth and a source star, the light curve created can be used to identify a planetary system.

Microlensing has several advantages over the other methods for exoplanet detecting. It can identify planets of much smaller masses and larger orbital radii than the 'hot Jupiters' discovered through RV and transit methods. This means it can detect planets that are rocky and much more like Earth. A second advantage is that microlensing can detect systems at much larger distances than RV and transit methods. The biggest drawback of microlensing is that it measures unique events. Unlike RV and transit events that can be measured and verified by repeat observations, microlensing events occur once, when background and foreground stars line up in the perfect position to create the lensing effect.

Other methods of detecting exoplanets, such as direct imaging and timing (with pulsars, eclipsing binaries or stellar oscillations), have achieved a small number of planetary discoveries.
Looking at the planets discovered so far we might think that Earth and our solar system is very rare and different to what the rest of the universe holds. However, we need to be careful about how we interpret our discoveries. Each method of exoplanet discovery tends to favour planets with a particular type of period and mass. This indicates the limits in our detection methods rather than limits in the types of planets out there.

Exoplanet masses are given as a ratio of Jupiter’s mass because so many of the exoplanets so far discovered are very large. The period indicates not only how quickly the planet moves around its star, but also its orbital radius. Smaller periods indicate planets that are closer to their star.

The distribution of masses, periods, radii and eccentricity of exoplanets so far discovered is not what astronomers expected. The planets and systems do not look like our solar system, nor do they fit simply into the accretion model, the model used to explain the formation of our solar system. Many exoplanets discovered have been described as ‘hot Jupiters’. Explaining how and why these planets ended up so close to their star became a very important task for astronomers as it was so unexpected. It is now understood that the systems we are observing are much older than our solar system. Astronomers believe that over time the large gas planets have migrated (drifted very slowly) toward their star. Smaller, rocky planets like our Earth, may have already fallen into their sun or been knocked out of orbit through the gravitational effects of such migration. This migration model also supports another oddity of so many exoplanets discovered: their highly eccentric orbits.
Exoplanet mass (in Jupiter masses) versus period in years by detection method. The clusters illustrate how the various detection methods seem to bias particular types of exoplanets. This scatterplot was generated using data from exoplanets.eu. The data from microlensing appears limited here as many of the discoveries do not have periods and as such do not appear on this plot.

Finding the right star

In the search for life-sustaining exoplanets, the stars themselves are the first target of interest. To find an Earth analogue, we would first seek stars like our sun; that is, a main sequence star of spectral type F, G or K. A main sequence star is a star that can be described as in mid life. These stars have featured strongly in exoplanet searches because they are numerous and their properties suit the RV method. They are long lived, which would enable enough time for a biosphere to form and they have not experienced the cataclysmic events of a post–main sequence star that would sterilise any life. M-type stars have not featured widely in past exoplanet searches, mainly due to their lower luminosities and more complicated spectral emissions. However, M-type stars are numerous, and space-based observatories and advancement in instrumentation means they are now considered excellent candidates for RV or transit methods.

The search for life

Our quest now turns to the search for life in our universe. The one planet with the only example of life so far discovered, the Earth, dictates our understanding of life. Life on Earth is a complicated and extraordinary balance. We understand that life on Earth evolved from much simpler organisms. The origin of those organisms is hotly debated. To understand the possibilities of life outside our solar system, it is imperative we recognise the possible sources of life on Earth.

Life based on carbon

The molecules that make up life on Earth are carbon based, thus these compounds are called organic molecules. The extraordinary thing about carbon is that it is able to form long chains and intricate structures. This property enables a huge array of molecules, some of which perform complex, self-regulating chemical reactions. The constituents of organic molecules — carbon, hydrogen, nitrogen and oxygen, with trace elements
of sulfur and phosphorus — are readily abundant in the universe. With this abundance and the versatility of carbon to bond into complicated structures, many scientists believe life’s origin lies in organic chemistry.

Organic molecules are not unique to the Earth or our solar system. Spectroscopy of planetary nebula, interstellar dust and circumstellar envelopes (gas and dust around stars) shows organic molecules. Hundreds of organic compounds have been discovered throughout our galaxy, and their presence within stellar nurseries suggests that at least some of the organic compounds found on Earth may have already existed when the solar system was created.

![Image of the Orion Nebula](image.png)

Many organic molecules can be found in space. This image shows infra-red spectroscopic data of the Orion Nebula from the European Space Agency’s Herschel Space Observatory.

Spectroscopy is not the only evidence of organic molecules beyond Earth. Meteorites known as carbonaceous chondrite, believed to be leftover from the formation of our solar system, have also been found to contain organic molecules.

**The importance of water**

The other molecule important to life that is found throughout the universe is water. Most water in space is not liquid, but ice. Ice is a main constituent of interstellar dust, but when that dust condenses in stellar nebular, temperatures can rise to a level that enables pockets of liquid water within the dust grains. Liquid water, even in miniscule amounts, enables organic chemicals to interact to form more complicated molecules.

On Earth, liquid water is integral to life. It is the major constituent of living tissue, accounting for around 70% of tissue mass. Water’s polar nature means that it is an excellent solvent of many minerals and compounds, which in turn enables chemical processes to occur. Water is required for metabolic processes within the cell. Most scientists agree that without liquid water, life on Earth would not have evolved. So the question becomes, how could organic molecules form life?

To date, no experiment in a laboratory has created life from organic molecules. However, many experiments have been able to produce complex organic molecules. By replicating the conditions of primordial Earth, scientists have been able to create molecules such as nucleic acids, which are the building blocks of molecules such as RNA and DNA. In addition, experiments on organic molecules found in meteorites have demonstrated their ability to form more complex molecules when exposed to liquid water.
Organic molecules, when extracted from carbonaceous chondrite, such as the Murchison, meteorite and then exposed to water form self-assembled vesicular structures that could be a precursor to living cells. Magnification 400x.

Water is crucial to life on Earth, so when we are search for exoplanets, the existence of liquid water is a key search parameter.

**The habitable zone**

Liquid water will only exist on the surface of a planet if the right conditions exist. The main requirement is a temperature at which water remains a liquid. Astronomers can calculate the region in which a planet needs to orbit a star to ensure liquid water is possible. This region is known as the habitable zone (HZ), or sometimes the ‘Goldilocks zone’, and it varies depending on the type of star.

The habitable zone is a significant factor for any life-sustaining exoplanet. This zone describes the distance from the sun that an exoplanet needs to be if it is to have liquid water on its surface. The size of this zone is approximated using the size and temperature of the star, which is limiting because albedo (how reflective the planet is), greenhouse effect, eccentricity, obliquity, rotation rate and geologic age all contribute to the surface temperature of a planet. To determine HZ, astronomers make assumptions about these other factors.
Chapter 15 Is there life beyond our solar system? © John Wiley & Sons Australia, Ltd

The habitable zone identifies the area around a star where liquid water could exist. Liquid water is assumed to be a prerequisite for life.

The HZ is a clear focus for searching for life-sustaining exoplanets. One of the problems in our quest to find a habitable planet is that so many of the exoplanets found so far have highly eccentric orbits. This means their orbits are far from circular. An eccentric orbit often results in the planet moving in and out of the predicted habitable zone. The likelihood of an exoplanet sustaining life is determined by its ability to maintain liquid water on its surface. However, moving in and out of the HZ may not prevent life. If an atmosphere is thick enough, and depending on the period of orbit, a planet may be able to maintain liquid water on its surface while outside the HZ.

Astronomers analyse the amount of time eccentric orbiting exoplanets spend within and outside the HZ in attempt to identify better targets for further examination. These studies use models to estimate the surface temperatures and atmospheric conditions of exoplanets. In the search for habitable exoplanets, these studies are imperative to reduce the number of candidates that are examined directly.

Size does matter

The last property to consider when examining a viable candidate for life on another planet is mass. The very existence of large planets orbiting close to their suns makes the prospect of finding smaller terrestrial planets in the same system unlikely. As the vast majority of exoplanets discovered are more similar in mass to Jupiter than Earth, we may need to consider the prospects of life outside terrestrial planets. If there is a possibility of life forming on these giant planets, and certainly many are within their habitable zones, it may not resemble life as we know it on Earth. A planet with a minimum mass of more than Jupiter would have gravitational effects and pressures like nothing comparable on Earth. This does not rule the possibility of life out; life on Earth is found in very extreme environments.

Microbiological life on Earth is found in many different environments. Extremophiles, which are organisms found in extreme environments, can survive and sometimes thrive in environments of extreme temperature by Earth standards (–75 °C to 115 °C), radiation, salinity, pH, pressure (up to 130 MPa), vacuum, variations in oxygen and other chemical extremes. It is very difficult to predict the environments that exoplanets could provide for life, but with the variability of life on Earth, it is not unimaginable that life could evolve on planets such hot Jupiters.

The prospect of finding Earth analogues may be unlikely if we focus on the data collected so far. However, missions such as Kepler are increasing the number of candidate exoplanets exponentially, giving a much broader picture of the types of systems that exist and moving toward discovering smaller terrestrial planets. The likelihood of life existing in some manner somewhere in the universe and us finding it seems high.

Is there anybody out there?

The most fantasised and romanticised search for life in our universe is the search for intelligent life. Science fiction writers have for many years deliberated on the possibility that we are not the only intelligent form of life. By just considering the sheer number of stars and galaxies out there, many conclude we cannot be alone.
Where are all the aliens?

Scientists and philosophers have also considered the question of life and intelligent life in our universe. Many would like to believe that we are not the only civilised beings, that there has to be many technologically advanced beings out there, some of which, must be more evolved than us and be able to travel between the stars. When this idea was put to physicist Enrico Fermi in a 1950 interview, he asked that if intelligent life is common in the Milky Way, and given the millions of years another life form may have had to evolve their technology, then why are we not inundated with space ships and visiting aliens?

This is called the Fermi paradox, and in essence it demonstrates the contradiction between the probability of intelligent life in the universe and our lack of contact with that life. Of course it is only a paradox if you accept its two premises:

1. Life in our universe is not rare.
2. Intelligent life and technological advancement are an expected outcome of billions of years of evolution.

Neither of these premises seem implausible given this is what happened on Earth. So was Fermi right?

There are several arguments that attempt to explain the Fermi paradox; some considerably more radical than others:

- Life on Earth is the first to evolve in the universe.
- Intelligent life on Earth is the first to evolve in the universe.
- Other intelligent civilisations may have risen and fallen in the billions of years the universe has existed.
- Other intelligent civilisations may have risen, but the technology to travel or communicate between the stars is impossible.
- Other intelligent civilisations may have risen and have the technology to travel or communicate between the stars, but we don’t understand them.
- Other intelligent civilisations may have risen and have the technology to travel or communicate between the stars, but choose not to.
- The aliens have made contact, but no one believes me.

Several of the ideas above were formulated into an equation by radio astronomer Frank Drake. In 1961, Drake developed an equation that tried to estimate the number of civilisations that exist in our galaxy with the means to communicate with us. He stipulated that the number of such civilisations, $N$, could be determined as follows:

$$N = R* f_p n_e f_l f_i f_c$$

where $R^*$ = the rate at which suitable stars are formed in our galaxy
- $f_p$ = the fraction of those with planets
- $n_e$ = the number of planets in each planetary system capable of bearing life
- $f_l$ = the fraction of those life-bearing planets on which life actually evolves
- $f_i$ = the fraction of those life forms that evolve intelligence
- $f_c$ = the fraction of those intelligent life forms who choose to communicate
- $f_i$ = the fraction of a star’s lifetime for which communicating life forms exist

Clearly this equation could not be solved with any kind of accuracy, but Drake’s equation clarified the many factors involved in searching for intelligent life in our universe, which in turn has significantly contributed to the design of targeted search projects.
SAMPLE PROBLEM 15.5

Given that the Milky Way galaxy is estimated to have 300 billions stars and the oldest known star in the galaxy is 13.6 billion years old, give an estimate for the rate at which stars might form in our galaxy.

Solution:

The rate of star formation is:

\[
\text{number of stars} = \frac{300 \text{ billion}}{13.6 \text{ billion years}} = \frac{300}{13.6} = 22 \text{ per year}
\]

The search for extraterrestrial intelligence (SETI)

The search for extraterrestrial intelligence (SETI) outside our solar system has been conducted in earnest since the 1960s. Frank Drake was one of the pioneers of applying our scientific understanding in a systematic and targeted search to find evidence of extraterrestrial intelligence. He used radio astronomy as his tool, and this remains the main tool used by SETI today.

SETI involves the search for signals produced by an alien civilisation attempting to contact other intelligent life (us). Radio waves are the logical choice for SETI as they can travel vast distances without significant distortion from interstellar gas and dust. The radio spectrum runs from 8.3 kHz to 3000 GHz. This represents wavelengths between 10 cm and 36 km.

SAMPLE PROBLEM 15.6

Radio station Triple M broadcasts on the frequency 105.1 MHz. What wavelength does this represent?

Solution:

Remember the wave equation: \( v = f \lambda \)

\[
\begin{align*}
\lambda &= \frac{v}{f} = \frac{3.0 \times 10^8 \text{ m/s}}{105.1 \times 10^6 \text{ Hz}} = 2.9 \text{ m}
\end{align*}
\]

Radio telescopes

Optical telescopes extend our vision by capturing more light and magnifying images. But many astronomical objects emit electromagnetic radiation outside the visible range. It has been said that to view the stars only in the visible part of the spectrum is like listening to a symphony with an ear that can hear only middle C and the two notes either side of it.

The first telescopes to observe frequencies outside the visible range were radio telescopes. In 1931 Karl Jansky was trying to remove the noise that was interfering with early radio transmissions when he realised that some of the noise was coming from space. The first radio telescope was made in 1937 when Grote Reber, a radio enthusiast, built one in his back yard. It was a parabolic dish nearly 10 m in diameter that could be directed at different parts of the sky. Reber spent five years using his telescope to locate radio sources in the sky before
publishing his work. He found that the Sun emitted radio waves, as did many stars. He also found that some sources of radio waves could not be seen in optical telescopes, making radio astronomy a particularly exciting prospect.

You cannot look through a radio telescope and see a picture in the way that you can through an optical telescope. The information comes in the form of numbers, which show the intensity of the radio sources at different wavelengths. Modern radio telescopes use computers to turn the numbers into pictures that are easier for people to analyse and appreciate.

In 1957, using materials from World War II battleships, the giant 76 m radio telescope at Jodrell Bank in England was completed. It was ready just in time to track the first spacecraft, the Russian Sputnik 1. The science of radio astronomy took off and in 1961 the Parkes radio telescope (featured in the film The Dish) was built in New South Wales. In 1963 in Puerto Rico, the Americans built the enormous 305 m diameter Arecibo radio telescope. It is fixed to the ground and relies on the rotation of the Earth to point in different directions. One of the main purposes of the Arecibo dish was to explore the chemistry and dynamics of the atmosphere. It has also discovered the first planet around a star other than the Sun, determined the rate of rotation of Mercury, mapped the distribution of galaxies in the universe, found ice at the poles of Mercury and made many other major astronomical discoveries in the past five decades.

Radio telescopes can be made to send out radio signals as well as receive them. In 1974, astronomers searching for intelligent life in the universe used the Arecibo dish to send radio signals into space hoping to hear a signal in return, like the one featured in the 1997 film Contact. This was very controversial, largely because people were concerned about a small group of scientists speaking to unknown beings on behalf of the whole planet. Whether we deliberately transmit radio signals or not may make no difference. If there are technologically advanced beings on other planets in our part of the galaxy, they will be able to detect the many transmissions that we send to each other that are continually leaking away from the planet at the speed of light.

Radio telescopes can also be used as radar telescopes. This involves sending out radio waves to nearby objects such as the Moon, Mars, Mercury and Venus. The radio signal is reflected back to the radio telescope, providing a very accurate measurement of the distance of these objects. This has enabled a very accurate measurement of the solar system. The surfaces of the planets have also been mapped in this way. Radar is particularly useful for mapping the surface of Venus because of the thick clouds that cover that planet. The radio waves pass through the clouds while light simply reflects off.

Much of the sky is invisible to optical telescopes because of clouds of gas and dust, or nebulae, in the universe. Some radio frequencies pass through these clouds, enabling radio telescopes to detect objects that will never be visible with an optical telescope.
REMEMBER THIS

Atoms have equal numbers of negatively charged particles (electrons) and positively charged particles (protons). If an atom gains or loses electrons it becomes charged and is called an ion.

One of the uses of radio telescopes is to map the occurrence of neutral hydrogen atoms in the sky. They are able to do this because hydrogen atoms emit radio waves of 1420 MHz when the proton and electron switch from spinning in the same direction to spinning in opposite directions. Hydrogen in hot stars is largely ionised, so tuning radio telescopes to 1420 MHz enables them to detect clouds of cool hydrogen without detecting stars. As these clouds do not emit light, radio astronomy is a great way of detecting where they are, thus improving our knowledge of the galaxy. All types of astronomical bodies can be studied using radio telescopes.

A radio view of hydrogen atoms in the universe

Radio telescopes need to be much larger than optical telescopes to achieve equivalent resolution. One method of improving their resolution is to link them to produce a telescope that has a much greater effective size. A series of radio antennas connected in this way is called an interferometer and can resolve much smaller objects than a single telescope. The Very Large Array (VLA) in New Mexico, where 27 dish antennas each 25 m in diameter are laid out in a Y shape, is an example. These can be used together to achieve the resolution of a single 36 km antenna. The Australia Telescope Compact Array in New South Wales is another example. It uses six 22 m dishes at Narrabri on a 6 km long railway track. It can also link up with the 64 m Parkes dish and another 22 m dish near Coonabarabran to form the Australian Long Baseline Array.

The Australia Telescope Compact Array
The SKA or Square Kilometre Array is a huge radio telescope planned by many different teams in countries around the world, including Australia. With the collecting power of this telescope, astronomers hope to be able to analyse radiation emitted when galaxies were forming, discover planets around other stars and gain a greater understanding of the early universe. It will have 100 times the sensitivity of any existing radio telescope.

**SAMPLE PROBLEM 15.7**

A radio telescope is used to measure the distances to nearby planets. In one test a reflected pulse is received by the telescope 12 minutes after the initial radio transmission. How far away was the planet?

**Solution:**

The speed of light is \(3.0 \times 10^8\) m s\(^{-1}\). The radio signal has travelled to the planet and returned in 12 minutes, so it took 6 minutes to reach the planet. Six minutes is 360 s.

\[
d = vt = 3.0 \times 10^8 \times 360 = 1.08 \times 10^{11} \text{ m}
\]

The planet is \(1.1 \times 10^{11}\) m from the Earth at the time of the measurement. (This is comparable to the distance between the Earth and the Sun, \(1.5 \times 10^{11}\) m.)

**REVISION QUESTION 15.5**

Give two examples of situations in which a radio telescope reveals information that is not detectable with optical telescopes.

**Why radio?**

Since it was first discovered, radio has been recognised as a medium for communication. SETI’s focus on the radio part of the electromagnetic spectrum comes from several important properties of the radio emission. Radio waves are low energy, so they require less power to be produced by an alien civilisation trying to communicate. Radio waves experience much less galactic absorption from the interstellar medium, and most stars are quiet in the radio part of the electromagnetic spectrum, so the host star (or our Sun) would not interfere with a transmission. There is a natural radio window that allows a large range of radio frequencies through the Earth’s atmosphere, and some significant naturally occurring frequencies lie within the radio window.

The cosmic radio window between 1 GHz and 10 GHz is a gap in the radio spectrum that enables clear signal to be measured from Earth.
The radio window illustrated above is very large (1–10 GHz), which is wonderful because so many different wavelengths are able to reach Earth’s surface to be analysed. The challenge of such a large window is that it becomes extremely difficult to pinpoint one specific broadcast frequency, and it is highly unlikely that an alien race, however advanced, would have the power required to broadcast a broadband signal across even one tenth of this spectrum. In 1959, physicists Giuseppe Cocconi and Phillip Morrison suggested, as many others have since then, that the frequency of 1420 MHz would be a likely candidate for a narrowband alien broadcast.

Also known as the 21 cm line, the 1420 MHz frequency represents the emission made by neutral hydrogen when its electron ‘flips’ as described previously. Similar emissions are measured for the hydroxyl radicals (OH) at 1612 MHz, 1665 MHz, 1667 MHz and 1720 MHz. Combined with the neutral hydrogen frequency this describes a window (termed the water hole), which has been the focus of much SETI work. As we shall see later, the modern Serendip program and SETI@home projects focus on the neutral hydrogen frequency.

The magnetic energy between the two states of an electron and proton in hydrogen-1 results in the emission of a photon at 21 cm wavelength when the electron ‘flips’ to the lower energy state

The first dedicated search for extraterrestrial intelligence, Project Ozma, was conducted by Drake in 1960 with a targeted search of the Sun-like stars Tau Ceti and Epsilon Eridani at the 1420 MHz (21 cm) frequency.

Deciding where and how to search

There are two types of signal we would look for as evidence of intelligent life elsewhere in the universe:

1. unintentional signal; that is, the noise created by a technologically advanced civilisation
2. intentional signal, which assumes the extraterrestrial intelligent life forms are trying to reach us.

There are many difficulties with searching for unintentional signals. The most significant is that because the signals are not directed at us they will be weak and difficult to identify. The weakness of any indirect signal means that only very close stars would be worth investigating, which gives a very small target group. Searching for an intentional signal is considered a more likely way of identifying extraterrestrial intelligence. To some extent, this is based on our ability to communicate. At this present time we have the technology to send a narrow beam and bandwidth signal into the centre of the galaxy. So we assume that a civilised alien race could do likewise. However, this assumption also has its issues. Firstly, deciding which bandwidth to search. We would assume an intentional signal would be broadcast on a wavelength that is common to the universe. It is this reasoning that led to the focus on the 21 cm line. Secondly, a narrow signal is very difficult to identify in our very large sky. Surveys of significant areas of sky are needed.

There are two main search methods in astronomy:

1. untargeted search that sweeps large portions of the sky
2. targeted search that focuses on selected stellar candidates.
Throughout the 1960s, the Soviets also developed SETI projects; however, their searchers spanned large areas of the sky, assuming several advanced civilisations would be attempting contact us with enormous powerful transmissions. The significance of the Russian search was that in their attempts to eradicate the significant interference from omnidirectional searches, they started using a process of correlating signals from different antennae. In the 1970s, NASA joined the SETI community through the Ames Research Centre in California, starting with Project Cyclops, a proposed telescope array of 1000 dishes. The project was never funded, but the analysis of the technical and scientific issues involved became a significant reference for further SETI projects and was often referred to as the ‘SETI bible’. NASA was forced to abandon its involvement in SETI due to funding cuts, and since 1989 SETI projects have been primarily funded through private means.

The SERENDIP (Search for ExtraTerrestrial Radio Emissions from Nearby Developed Intelligent Populations) project was initiated at University of California, Berkeley in 1976, originally using the 26 metre Hat Creek antenna and the 64 metre Goldstone antenna in California. The project moved to the 92 m antenna at Greenbank in 1986. In 1992, it moved again to the 302 metre Arecibo telescope, the world’s largest single-dish radio telescope, in Puerto Rico. The initial project used a 100 channel receiver, when it moved to Greenbank the receiver was capable of 65 000 channels. The move to the Arecibo telescope has seen three upgrades, the latest is a 128 million channel digital spectrometer covering 200 MHz of bandwidth. This receiver uses the 7-beam, Arecibo L-band Feed Array (ALFA), piggybacking the telescope while it is being used for other projects. It is able to do real-time spectrometry over the 200 MHz bandwidth, searching for narrow band signals.

Piggybacking involves mounting a receiver onto a telescope permanently and then making use of the observation plan set for other projects. The data collection equipment is autonomous and silent (does not interfere with the ongoing data of the host project). This enables the collection of large amounts of high quality data at a lower cost. Piggyback systems do have several disadvantages, the main one being that there is no control over where in the sky observations are made. This makes it difficult to get full and uniform sky coverage. In addition, not all astronomers are convinced that the piggyback equipment is silent, and it will often be switched off if they suspect it of interfering with the host project.

Arecibo is the largest radio telescope in the world, with a diameter of 305 metres. It is built into the hills of Arecibo, Puerto Rico and is the most sensitive Earth-based radio telescope.
Dealing with the data

The amount of data generated from sky surveys is huge. The process of sorting through signal data to find possible extraterrestrial signals is bigger than the collection of data itself. In 1997, a team at UC Berkeley proposed using the personal computing power of 100,000 home users to perform the massive computational task of analysing a continuous recording of a 2.5 MHz bandwidth signal centred on the 21 cm line. The signal was tapped off the SERENDIP receiver and SETI survey operating at Arecibo. Since its initial launch in 1999, SETI@home has had over 5.2 million users, and at the time of writing had 1.525 million current users. The latest version of the BOINC (Berkeley Open Infrastructure for Network Computing) software was developed for SETI@home by UC Berkeley and is now used in over 100 projects ranging from searching for a cure for Alzheimer’s to predicting global temperatures.

In May 2011, UC Berkeley announced they would be using the SETI@home community to analyse data collected from a targeted search of 86 Earth-like exoplanets discovered by the Kepler space observatory. Using the Robert C Byrd Green Bank radio telescope, data was collected on 86 planets identified by Kepler to be within the habitable zone of their stars. This was the first time that SETI@home users were part of a targeted SETI survey.

SETI@home has been hugely successful as a large scale multi-user platform and has led the way for many other projects requiring large scale processing. It has not yet been successful in detecting extraterrestrial intelligence, but has made significant contributions to radio astronomy through the wealth of technological developments and scientific understanding that have been pioneered for the project. SETI has developed a long history of scientific endeavour and human ingenuity.

Shouting out

If we expect extraterrestrial intelligent life to send messages to us, we need to send messages out as well. In 1974, Frank Drake and Carl Sagan sent a signal from the Arecibo telescope. Its target was the M13 globular cluster. It was sent in binary code and contained information on human DNA, the Earth’s population at the time and the atomic numbers of carbon, nitrogen, oxygen and phosphorus. Several scientists at the time questioned the wisdom of the act, and Drake and Sagan did not ask permission of any governing body before sending the signal. Most of the scientific community were not concerned as they understood the message would take 25,000 years to reach the cluster.

The ‘Cosmic Call’ messages were a set of messages created by Canadian scientists Yvan Dutil and Stephane Dumas, sent from the RT-70 radio telescope in Ukraine in 1999 and 2003. They repeated the message sent previously from Arecibo, but also included text, audio, video and other image files submitted by everyday people from around the world. The messages were sent to five different star clusters and will start to arrive from 2036 through to 2059.
The Pioneer spacecrafts included messages to any potential extraterrestrial intelligent life who happened to find them. The prospect of them being found is ridiculously small, and yet it was considered important to include them.

Throughout history humans have sought new knowledge and understanding of our purpose. The search for life outside our solar system continues that quest. Although imagined many times by science fiction writers, nothing will prepare us for the moment when a signal of life is confirmed.

Chapter review

Summary

- Our understanding of the make-up of the universe is based on our ability to interpret the light from stars.
- The electromagnetic spectrum describes the range energies light can have.
- White light can be separated into its constituent colours through the process of dispersion.
- Spectroscopy is the process of analysing the dispersion of light.
- Spectra can be continuous or discrete, absorption or emission.
- Spectra are used to determine the chemical make-up of stars by observing the distinct lines that signify particular elements.
- Electromagnetic radiation is produced when electrons accelerate.
- Incandescent sources of light make their light through heat and have a continuous spectrum.
- A blackbody curve can be used to determine the temperature of stars, which are then classified into spectral types.
- The wave model is used to explain many properties of light and is applied using the wave equation: $c = \lambda f$. 
The Doppler effect enables astronomers to determine how fast stellar objects are moving in relation to Earth. The search for exoplanets uses several methods including radial velocity, transit, direct imaging and microlensing. The exoplanets found so far challenge our understanding of planet formation; many are very large gas giants orbiting very close to their suns and with eccentric orbits. The way in which exoplanets are discovered can be biased toward particular types of planets. The search for life on other planets is based on a search for liquid water which can be found in the habitable zone around a star. The Fermi paradox and the Drake equation both express the probabilities associated with the search for intelligent life in the universe. The search for extraterrestrial intelligence (SETI) is based in radio astronomy due to the signature of the 21 cm neutral hydrogen line and the ground-based radio window. Multiple projects using targeted and untargeted methods have, to date, not revealed intelligent life outside of Earth.

Questions

The key is in the light

1. Define the following terms: refraction, reflection, dispersion, spectrum, spectroscopy.
2. a. White light enters a crown glass rectangular prism. Sketch the path of red and deep blue light through the glass and back into air. How does the direction of the emerging coloured rays compare with that of the incoming white ray?
   b. Suggest why a glass triangle is used to observe the visible spectrum, rather than a glass rectangle.
3. Explain the difference between absorption and emission spectra.
4. Consider the spectra below taken form a celestial body. What information could you take from this data?
   
   ![Graphical and Visual Spectra]

5. Explain how incandescent light is produced
6. What type of spectrum does an incandescent source have? Why?
7. Describe how the shape of the emission curve of a blackbody changes as the object gets hotter.
8. How can we use our understanding of blackbody emission curves to determine the temperature of stars?
9. Why does the spectral type only describe a star’s surface temperature?
10. Betelgeuse appears red in images. What class of star is Betelgeuse and what does this indicate about its properties?

11. Explain how the spectra from a star can enable us to determine the chemicals present in the star.

**The wave properties of light**

12. How does the period of a wave relate to its frequency?

13. Calculate the frequency of the minute hand on a clock.

14. What type of wave is light modeled as?

15. Calculate the wavelength of orange light in a given its frequency is $4.8 \times 10^{14}$ Hz.

16. Would yellow light have a longer or shorter wavelength than blue?

17. Which travels faster, green light or red light?

18. Which part of the spectrum is light with a wavelength of $4.5 \times 10^{-11}$ m.

19. A spectral line is found at 385 nm. What is the frequency of this light? Is it visible?

**Using the Doppler shift**

20. What causes the red shift in light from distant galaxies?

21. The light from the Andromeda galaxy is shifted toward blue. What does this mean?

22. What are the limitations of Doppler observations?

23. Consider the images below. What can you conclude about the relative motion of the objects and Earth?
The search for exoplanets

24. Why is finding exoplanets so difficult?
25. How does our understanding of gravity help us find exoplanets?
26. Create a table that summarises the different techniques used for finding exoplanets, identifying their success rate, their advantages and disadvantages.
27. Using the above spectrum, calculate the radial velocity of objects A and B.
28. Would you expect the velocities calculated in question 27 to be due to the movement about a star or something else? Justify your answer.

Questions 29–32 relate the scatterplot of mass versus period for detection type shown below.

29. Why is the mass of the exoplanets measured in Jupiter masses?
30. What is the relationship between the period of a star’s orbit and its radius?
31. Why would we conclude that certain methods of detection favour particular types of planets?
32. Does this data support the idea that our solar system is unique and we will never find another one like it? Justify your answer.

Life outside the solar system

33. What are the chemical constituents of life?
34. How do we know that these constituents are relatively abundant in the universe?
35. How do meteorites help us understand the origins of life?
36. Why is liquid water so important in the search for life?
37. What factors influence the habitable zone of a star?
38. What is an eccentric orbit, and why is this an issue for life on an exoplanet?
39. Other than the habitable zone, what factors affect the prospect for life on another planet?
Search for intelligent life

40. Explain the Fermi paradox.

41. If the Drake equation is impossible to calculate accurately, why is it valuable?

42. Sample problem 15.6 calculated the rate at which stars might form in our galaxy. Could this value be used for $R^*$ in the Drake equation? Why or why not?

43. Search the internet to get values for $f_p$ and $n_e$. Give reasoning as to why you believe them to be valid.

Listening out for a signal

44. Why is the radio part of the spectrum thought to be the best frequency to use in SETI?

45. What part of the spectrum is defined as radio?

46. Show why the 1420 MHz frequency of neutral hydrogen is called the 21 cm line.

47. What are the wavelengths for the hydroxyl radicals at 1665 MHz and 1720 MHz?

48. Describe two types of search methods employed in SETI.

49. Why is processing the data from sky surveys difficult and how is this problem solved?

50. Do you think it is a good idea to be ‘shouting out’ to the universe by sending messages into space?