Surfing

NSW PHYSICS 7&8

Module 7 The Nature Of Light

Module 8 From the Universe To the Atom

Brian Shadwick

Science Press

First published 2018

Science Press
Bag 7023 Marrickville NSW 1475 Australia
Tel: (02) 9516 1122 Fax: (02) 9550 1915
sales@sciencepress.com.au
www.sciencepress.com.au

Contents

Light: Quantum Model

INQUIRY QUESTION

What evidence supports the particle model of light and what are the implications of this evidence for the development of the quantum model of light?

CONTENT FOCUS Analyse the experimental evidence gathered about black body radiation, including Wien's law: $\lambda_{max} = \frac{b}{T}$ related to Planck's contribution to a changed model of light.

CONTENT FOCUS Investigate the evidence from photoelectric effect investigations that demonstrated inconsistency with the wave model for light.

CONTENT FOCUS Analyse the photoelectric effect: $E_k = hf - \Phi$ as it occurs in metallic elements by applying the law of conservation of energy and the photon model of light.

Light and Special Relativity

INQUIRY QUESTION

How does the behaviour of light affect concepts of time, space and matter?

CONTENT FOCUS Analyse and evaluate the evidence confirming or denying Einstein's two postulates: the speed of light in a vacuum is an absolute constant and all inertial frames of reference are equivalent.

CONTENT FOCUS Investigate the evidence, from Einstein's thought experiments and subsequent experimental validation, for time dilation: $t = \frac{t_o}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$ and length contraction: $L = L_o\sqrt{\left(1 - \frac{v^2}{c^2}\right)}$.

CONTENT FOCUS Analyse experimental validation for special relativity for example observations of cosmic-origin muons at the Earth's surface, atomic clocks (Hafele-Keating experiment) evidence from particle accelerators and evidence from cosmological studies.

CONTENT FOCUS Describe the consequences and applications of relativistic momentum with reference to $p_v = \frac{mv}{\sqrt{\left(1 - \frac{v^2}{c^2}\right)}}$ and the limitation on the maximum velocity of a particle imposed by special relativity.

CONTENT FOCUS Use Einstein's mass-energy equivalence relationship: $E = mc^2$ to calculate the energy released by processes in which mass is converted to energy. (Note that the production of energy in the Sun is covered in Module 8.)

Module 8 From the Universe To the Atom

Origins Of the Elements

INQUIRY QUESTION

What evidence is there for the origins of the elements?

CONTENT FOCUS Investigate the processes that led to the transformation of radiation into matter that followed the 'Big Bang'.

CONTENT FOCUS Investigate the evidence that led to the discovery of the expansion of the Universe by Hubble.

CONTENT FOCUS Analyse and apply Einstein's description of the equivalence of energy and mass and relate this to the nuclear reactions that occur in stars.

CONTENT FOCUS Account for the production of emission and absorption spectra and compare these with a continuous black body spectrum.

CONTENT FOCUS Investigate the key features of stellar spectra and describe how these are used to classify stars.

CONTENT FOCUS Investigate the Hertzsprung-Russell diagram and how it can be used to determine the following about a star: its characteristics and evolutionary stage, its surface temperature, its colour and its luminosity.

CONTENT FOCUS Investigate the types of nucleosynthesis reactions involved in main sequence and post main sequence stars, including the proton-proton chain and the CNO (carbon-nitrogen-oxygen) cycle.

Structure Of the Atom

INQUIRY QUESTION

How is it known that atoms are made up of protons, neutrons and electrons?

CONTENT FOCUS Investigate, assess and model the experimental evidence supporting the existence and properties of the electron, from early experiments examining the nature of cathode rays.

CONTENT FOCUS Investigate, assess and model the experimental evidence supporting the existence and properties of the electron, from Thomson's charge-to-mass experiment.

CONTENT FOCUS Investigate, assess and model the experimental evidence supporting the existence and properties of the electron, from Millikan's oil drop experiment.

CONTENT FOCUS Investigate, assess and model the experimental evidence supporting the nuclear model of the atom from Geiger-Marsden experiment.

CONTENT FOCUS Investigate, assess and model the experimental evidence supporting the nuclear model of the atom from Rutherford's atomic model.

CONTENT FOCUS Assess the limitations of the Rutherford atomic model.

CONTENT FOCUS Investigate, assess and model the experimental evidence supporting the nuclear model of the atom from Chadwick's discovery of the neutron.

Quantum Mechanical Nature Of the Atom

INQUIRY QUESTION

How is it known that classical physics cannot explain the properties of the atom?

CONTENT FOCUS Investigate the line emission spectra to examine the Balmer series in hydrogen.

CONTENT FOCUS Relate qualitatively and quantitatively the quantised energy levels of the hydrogen atom and the law of conservation of energy to the line emission spectrum of hydrogen using $E = hf$, $E = \frac{hc}{\lambda}$, and $\frac{1}{\lambda} = R\left[\frac{1}{n_f^2} - \frac{1}{n_i^2}\right]$.

CONTENT FOCUS Assess the limitations of the Bohr atomic model.

CONTENT FOCUS Investigate de Broglie's matter waves, and the experimental evidence that developed the formula $\lambda = \frac{h}{mv}$.

CONTENT FOCUS Analyse the contribution of Schrödinger to the current model of the atom.

Properties Of the Nucleus

INQUIRY QUESTION

How can the energy of the atomic nucleus be harnessed?

CONTENT FOCUS Analyse the spontaneous decay of unstable nuclei, and the properties of the alpha, beta and gamma radiation emitted.

CONTENT FOCUS Analyse relationships that represent conservation of mass-energy in alpha and beta decay.

CONTENT FOCUS Examine the model of half-life in radioactive decay and make quantitative predictions about the activity or amount of a radioactive sample using the relationships: $N_t = N_0 e^{-\lambda t}$ and $\lambda = \frac{\ln(2)}{t_{1/2}}$ where N_t = number of particles at time t, N_0 = number of particles present at $t = 0$, λ = decay constant, $t_{1/2}$ = time for half the radioactive amount to decay.

CONTENT FOCUS Model and explain controlled and uncontrolled chain reactions.

CONTENT FOCUS Predict quantitatively the energy released in nuclear decays or transmutations, including nuclear fission and nuclear fusion, by applying the law of conservation of energy, mass defect, binding energy and Einstein's mass-energy equivalence relationship: $E = mc^2$.

CONTENT FOCUS Model and explain the process of nuclear fission and nuclear fusion, including the concepts of controlled and uncontrolled chain reactions and account for the release of energy in the process.

CONTENT FOCUS Analyse relationships that represent conservation of mass-energy in spontaneous and artificial nuclear transmutations, including nuclear fission and nuclear fusion.

Deep Inside the Atom

INQUIRY QUESTION

How is it known that human understanding of matter is still incomplete?

CONTENT FOCUS Analyse the evidence that suggests that protons and neutrons are not fundamental particles and the existence of subatomic particles other than protons, neutrons and electrons.

CONTENT FOCUS Investigate the standard model of matter, including quarks, and the quark composition hadrons, leptons and the fundamental forces.

CONTENT FOCUS Investigate the operation and role of particle accelerators in obtaining evidence that tests and/or validates aspects of theories, including the standard model of matter.

Introduction

This book covers the Physics content specified in the NSW Physics Stage 6 Syllabus. Sample data has been included for suggested experiments to give you practice to reinforce practical work in class.

Each book in the *Surfing* series contains a summary, with occasional more detailed sections, of all the mandatory parts of the syllabus, along with questions and answers.

All types of questions – multiple choice, short response, structured response and free response – are provided. Questions are written in exam style so that you will become familiar with the concepts of the topic and answering questions in the required way.

Answers to all questions are included.

A topic test at the end of the book contains an extensive set of summary questions. These cover every aspect of the topic, and are useful for revision and exam practice.

Words To Watch

account, account for State reasons for, report on, give an account of, narrate a series of events or transactions.

analyse Interpret data to reach conclusions.

annotate Add brief notes to a diagram or graph.

apply Put to use in a particular situation.

assess Make a judgement about the value of something.

calculate Find a numerical answer.

clarify Make clear or plain.

classify Arrange into classes, groups or categories.

comment Give a judgement based on a given statement or result of a calculation.

compare Estimate, measure or note how things are similar or different.

construct Represent or develop in graphical form.

contrast Show how things are different or opposite.

create Originate or bring into existence.

deduce Reach a conclusion from given information.

define Give the precise meaning of a word, phrase or physical quantity.

demonstrate Show by example.

derive Manipulate a mathematical relationship(s) to give a new equation or relationship.

describe Give a detailed account.

design Produce a plan, simulation or model.

determine Find the only possible answer.

discuss Talk or write about a topic, taking into account different issues or ideas.

distinguish Give differences between two or more different items.

draw Represent by means of pencil lines.

estimate Find an approximate value for an unknown quantity.

evaluate Assess the implications and limitations.

examine Inquire into.

explain Make something clear or easy to understand.

extract Choose relevant and/or appropriate details.

extrapolate Infer from what is known.

hypothesise Suggest an explanation for a group of facts or phenomena.

identify Recognise and name.

interpret Draw meaning from.

investigate Plan, inquire into and draw conclusions about.

justify Support an argument or conclusion.

label Add labels to a diagram.

list Give a sequence of names or other brief answers.

measure Find a value for a quantity.

outline Give a brief account or summary.

plan Use strategies to develop a series of steps or processes.

predict Give an expected result.

propose Put forward a plan or suggestion for consideration or action.

recall Present remembered ideas, facts or experiences.

relate Tell or report about happenings, events or circumstances.

represent Use words, images or symbols to convey meaning.

select Choose in preference to another or others.

sequence Arrange in order.

show Give the steps in a calculation or derivation.

sketch Make a quick, rough drawing of something.

solve Work out the answer to a problem.

state Give a specific name, value or other brief answer.

suggest Put forward an idea for consideration.

summarise Give a brief statement of the main points.

synthesise Combine various elements to make a whole.

Surfing

NSW PHYSICS 7&8

Module 7

The Nature Of Light

Content Focus

In this module you will:

- Examine evidence for the properties of light and evaluate the implications of this evidence for modern theories of physics.
- Study theories and models developed by early physicists, including Newton and Maxwell, about mechanics, electricity and magnetism and the nature of matter.
- Explore how major discoveries in physics in the 20th century challenged existing theories and models and led to the development of quantum theory and the theory of relativity.
- Understand how technologies arising from these new theories have shaped the modern world.
- Engage with all the Working Scientifically skills for practical investigations involving the focus content to examine trends in data and to solve problems and communicate scientific understanding about the nature of light.

Investigate Maxwell's contribution to the classical theory of electromagnetism, including unification of electricity and magnets, prediction of electromagnetic waves and prediction of velocity.

1 James Clerk Maxwell

James Clerk Maxwell (1831-1879) was a Scottish scientist in the field of mathematical physics.

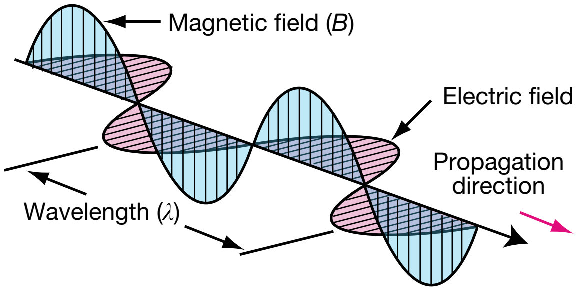
Around **1862**, Maxwell proposed that the speed of propagation of an electromagnetic wave would be the same as the speed of light.

He considered this to be more than just a coincidence, commenting, 'We can scarcely avoid the conclusion that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic waves'.

This resulted in Maxwell proposing that light must be a wave in a medium which was the same cause of electrical and magnetic waves. (Note that this medium, the aether, was later proven by Einstein not to be necessary for the propagation of light or magnetism or electrical field, and was proposed by him to not exist.)

In the 1830s Michael Faraday converted electric energy into magnetic energy using an insulated wire and a galvanometer and used this experiment as inspiration for 'On Faraday's Lines Of Force', a paper in which he derived electric and magnetic equations by comparing the flow of liquid to lines of electrical and magnetic force.

James Clerk Maxwell (1831-1879).



Maxwell understood the significance of Faraday's work and having already proposed that electromagnetic waves travelled at the speed of light he proposed a theory connecting light, magnetism and electricity into a single theory, He developed a set of 20 simultaneous equations containing 20 variables that showed that electric and magnetic fields are two complementary components of electromagnetic fields. In **1864**, at the age of 33 he put forward his famous theory of electromagnetic radiation which proposed that:

- Electricity, magnetism, and light could all be explained using the same theory in physics.
- Light was propagated by alternating electric and magnetic fields, which he believed would vibrate perpendicular to one another.

Around **1867** Maxwell predicted thatthere would be a continuous range of electromagnetic radiations extending beyond ultraviolet and below infra-red. This was the first prediction of a continuous spectrum of electromagnetic radiation.

QUESTIONS

1. When his theory on electromagnetism was proposed in 1864, it was not well accepted by many scientists who claimed that it was 'too different to warrant serious consideration'. What influenced these scientists to be opposed to new ideas like Maxwell's and many other brilliant minds of the mid 1800s?
2. List Maxwell's contributions to the classical theory of electromagnetism.

CONTENT FOCUS

Describe the production and propagation of electromagnetic waves and relate these processes qualitatively to the predictions made by Maxwell's electromagnetic theory.

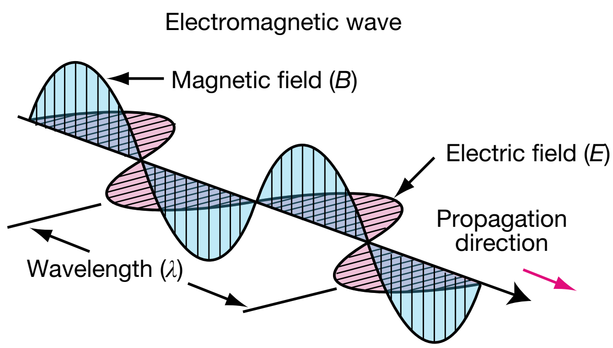
2 Transverse Electromagnetic Waves

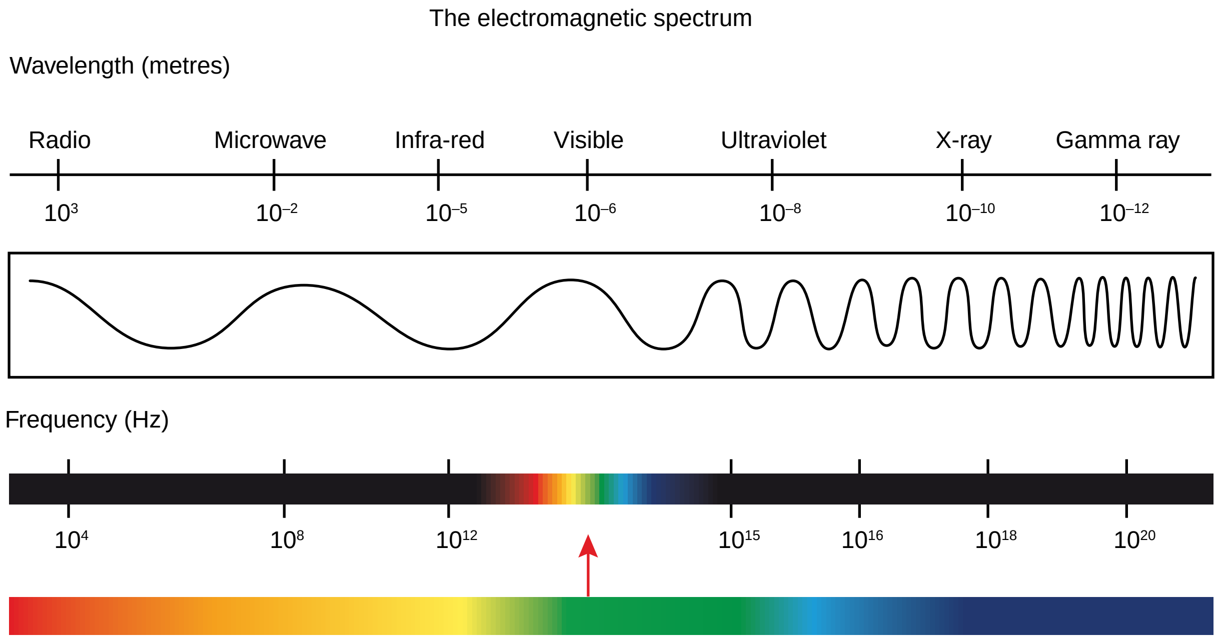
Science is a truly international enterprise. It progresses because scientists are continually investigating to improve upon, or add to, existing ideas. The investigations into the **electromagnetic spectrum** show how scientists from many countries have contributed to our existing knowledge of rays that reach us from outer space. Until 1800 the only waves known were those in the visible spectrum. Then followed some important discoveries.

- 1800 William Herschel, a British astronomer, discovered infra-red radiation (heat waves).
- 1801 German chemist Johann Ritter discovered UV radiation.
- 1867 James Clerk Maxwell, British mathematical physicist, predicted the existence of a continuous electromagnetic spectrum of waves.
- 1887 German scientist Heinrich Hertz discovered radio waves. (They were thought to be of no use!)
- 1895 German physicist Wilhelm Roentgen discovered X-rays.
- 1896 French physicist Henri Becquerel discovered uranic rays – radioactive rays emitted by uranium.
- 1898 Marie Curie discovered radium.
- 1899 Ernest Rutherford identified alpha and beta radiation (particles not electromagnetic radiation).
- 1900 Frenchman Paul Villard discovered gamma rays.
- 1926 Scotsman John Logie Baird demonstrated TV for the first time.

Through these discoveries the major electromagnetic waves were identified. Electromagnetic transverse waves are different from transverse matter waves in that they have the following properties.

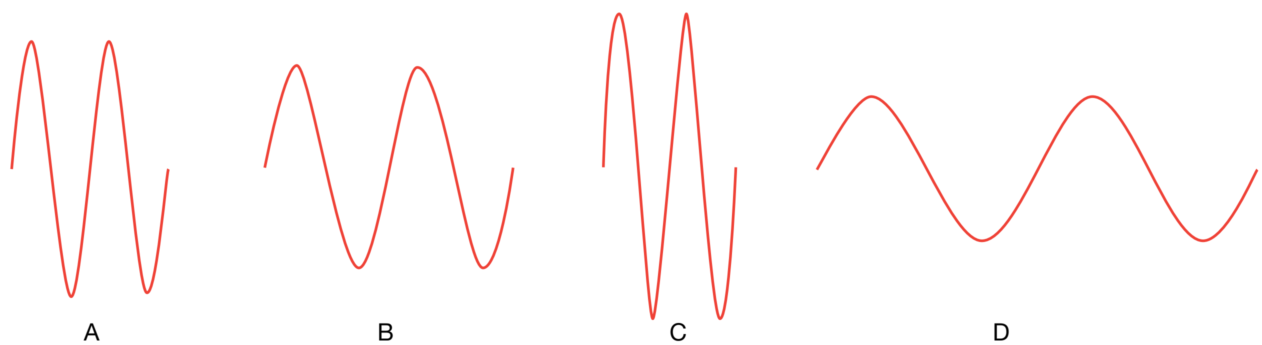
- Electromagnetic waves can travel through a vacuum.
- They all travel at the speed of light (3×10^8 m s^{-1}) in a vacuum – they slow down a little in other media.
- Electromagnetic waves are proposed to be **self-propagating alternating electric and magnetic fields**.
- Because the motion of the changing magnetic and electric fields are at right angles to the direction in which they carry energy, electromagnetic waves are also classified as transverse waves.
- Because electromagnetic waves are really hard to draw, we usually draw them as transverse matter waves. The flaw in doing this is that the energy carried by a transverse wave is indicated by the amplitude of the wave but this is not the case with electromagnetic waves.
- In electromagnetic waves, the energy is directly proportional to the frequency of the photons which constitute the radiation as given by Planck's quantum theory equation, $\boldsymbol{E = hf}$, which you shall learn about later.
- The **wavelength** of an electromagnetic wave is the distance between the peaks of successive magnetic or electric field pulses.
- We usually refer to the **intensity** of an electromagnetic wave rather than to its amplitude. The intensity of an electromagnetic wave depends on the number of photons in the beam. Each photon will have energy dependent on its frequency.
- The **period** of an electromagnetic wave is the time for one wavelength to pass a given point.
- The **frequency** of an electromagnetic wave is the number of wavelengths that pass a point each second. Frequency is measured in hertz (Hz).



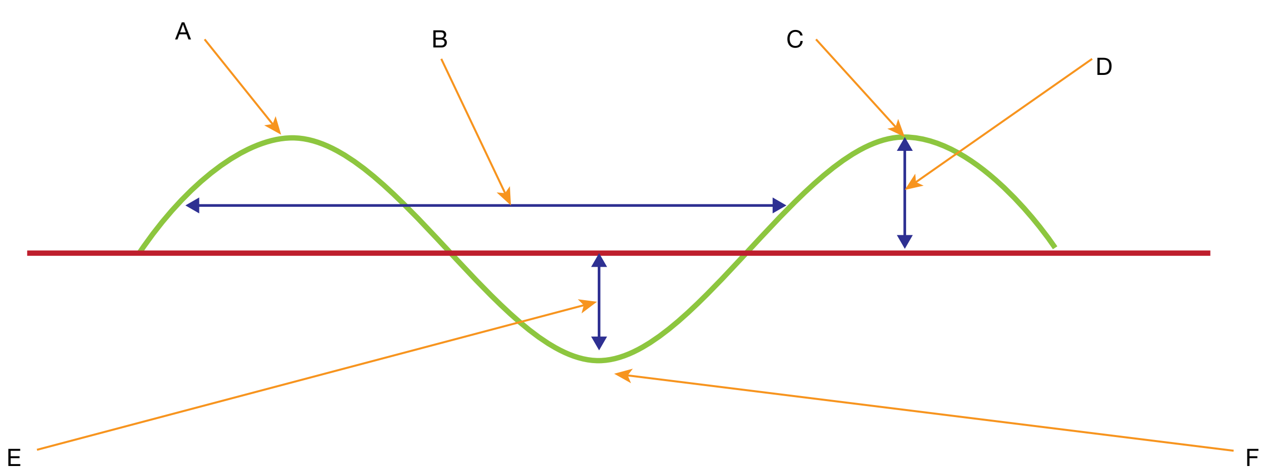


QUESTIONS

1. (a) The waves shown below all represent electromagnetic waves travelling for the same interval of time. List them in order of increasing wavelength, amplitude, and then in order of increasing frequency.
   (b) Measure the wavelength and amplitude of each wave.



2. Identify each of the labelled parts of the wave shown below.



3. Examine the diagram of the electromagnetic spectrum on the previous page.
   (a) Which visible light photons (the particles that carry electromagnetic energy) would carry more energy, green photons or yellow photons? Justify your choice of answer.
   (b) On the basis of this information, would you say that the energy carried by electromagnetic photons is proportional to their wavelength, frequency or amplitude? Justify your answer.
   (c) An electromagnetic photon has a wavelength of 1.0 m. What type of ray is it?
   (d) An electromagnetic photon has a wavelength of 1.0 cm. What type of ray is it?
   (e) An electromagnetic photon has a wavelength of 1.0 mm. What type of ray is it?
   (f) An electromagnetic photon has a wavelength of 1.0 μm. What type of ray is it?
   (g) An electromagnetic photon has a wavelength of 1.0 nm. What type of ray is it?
4. (a) What is the distinguishing property of all electromagnetic waves?
   (b) Microwaves, rather than radio waves are used to communicate with satellites and the space station. Suggest a reason for this.
   (c) Most of the data collected by astronomers in their study of celestial objects from the Earth's surface, is obtained from visible light, radio and microwaves. Explain why this data is from such a small section of the electromagnetic spectrum.
5. (a) In terms of particle movement, define a transverse wave.
   (b) In terms of particle movement, define a longitudinal wave.
   (c) Given that electromagnetic waves do not involve the oscillation of particles, explain how they can be classified as transverse waves.
6. A logical thinking puzzle. Use the clues to arrange electromagnetic waves (represented by the letters B, E, G, H, J, K, L) in order of increasing wavelength, and then use the diagram of the electromagnetic spectrum on the previous page to identify the radiation each letter represents. You may choose to use the grid to help you solve this problem.
   - L has a shorter wavelength than E.
   - L doesn't have the shortest wavelength.
   - G is more energetic than H.
   - G does not have the shortest wavelength.
   - J represents infra-red radiation.
   - H is not visible light and L is not microwave radiation.
   - G has a longer wavelength than E.
   - K lies between E and J on the electromagnetic spectrum.

	→ Increasing wavelength →						
	γ	X	UV	Vis	IR	M	R/TV
B							
E							
G							
H							
J							
K							
L							

Conduct investigations of historical and contemporary methods used to determine the speed of light and its current relationship to the measurement of time and distance.

3 Historical Measurements Of the Speed Of Light

The accepted value for the speed of light (or any other electromagnetic radiation) today is 299 792 458 m s^{-1} in a vacuum. Of course, when light (or any other electromagnetic waves) travel in denser mediums this speed is reduced – it is refracted.

This is so fast that scientists throughout the ages have had difficulties in determining the exact figure because their technology was not accurate enough to get a decisive value. The first known people to consider how fast light travelled were the ancient Greeks who considered, on the basis that stars appear as soon as you open your closed eyes, that the speed of light was infinite. This was supported by most people including Roger Bacon in the 13th century, Dutch scientist Isaac Beeckman in 1629 and even the famous Johannes Kepler in the 17th century. Some of the more notable attempts are summarised in the material below.

(Note that the values calculated by these scientists vary from resource to resource, so it is difficult to obtain reliable figures. The values used here must, despite the degree of accuracy they sometimes state, therefore be taken as indicative rather than accurate.)

- 1638: Galileo: at least 10 times faster than sound
- 1675: Ole Roemer: 301 000 000 m s^{-1}
- 1677: Christiaan Huygens: 201 168 000 m s^{-1}
- 1728: James Bradley: 301 000 000 m s^{-1}
- 1848: Hippolyte Louis Fizeau: 315 000 000 m s^{-1}
- 1848: Marie Alfred Cornu: 300 400 000 m s^{-1}
- 1862: Leon Foucault: 298 000 000 m s^{-1}
- 1879: Albert Michelson: 299 310 000 m s^{-1}
- 1926: Albert Michelson: 299 798 000 m s^{-1}
- 1958: Keith Davy Froome: 299 7920500 m s^{-1}
- 1972: US National Bureau of Standards: 299 792 458 m s^{-1}
- 1983: 299 792 458 m s^{-1} (Conference of Weights And Measures. Internationally accepted value.)

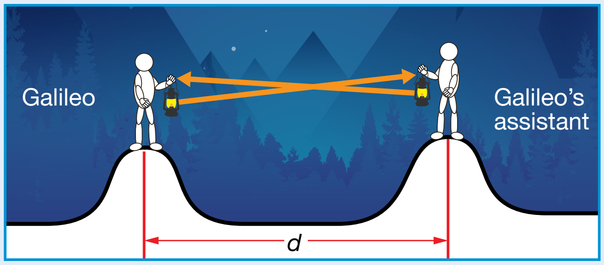
1638 Galileo – Light speedometer

Galileo's idea to measure the speed of light was to have two people at a known distance from one another with covered lanterns. One of the lantern bearers uncovers his lantern and as soon as the other one observed the first lantern's light he immediately uncovers his own. This process was repeated several times so that the participants became well practised and improved their reaction times as much as possible.

Once they became accustomed to the process, they repeated the process over ever greater distances until finally needing telescopes to view one another's lantern lights. It is thought that Galileo used a water clock to measure the time lag for the experiment.

Galileo couldn't detect a perceptible time lag from this experiment and concluded that light 'if not instantaneous, it is extraordinarily rapid'. He did, however, state that light must travel at least ten times faster than sound.

Galileo and the speed of light



- Galileo turns on his lantern and starts his clock.
- When his assistant sees Galileo's light, he turns on his lantern.
- When Galileo sees the light from his assistant's lantern he notes the time.

1675 Ole Roemer – The moons of Jupiter

Danish Astronomer Ole Roemer made the first real measurements of the speed of light about 50 years after Galileo, making a systematic study of the motion of Io, one of the moons of Jupiter.

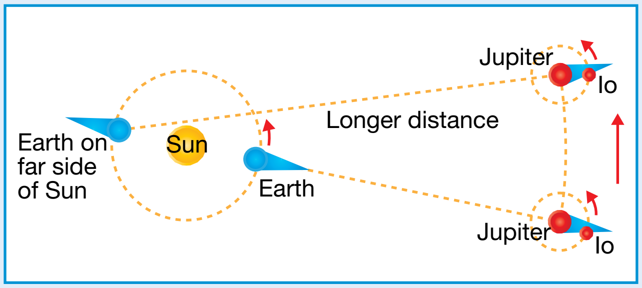
He studied the time it took for Io to travel behind Jupiter – its eclipse time. He found that over several months the eclipses seemed to take increasingly longer than he expected for several months and then to start to take shorter and shorter times for the next few months.

In September 1676, he correctly predicted that the Io eclipse on 9 November would be about ten minutes 'late'. Roemer proposed that this lag in time was because the Earth and Jupiter moved in different orbits and as they did so the distance between them was changing. The light reflected from Io would take varying times depending on this distance.

He estimated that for the eclipse he observed the light took 22 minutes to reach the Earth at a speed of 2.14×10^8 m s^{-1}, about 29% less than the accepted value today.

The speed of light was originally measured by Ole Roemer by measuring the orbital period of Io (Jupiter's moon).

- When Earth was closer, the orbital period was 42.5 hours.
- When farther away, the period was longer.
- The change in the Earth's distance divided by the change in observed period is the speed of light.



1677 Christiaan Huygens

Christiaan Huygens used Roemer's estimate and combined it with better estimates of the distances between the Sun and the planets to derive a new speed of light. He calculated the speed of light to be around 201 168 000 m s^{-1}.

Ole Roemer (1644-1710).

1728 James Bradley

English astronomer James Bradley measured the speed of light by how stars appear to change in position as the angle of the Earth changes as it orbits the Sun. This is known as stellar aberration.

The distance that the stars appear to move is proportional to the speed that the Earth moves, divided by the speed of light.

Bradley used the current estimate of the distance between the Earth and the Sun to determine the distance that the Earth must travel in that time and calculated the speed of lights as 301 000 000 m s^{-1}, in error by only about 0.4%!

James Bradley determined that the stellar aberration is approximately the ratio of the speed the Earth orbits the Sun to the speed of light.

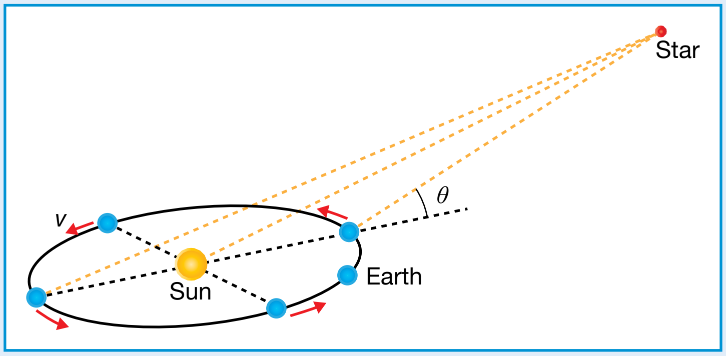
Stellar aberration causes the apparent position of stars to change due to the motion of the Earth around the Sun.

Bradley used stellar aberration to calculate the speed of light by knowing:

- The speed of the Earth around the Sun.
- The stellar aberration angle.

His independent confirmation, after 53 years of struggle, finally absolutely ended the opposition to a finite value for the speed of light.

He calculated the speed of light in a vacuum as **c = 301 000 km s^{-1}.**



1848 Armand Hippolyte Louis Fizeau

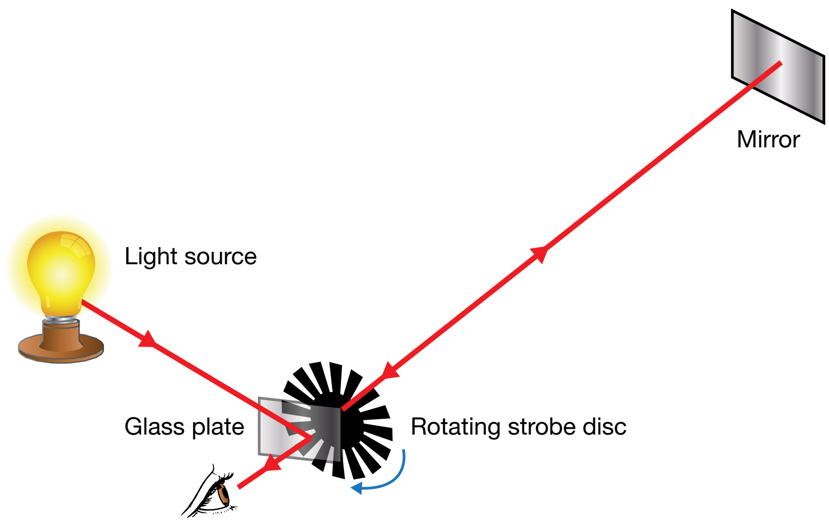
The main problem with early measure of the speed of light was the lack of accuracy of distances used in the calculations. In 1848 Fizeau attempted to solve this problem by shining a beam of light between the teeth of a rapidly rotating cog wheel. This meant that the light source was constantly being covered and uncovered.

He used a mirror to reflect the light back so that it passed through the cog wheel a second time. This design eliminated the need for two sources of light and the error associated with human reaction times as in Galileo's experiment.

His idea was that depending on the speed of the wheel, the reflected light would either pass through the gaps between the cogs or be blocked by them.

Doing the experiment with wheels with hundreds of cogs rotating very fast meant that measurements could be made to a higher degree of accuracy than ever before. His value of 315 000 000 m s^{-1}, about 5.1% different from the modern value was less accurate than Bradley's, but much more reliable and valid.

Hippolyte Fizeau (1819-1896).



1848 Marie Alfred Cornu

Alfred Cornu repeated Fizeau›s toothed wheel measurement in a series of experiments in 1872-76. His goal was to obtain a more accurate value for the speed of light.

Instead of estimating the intensity minimum of the light being blocked by the adjacent teeth, a relatively inaccurate procedure, Cornu measured the rotation rates of the wheel electrically and recorded the measurements on a chart and compared them to the observatory clock.

A telegraph key arrangement allowed Cornu to mark on this same chart the exact moments he judged that the light beam passed through the rotating teeth of the wheel. His light path was 54 m long, nearly times as long as that used by Fizeau.

Cornu made repeated observations, averaging the values obtained with the wheel spun clockwise and anticlockwise. His experiment enabled him to get a value for the speed of light of 300 400 000 m s^{-1}, within 0.2% of the modern value.

Alfred Cornu (1841-1902).

1862 Leon Foucault

Leon Foucault, another French physicist used a similar method to Fizeau. He shone a light on a rotating mirror and reflected it back to a fixed mirror 18 metres away and then reflected it back to the first rotating mirror.

While the light was travelling between the mirrors, the rotating mirror also travelled some circular distance. This resulted in the reflected beam hitting the rotating mirror at a slightly different angle. By measuring this angle Foucault was able to calculate the speed of light as 298 000 000 m s^{-1}. The difference of this to the modern value is about 2×10^{-4}%.

Jean Bernard Leon Foucault (1819-1868).

1879 Albert Michelson

Michelson redesigned Foucault's method to provide greater accuracy. He increased the distance between the mirrors to 610 m instead of 18 m. He also used much higher quality reflecting mirrors and obtained a value for the speed of light of 299 310 000 m s^{-1}, within 0.6% of today's value.

In 1926 he repeated his experiment using improved technology and obtained a value of 299 798 000 m s^{-1}.

1950s onwards

The expansion of scientific knowledge in the 1900s, particularly the debate over the existence of the aether, a medium invented to allow light to travel through space, the nature of electromagnetic radiations and Einstein's theory of special relativity led to the development of extremely accurate measuring devices, notably Michelson's interferometer for which he was awarded the Nobel Prize in Physics in 1907. In 1958 Keith Froome obtained a value of 299 792.5 km s^{-1} using a microwave interferometer and a Kerr cell shutter.

Keith Davy Froome (1921-).

After 1970 the development of lasers with very high spectral stability and accurate caesium clocks made even better measurements possible. Up until then, the changing definition of the metre had always stayed ahead of the accuracy in measurements of the speed of light. But by 1970 the point had been reached where the speed of light was known to within an error of plus or minus 1 m s^{-1}.

More recent measurements using laser beams, electronic circuits and interferometry have led to an acceptance of the value for the speed of light as 299 792 458 m s^{-1}.

QUESTIONS

1. What were the two factors which contributed to the inaccuracies in early measurements of the speed of light?
2. Human reaction time is at best about 0.2 s.
   (a) How far would light travel in 0.2 s?
   (b) How far apart would Galileo's two lanterns have to be so that the human error contributed say, 50% error to his calculated speed?
   (c) What are the implications of your answer to (b) for experiments designed to measure the speed of light?
3. Research and summarise one of the more modern ways in which the speed of light has been determined.

4 Measuring the Speed Of Light – Home Experiment

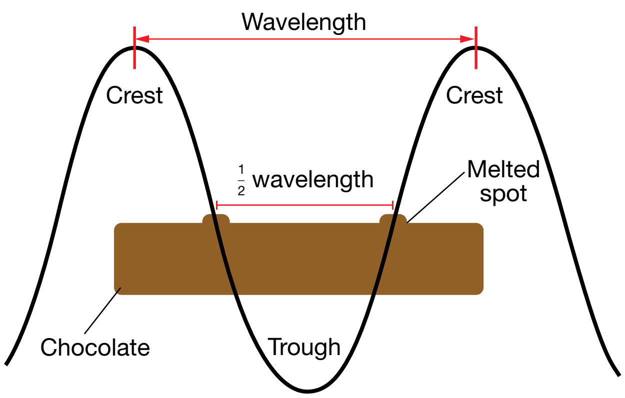
All you need to do this home experiment is a microwave, ruler, bar of chocolate and a calculator. The frequency of a microwave oven you will use is 2450 MHz = 2 450 000 000 Hz.

The way it affects the chocolate is shown in the diagram. As it heats food, it will also heat the chocolate. There will be at least two heat spots initially as shown in the diagram. If your bar of chocolate is more than 6 cm long you may get three heat spots. These heat spots will be half the wavelength of the microwave apart.

From $v = f\lambda = 3 \times 10^8 = 2.45 \times 10^9 \times \lambda$

From which $\lambda = \dfrac{3 \times 10^8}{2.45 \times 10^9} = 0.122 \text{ m} = 12.2 \text{ cm}$

Therefore half a wavelength = 6.1 cm.



Method

- Take the turntable out of the microwave. The chocolate must be stationary when it is heated.
- Put a plate upside down over the rotor in the middle of the microwave base that turns the turntable.
- Place your bar of chocolate upside down (flat side upwards) so that its centre is as close as possible to the centre of the plate.
- Set the timer of the microwave for about 40 seconds. This is probably too long, but you will be turning it off manually.
- Turn the oven on and heat the chocolate until it starts to melt in two or three places. This should take about 20 seconds.
- Immediately you see the melted hot spots on the chocolate through the door, turn the microwave off.
- Take the plate and the chocolate out of the microwave – carefully! The chocolate will be hot. Measure the distance between the centre of the melted spots as accurately as you can. This distance represents half the wavelength of the microwaves. (Remember to change it to metres.)

QUESTIONS

1. Use the formula $v = f\lambda$ to calculate your value for v, the speed of light.
2. Compare your answer to the accepted value (299 792 458 m s^{-1}).
3. Calculate the percentage error in your experimental results from:

$$\% \text{ Error} = \frac{\text{your experimental value}}{\text{real value} = 299\ 792\ 458} \times \frac{100}{1}$$

4. Write up your experiment in the usual way and give it to your teacher to assess.

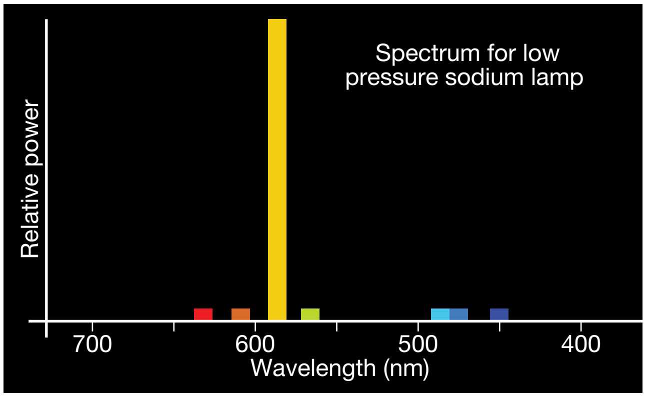
Conduct an investigation to examine a variety of spectra produced by discharge tubes, reflected sunlight or incandescent filaments.

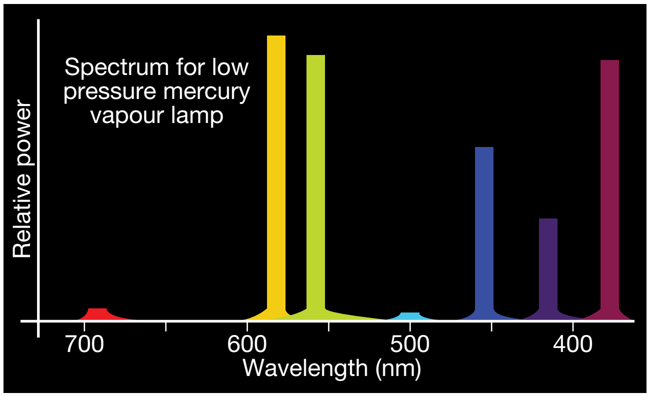
5 Comparing Spectra From Lighting Sources

The nature of the spectrum of any source of radiation depends not only on the composition of the source, but as shown by Planck's work, the temperature of the source particularly if it is a solid. With elements and compounds, and even stars, the individual composition and its surface temperature will be constant and therefore the spectrum they produce will be the same every time it is produced. The spectrum is a 'fingerprint' for the object.

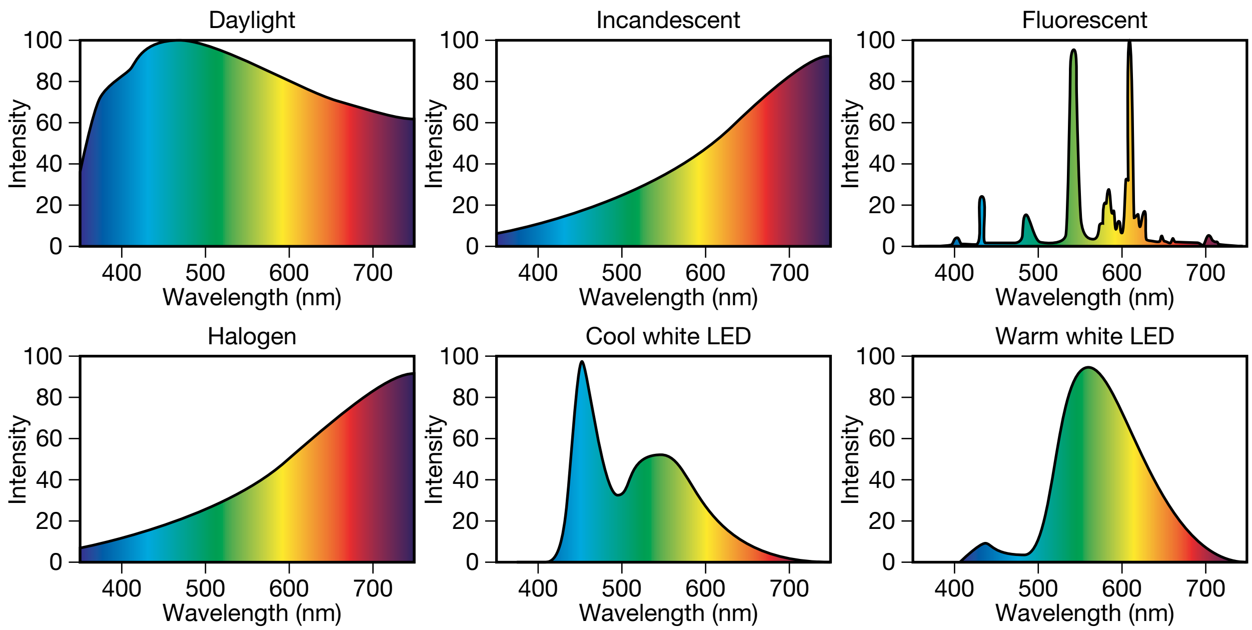
This applies also to individual light sources, but different low temperature light sources made by different manufacturers will produce different spectra because they will not all be identical in composition. The spectra made by the same manufacturer on different production runs might also show different spectra because there may be slight differences in the composition of the materials used in their manufacture.

Light sources which have filaments that get very hot will all usually produce continuous spectra, but low temperature vapour light sources such as mercury or sodium vapour lamps will produce light more consistent with their composition rather than their temperature. So, sodium vapour lamps will tend to be yellow in colour and mercury vapour lamps purple.



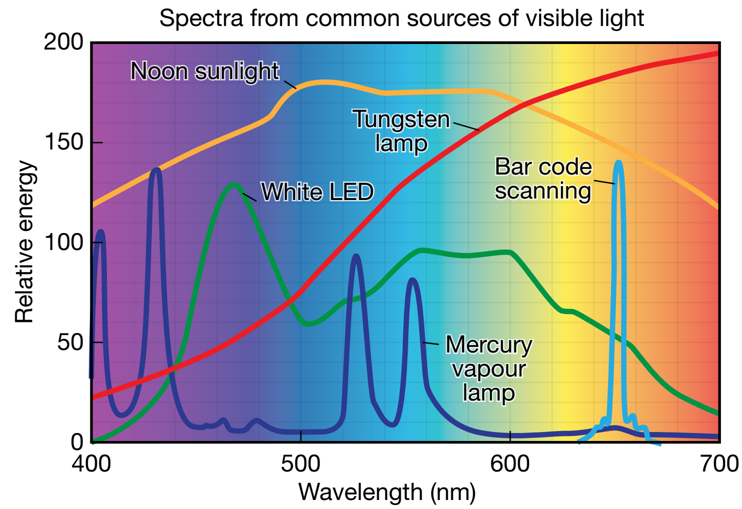


The graphs below compare the typical spectra emitted by several types of lights, compared to sunlight.

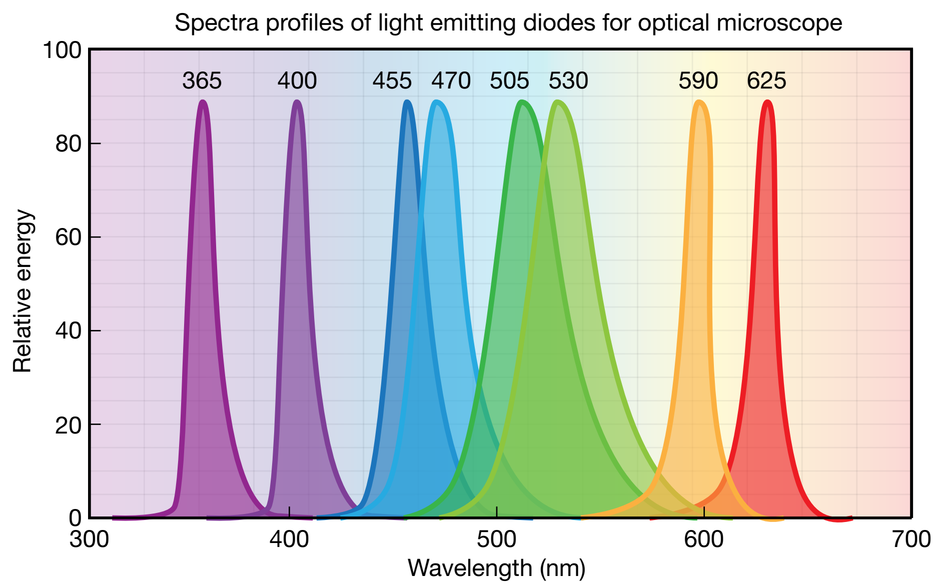


These graphs are a little easier to compare when they are superimposed on each other. Note that the tungsten lamp is a typical incandescent light globe.

Note also, that because of their energy inefficiency, incandescent light globes are no longer allowed to be manufactured in Australia. If you still have some of them in your lighting fixtures at home, that is okay, but when they 'blow', they will have to be replaced with more energy efficient globes.

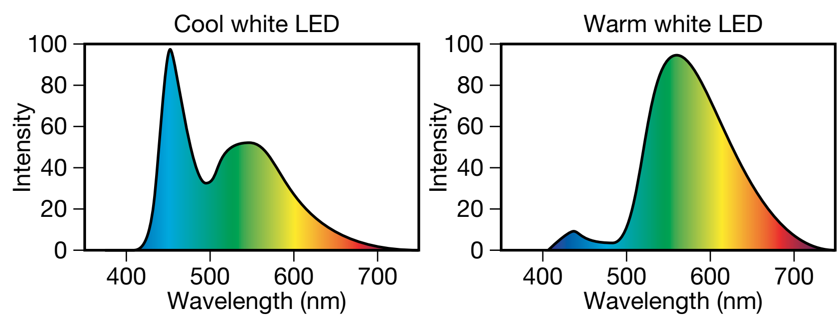


Modern technology enables LED globes with a wide variety of colour characteristics to be manufactured. These have found use in many decorative situations.

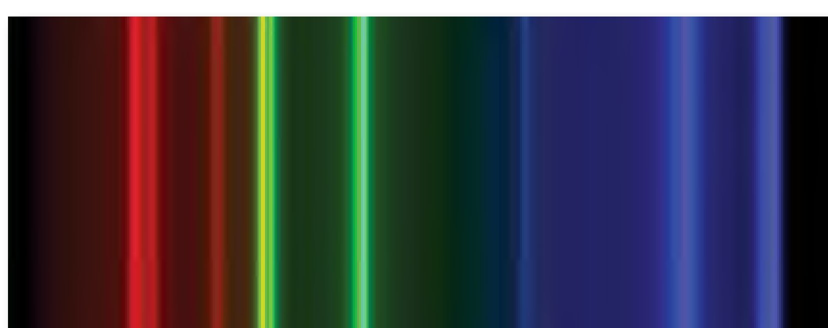


QUESTIONS

1. Consider the spectra of the cool white LED and the warm light LED shown. In terms of the given spectra, account for the descriptions of these LEDs as 'cool' or 'warm'.



2. This spectrum is that of mercury.
   (a) Given this spectrum, what colour would you expect see emitted from a mercury vapour lamp?
   (b) The colour of a mercury vapour lamp is a light purple colour. Explain why it is this colour, and maybe not the colour you predicted.



CONTENT FOCUS

Investigate how spectroscopy can be used to provide information about the identification of elements.

6 Spectroscopy and Elements

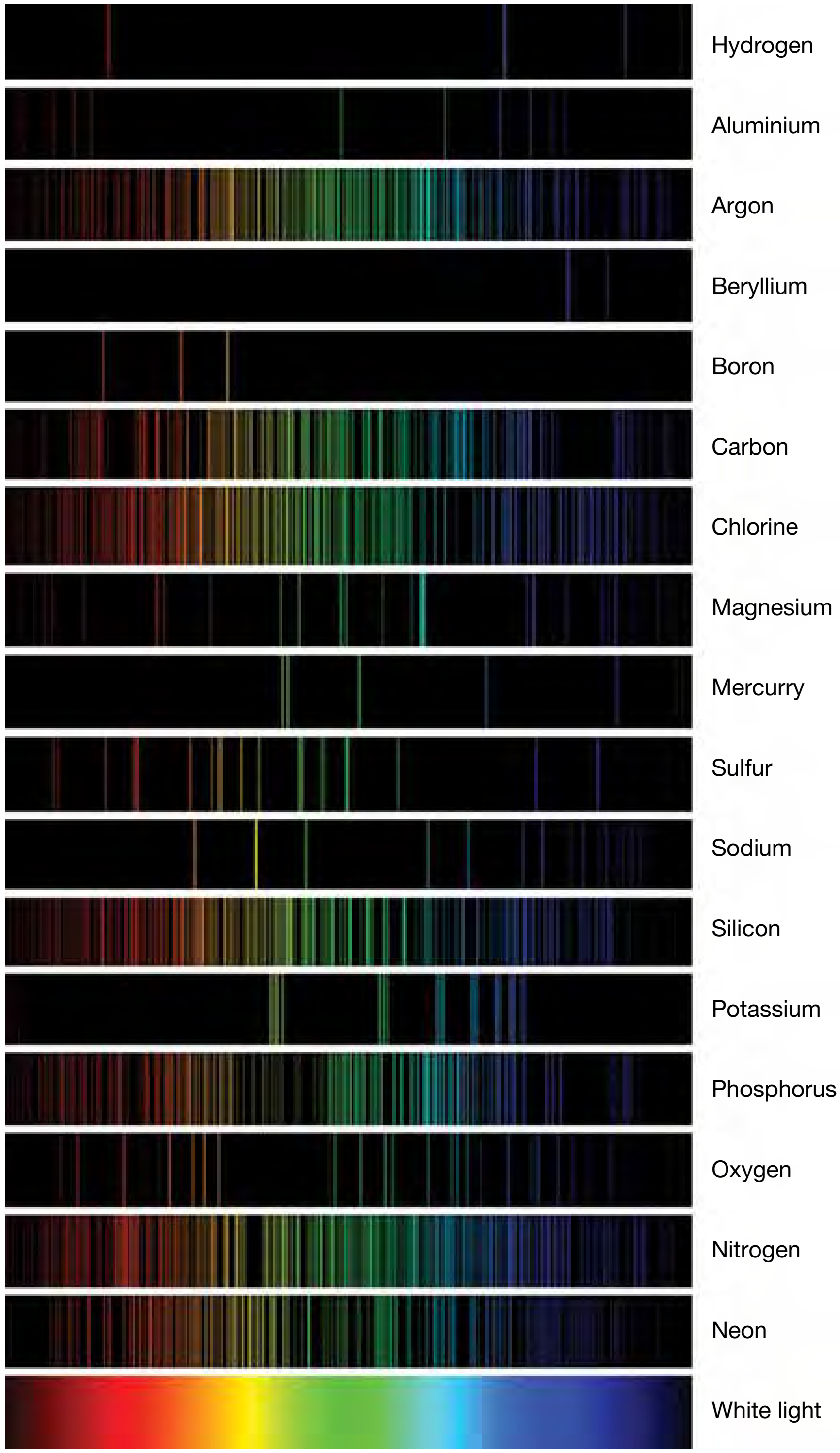
Spectroscopy is the study of the interaction between matter and electromagnetic radiation. Initially spectroscopy originated through the study of visible light dispersed through a prism. It now covers the study of the spectra produced by several other bands of electromagnetic radiation as well as including X-rays, UVL and near infra-red.

Spectroscopic techniques are used to identify elements in stars and the structure of chemical compounds and is used extensively in forensic science. Radio frequency spectroscopy of nuclei in a magnetic field has been employed in magnetic resonance imaging (MRI) to visualise the internal soft tissue of the body with unprecedented resolution.

Microwave spectroscopy was used to discover the so called three degree blackbody radiation, the remnant of the Big Bang from which the Universe is thought to have originated. The internal structure of the proton and neutron and the state of the early Universe up to the first thousandth of a second of its existence are being unravelled with spectroscopic techniques using high energy particle accelerators.

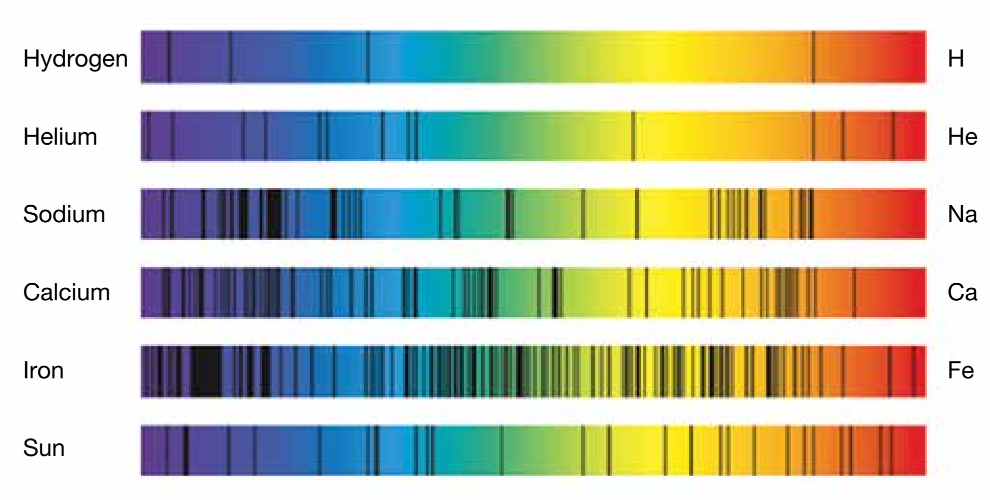
The constituents of distant stars, intergalactic molecules, and even the primordial abundance of the elements before the formation of the first stars can be determined by optical, radio, and X-ray spectroscopy. Optical spectroscopy is used routinely to identify the chemical composition of matter and to determine its physical structure.

The diagram shows the individuality of the spectra of elements. Each spectrum acts as an identifying 'fingerprint' for each element.

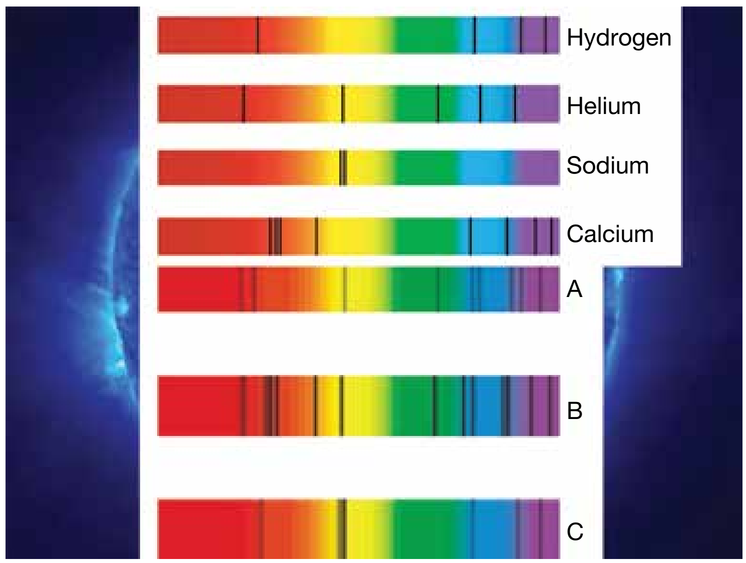


QUESTIONS

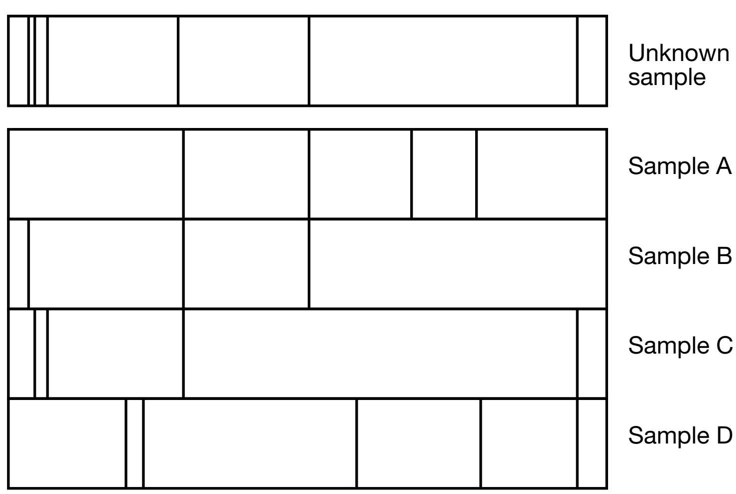
1. Consider the following spectra of five elements and the Sun.
Which of the five elements shown are part of the Sun's elemental composition? Justify your answer.



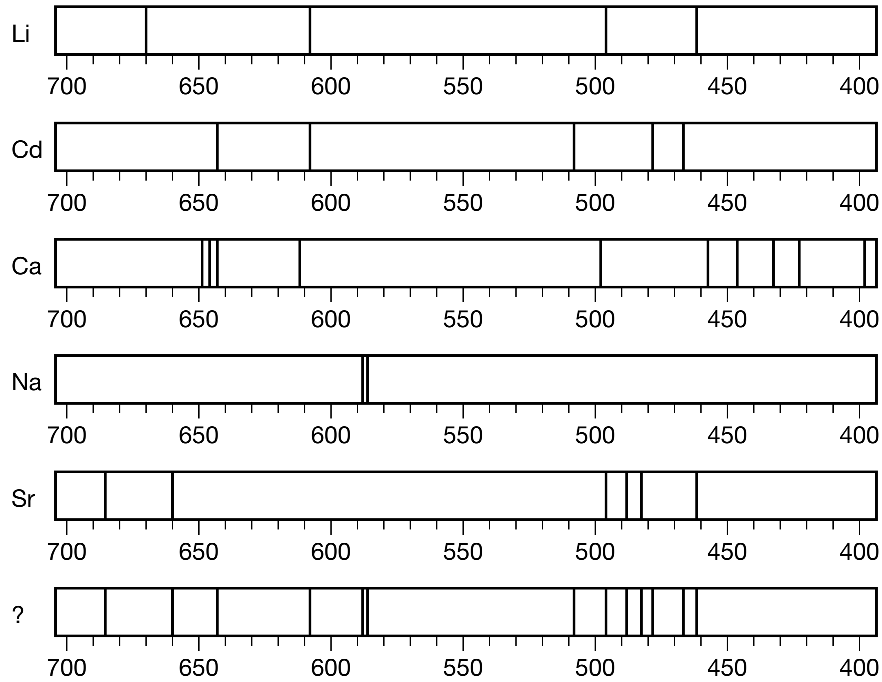
2. Consider the spectra of three starrs A, B and C shown along with the spectra of four elements commonly found in stars.
(a) Which of the four elements are in star A?
(b) Which of the four elements are in star B?
(c) Which of the four elements are in star C?



3. Consider the simple line spectra shown. Which of the elements A, B, C and D are contained in the unknown sample?



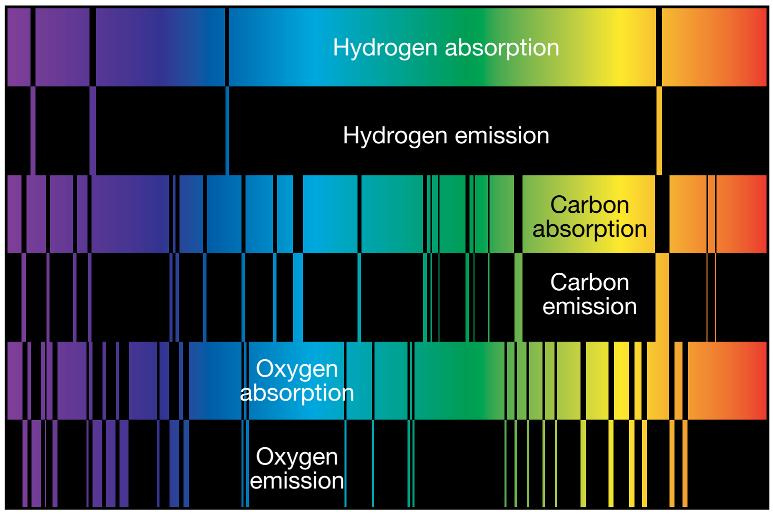
4. Consider the diagram showing the spectra of several elements and an unknown substance.
Which of the elements shown are contained in the unknown substance?



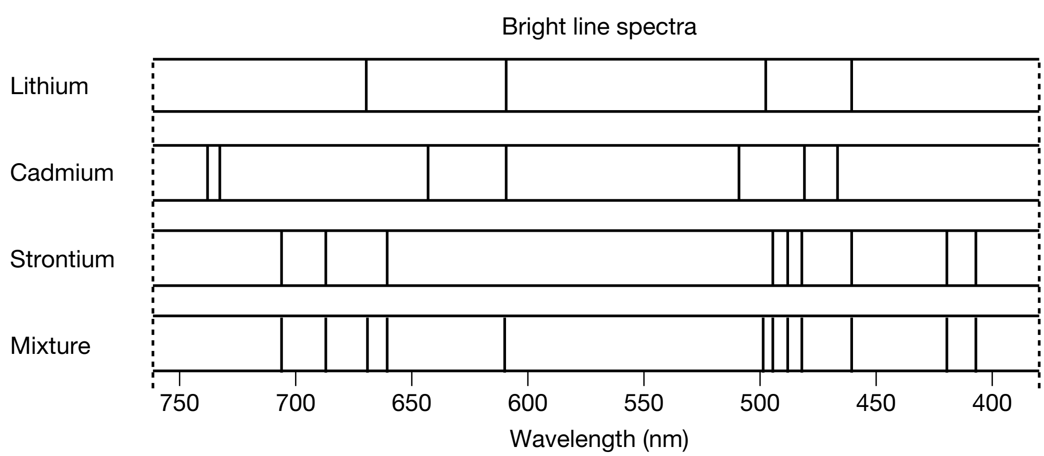
5. The diagram shows the absorption and emission spectra of hydrogen, carbon and oxygen.

(a) What is the difference between an emission spectrum and an absorption spectrum?

(b) Careful examination of the spectra shows us that the black lines in each absorption spectrum are in identical places to the coloured lines in each emission spectrum. Explain this.



6. Consider the diagram showing the spectra of several elements and an unknown substance.
Which of the elements shown are contained in the unknown substance?



Answers

1 James Clerk Maxwell

1. The power of the ideas of scientists like Sir Isaac Newton and the fact that Maxwell's work was based on mathematics, not proper scientific experiments caused it to be considered less reliable than 'proper science'.
2. Maxwell:
   - Calculated that the speed of propagation of an electromagnetic was the same as the speed of light.
   - Proposed that light must be a wave in a medium which was the same cause of electrical and magnetic waves.
   - Proposed that electricity, magnetism, and light could all be explained using the same theory in physics.
   - Proposed that light was propagated by alternating electric and magnetic fields, which he believed would vibrate perpendicular to one another.

2 Transverse Electromagnetic Waves

1. (a) Wavelength = CABD
   Amplitude = DBAC
   Frequencies are equal (See the question – 'same interval of time'.)

   (b)

Wave	Wavelength (mm)	Amplitude (mm)
A	10	16
B	16	13
C	8.5	15
D	28	8

2. A = Crest
   B = Wavelength
   C = Crest
   D = Amplitude
   E = Amplitude
   F = Trough
3. (a) Green photons. Green is closer to the high frequency end of the visible spectrum, and energy carried by photons depends on their frequency, or, alternatively, general knowledge tells us that gamma rays are most dangerous, so we could infer that the gamma ray end of the spectrum is the high energy end, and green is closer to this.
   (b) Because energy increases as frequency increases and as wavelength decreases, then energy is more likely to be proportional to the frequency (inversely proportional to the wavelength).
   Note that amplitude is a property of transverse matter waves and we use these only to represent electromagnetic waves because the magnetic/electric field diagrams are too difficult to draw.
   (c) Radio wave.
   (d) Microwave.
   (e) Short wavelength microwave or long wavelength infra-red (they overlap and the name depends on what we use them for).
   (f) Visible light.
   (g) Short wavelength ultraviolet or long wavelength X-rays.
4. (a) They all travel at the speed of light = 3×10^8 m s^{-1} in vacuum.
   (b) Microwaves are used as their small wavelength allows the use of small antennas and dishes. Microwaves are also more directional than radio waves, and their higher frequency means they can carry more information.
   (c) These are the frequencies that pass through the atmosphere. Others are absorbed and do not make it to the surface.
5. (a) Particle oscillation is at right angles to the direction of energy transfer.
   (b) Particle oscillation is back and forth in the same plane as energy transfer.
   (c) The mechanism by which electromagnetic waves propagate, the alternating electric and magnetic fields are at right angles to the direction of energy transfer.
6.

	Increasing wavelength →					
	γ	X	UV	Vis	IR	M	R/TV
B	●						
E			●				
G						●	
H							●
J					●		
K				●			
L		●					

3 Historical Measurements Of the Speed Of Light

1. The two main limiting factors were the very limited technologies available to measure both the distance that light travelled in the experiments and how long it took to travel this distance because of the fact that the speed of light was so great.
2. (a) Distance = 299 792 458 × 0.2 = 59 958 491.6 m
   = 59 958.5 km
   (b) If the human error was 50% of the value, then the time would have to be 0.4 s, so the distance the lanterns would have to be apart would be 59 958.5 km (remember the light travels there and back – a total distance of twice this).
   (c) Early measurements could not be accurated because of the high speed light and the limited accuracy of measuring instruments. It is only with modern technology that reasonable measures can be made.
3. Various.

4. Measuring the Speed Of Light – Home Experiment

Various.

5 Comparing Spectra From Lighting Sources

1. In colour, we consider bluish or white light to be cool and yellow or reddish light to be warm. The cool LED spectrum indicates a more even mix of the visible spectrum colours, so the light will appear whiter than the warm LED which has no blue in its spectrum to 'cancel out' the higher intensity red end of its spectrum.
2. (a) The spectral lines, although not continuous would suggest a fairly even mix of colours and so perhaps a white light should result.
   (b) The light purple colour can only be due to the intensity of the blue/purple spectral lines compared to the red/green lines resulting in the overall light purple in our vision.

6 Spectroscopy and Elements

1. The spectra indicate that the Sun contains only hydrogen and helium out of the elements shown. None of the spectral lines from the other elements are present in the spectrum of the Sun.
2. (a) Star A contains hydrogen and helium only.
   (b) Star B contains helium and calcium only.
   (c) Star C contains hydrogen and sodium only.
3. Elements B and C only.
4. Elements strontium, cadmium and sodium only.