CHAPTER 24

Spectroscopy: analysing the spectra of stars

Spectroscopy is a vital tool for astronomers and provides a wealth of information

Producing spectra

24.1

- ***Account for the production of emission and absorption spectra and compare these with a continuous black body spectrum***

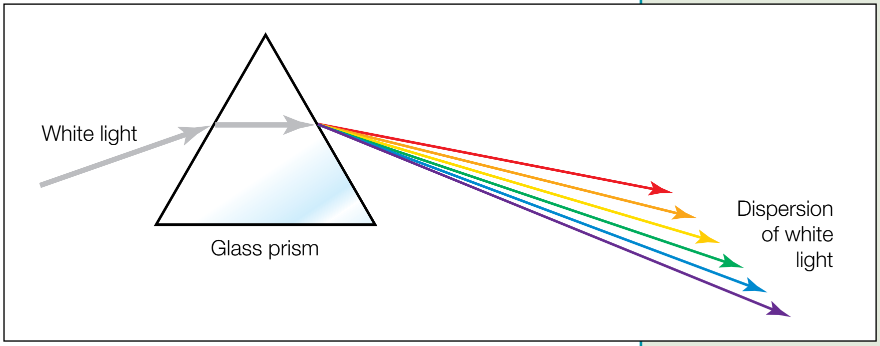


Figure 24.1 White light is dispersed into its component colours by a triangular prism

A spectrum is observed by allowing the light from a source to pass through a device that spreads the wavelengths apart. A triangular prism used for the dispersion of white light into the colours of the rainbow—and indeed raindrops, which produce rainbows—are examples of the production of a spectrum. The human eye perceives a combination of colours and wavelengths as one resultant colour, or white if the right combination of colours is present. This is why spectra cannot be observed with the human eye alone.

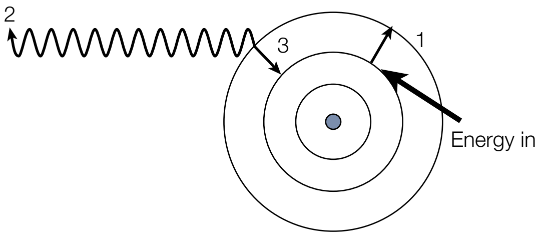
Emission spectra are produced when a body of low pressure gas atoms are heated or energised, 'excited', by other means such as a strong electric field. Electrons in the atoms absorb the energy and 'jump' to a higher energy level.

Niels Bohr, in his model of the atom, described the allowable orbits of electrons in terms of energy levels that electrons could 'jump' between. When moving up to higher energy levels, the electron would absorb an amount of energy equal to the energy difference between the two levels. The 'excited' atom will return to its normal 'ground' state when the electron loses energy by emitting a photon of light and 'falling' to a lower allowed energy level. The frequency of the emitted photon is determined by the equation $E = hf$, where E is the energy difference between the two allowed energy levels the electron moves between, and h is Planck's constant. As the allowed energy levels are fixed for a particular element, only certain frequencies, characteristic of that element, can be emitted.

The release of the absorbed energy by an electron occurs only at certain frequencies so that the observed spectrum has bright lines against a dark background (see Fig. 24.4a). Useful emission spectra sources include gas discharge tubes, fluorescent light tubes, and sodium or mercury vapour street lights.

Absorption spectra are produced when electrons in atoms, ions or molecules in the atmosphere of a star absorb radiation at set wavelengths. The absorbed

Figure 24.2 A low-pressure sodium vapour street light



An electron jumps up an energy level (1) when it absorbs energy. It releases the energy as a photon of light (2) with a set frequency when it returns to its original enrgy level (3).

Figure 24.3 The source of emission spectra

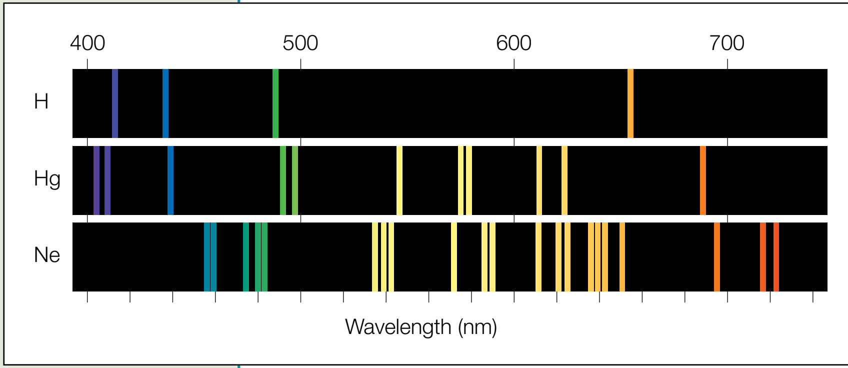


Figure 24.4 (a) Emission spectra for hydrogen, mercury and neon

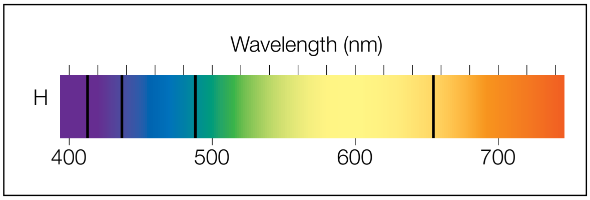
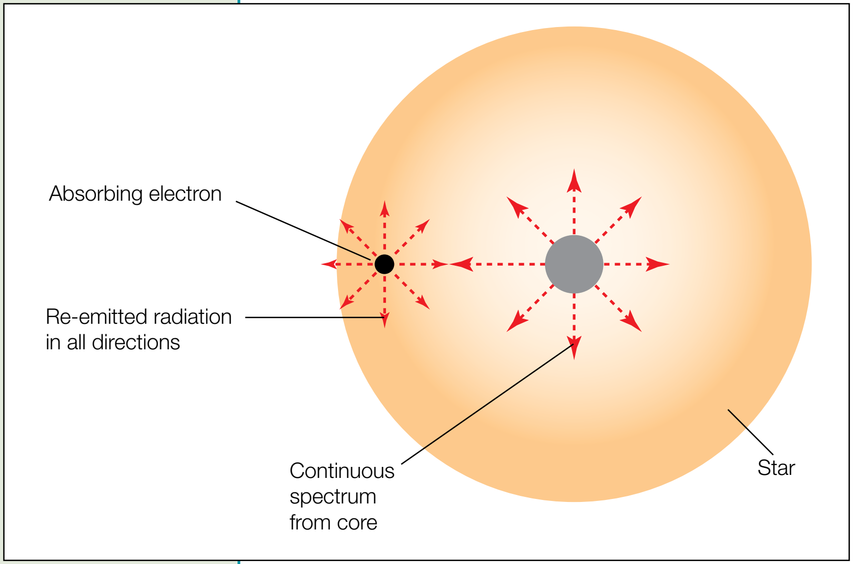


Figure 24.4 (b) An absorption spectrum for hydrogen

Figure 24.5 The production of an absorption line within a star



wavelengths are determined by the differences in the energy levels that the electrons jump between. The absorbed wavelengths, originally emitted from the core of the star, are re-emitted very soon after they are absorbed. Only a fraction of the re-emitted radiation is in the original direction (from the core). As the core of a star produces a continuous spectrum due to the black body radiation from such a high-temperature source, the wavelengths, which have been absorbed and then re-emitted in all directions, appear as dark lines against the bright continuous spectrum, as shown in Figure 24.4 (b). Figure 24.5 shows the mechanism occurring in a star that produces an absorption line in an absorption spectrum.

Continuous spectra are produced from hot bodies, like the tungsten filament in an incandescent light globe. (For more about black body radiation, see Chapter 11.) The core of a star, a region of dense nuclei heated to many million kelvin, is also a source of a continuous spectrum. As the temperature of the body increases, the peak wavelength of the radiation becomes shorter, as well as the amount of energy emitted increasing in proportion to the temperature in kelvin to the power of 4 (T^4). This causes the colour of the object to change from red through to orange, yellow and then white.

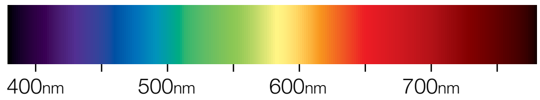


Figure 24.6 A continuous spectrum

When the peak wavelength of a continuous spectrum corresponds to green, the object appears white, not green. This is because at such a temperature, there is a significant amount of blue being emitted. Our eyes perceive this colour mixture as white.

Measuring spectra

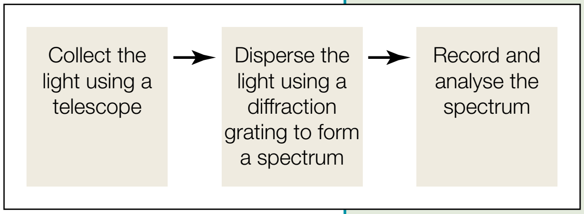
24.2

■ *Describe the technology needed to measure astronomical spectra*

There are three basic components required to measure astronomical spectra. First, the light must be gathered, so a telescope is required. Second, the collected light must be dispersed using a spectroscope. A diffraction grating is used to do this (acting in a similar way to a glass prism). The light will reflect off the diffraction grating at different angles, according to its different wavelengths. With the light separated into its range of wavelengths, the third requirement is a detecting or recording device. The first spectra were simply observed with the naked eye and recorded by hand. Photographic plates were able to make a permanent record of stellar spectra; however, for every 100 incident photons on photographic film, only one is captured and converted into the image. Charged coupled devices (CCDs) are far more efficient, converting 80%–90% of photons into the recorded image. This means that less exposure time is required to obtain the spectra, and smaller telescopes can be used.

This information is shown in a flow chart in Figure 24.7.

Figure 24.7 The requirements to obtain stellar spectra



Stellar objects and types of spectra

24.3

■ *Identify the general types of spectra produced by stars, emission nebulae, galaxies and quasars*

Emission spectra are observed from many **nebulae**. These are interstellar gas clouds at very low pressures heated by a nearby star. The heated gas molecules and atoms emit light at certain frequencies in a similar fashion to the gas in a fluorescent light. Quasars are also sources of emission spectra. Quasars are very distant, very luminous objects, thought to be huge black holes at the centre of a galaxy being consumed. They are as luminous as hundreds of normal galaxies. The material being accelerated by the black hole's extreme gravity causes the emission spectra.

Quasars (quasi-stellar objects) were first believed to be stars; however, the red-shift evident in their spectra showed that they are receding from us at such fast speeds that some of them must be around 13 billion light-years away, near the edge of the observable Universe. Quasars may emit energy equal to many thousands of galaxies, making them extraordinarily luminous objects. The true nature of the approximately 100,000 known quasars is still uncertain.

Absorption spectra are produced by stars. The relatively cooler outer layer of gases in a star's atmosphere are responsible for absorbing particular frequencies of the light coming from the star's core. The gaseous atoms that have absorbed a photon of light then re-emit the light at the same frequencies, but in all directions. To an observer, these re-emitted frequencies appear dark against a bright continuous background. Some stars, known as Wolf-Rayett stars, exhibit emission spectra. It is thought that these stars do not have a cooler outer atmosphere to absorb frequencies so the spectrum observed is coming directly from the radiative, inner layers. These stars are quite rare.

Galaxies appear to emit a continuous spectrum—a result of the combination of the emission spectra from interstellar nebulae and the absorption spectra produced by the hundreds of billions of stars in the galaxy. However, closer analysis reveals that galaxies not actively producing new stars show absorption lines (especially calcium and magnesium) but have little or none of the emission lines produced by nebulae. Younger galaxies still producing new stars also show emission lines.

Table 24.1 A summary of objects and spectra types they produce

Object	Type of spectra produced	Comments
Stars	Absorption	Absorption occurs in the atmosphere of the star
Emission nebula	Emission	Produced by the heating of low-density gases by nearby stars
Quasars	Emission	Possibly from matter being accelerated into a massive black hole
Galaxies	Continuous	May be absorption or emission depending on abundance of nebulae in galaxy

24.4 The key features of stellar spectra

■ ***Describe the key features of stellar spectra and describe how these are used to classify stars***

PFA

H2

'Analyses the ways in which models, theories and laws in physics have been tested and validated'

Background

The classification of stars by their spectra began before astronomers fully understood the link between the patterns within the spectra and the surface temperature of the star.

How has this model evolved over time?

In 1814 Joseph Fraunhofer carefully studied the hundreds of absorption lines present in the Sun's spectrum.

The original classification system used the letters A through to O based on the strength of the hydrogen absorption lines present (the Balmer series). It happens that a surface temperature of about 10 000 K produces the strongest Balmer series absorption lines. These stars were assigned the spectral type A based upon this. Cooler red stars exhibit very weak Balmer series lines in their spectra, and were assigned the letter M for their spectral type. However, very hot stars have no discernable Balmer series lines. These stars were assigned the letter O. The reason for the lack of hydrogen lines in such stars is that at such temperatures (above 20 000 K), hydrogen is completely ionised. That is, the electron in hydrogen responsible for the production of the hydrogen lines in the spectrum is no longer associated with the nucleus of the hydrogen atom (a single proton). It exists as a free electron.

Subsequent observation of black body radiation experiments and laboratory observations of hot gas spectra enabled astronomers to match the spectral types to surface temperatures of stars. The previous alphabetical order was found to be in need of a complete overhaul. Rather than re-assign all the letters, the spectral types were simply placed in the order hottest to coolest and simplified to eliminate overlapping and confusing spectra. This work was mainly done at Harvard University from 1918 to about 1924. The re-organised order, O B A F G K M, is still used today in the Hertzsprung-Russell diagram, a useful tool used by astronomers to assist in the classification of stars.

SR

Animation: spectroscopy

Where to from here?

The advent of infrared astronomy, possible with satellite-based telescopes, has led to recent modification of the spectral types classification. Stars previously too cool to classify (as they were not detectable by light telescopes) are now assigned the spectral types R, N or S, depending on the elements present in their spectra.

Other additions include the WR (Wolf-Rayet) and the T (T Tauri) categories.

TR

PFA scaffold H2

WWW

USEFUL WEBSITE

Further reading on stellar spectra:
http://www.shef.ac.uk/physics/people/pacrowther/spectral_classification.html

The key features of a star's spectrum used by astronomers when classifying the star include the appearance and intensity of spectral lines, the relative thickness of certain absorption lines, and the wavelength at which peak intensity occurs. The apparent colour of the star is determined by its surface temperature, as shown in Figure 24.8.

Table 24.2 Relationship between colour and surface temperature of stars

Spectral class	Effective temperature (K)	Colour	H Balmer features	Other features
O	28 000–50 000	Blue	Weak	Ionised He^+ lines, strong UV continuum
B	10 000–28 000	Blue-white	Medium	Neutral He lines
A	7 500–10 000	White	Strong	Strong H lines, ionised metal lines
F	6 000–7 500	White-yellow	Medium	Weak ionised Ca^+
G	4 900–6 000	Yellow	Weak	Ionised Ca^+, metal lines
K	3 500–4 900	Orange	Very weak	Ca^+, Fe, strong molecules, CH, CN
M	2 000–3 500	Red	Very weak	Molecular lines, e.g. TiO, neutral metals
L?	<2 000	Tentative new (2000) classification for very low mass stars.		

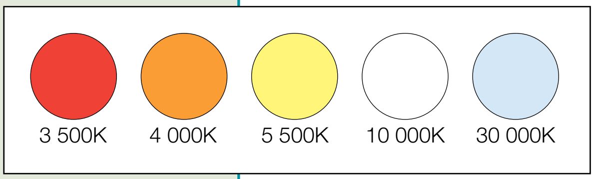


Figure 24.8 How the colour of a star varies with surface temperature

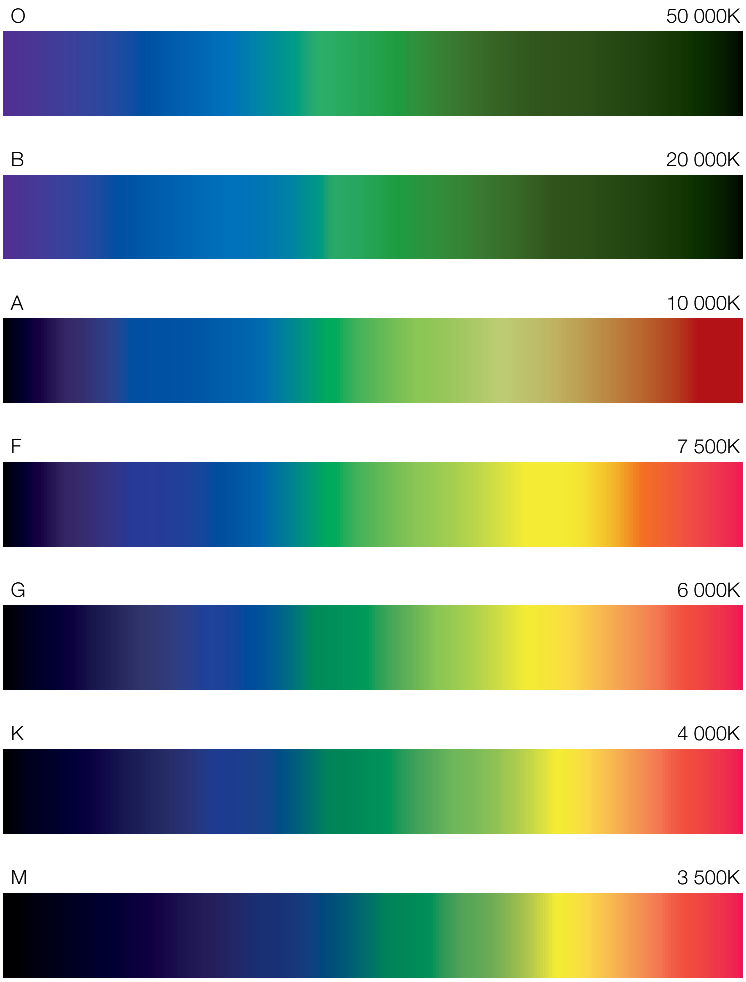


Figure 24.9 Examples of stellar spectra

USEFUL WEBSITE

This site is an interactive black body radiation simulator showing a continuous spectrum for the chosen black body temperature: http://webphysics.davidson.edu/Applets/java11_Archive.html

Table 24.3 Table of luminosity classes with examples

Symbol	Class of star	Example
O	Extreme, luminous supergiants	–
Ia	Luminous supergiants	Betelgeuse
Ib	Less luminous supergiants	Antares
II	Bright giants	Canopus
III	Normal giants	Aldebaran
IV	Sub-giants	Procyon
V	Main sequence	Sun
sd	Sub-dwarfs	Kapteyn's Star
wd or D	White dwarfs	Sirius B

NOTE: A 'white dwarf' is the remnant of a star in the final stages of cooling down after its nuclear fuel has been depleted. Despite their relatively high surface temperature they are very dim due to their size, about the same as the Earth. It is no longer fusing nuclei in its core, unlike 'dwarf' and 'sub-dwarf' stars, which are so-named due to their comparatively small size.

The location of the various luminosity classes is shown on a Hertzsprung-Russell diagram in Figure 24.10.

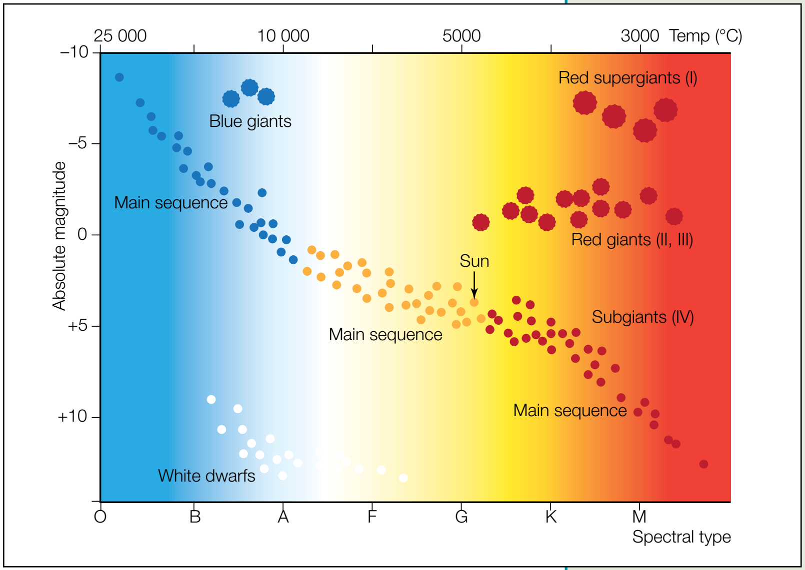


Figure 24.10 A Hertzsprung-Russell diagram with luminosity classes shown

The information about a star from its spectrum

24.5

- ***Describe how spectra can provide information on surface temperature, rotational and translational velocity, density and chemical composition of stars***

Surface temperature

The surface temperature of a star can be determined in two ways, both by examining the star's spectrum. By studying the absorption lines in the spectrum and comparing the pattern and intensity against reference stellar spectra, the star can be assigned a spectral class and a corresponding surface temperature. Alternatively, the intensity versus the wavelength of the radiation being emitted by the star is plotted. The wavelength at which the intensity is greatest (peak intensity wavelength) is then used in Wien's law to determine the effective surface temperature of the star.

$$\lambda_{max} T = W$$

NOTE: This equation is not given in the syllabus.

Where:

λ_{max} = the peak intensity wavelength (m)

T = the effective surface temperature of the star

W = Wien's constant (2.9×10^{-3} m K)

What is the 'surface' of a star if a star is a ball of gas? A layer of a star called the photosphere is a region where the temperature has cooled sufficiently for light to be produced. The more massive a star, the hotter is the photosphere. The photospheres of stars range in temperature from a few thousand K to 50 000 K. The temperature here is often referred to as the star's 'effective' surface temperature, acknowledging that a star does not have an actual surface in the same way a solid planet has. Molecules, elements and ions within the photosphere give rise to the star's spectral features.

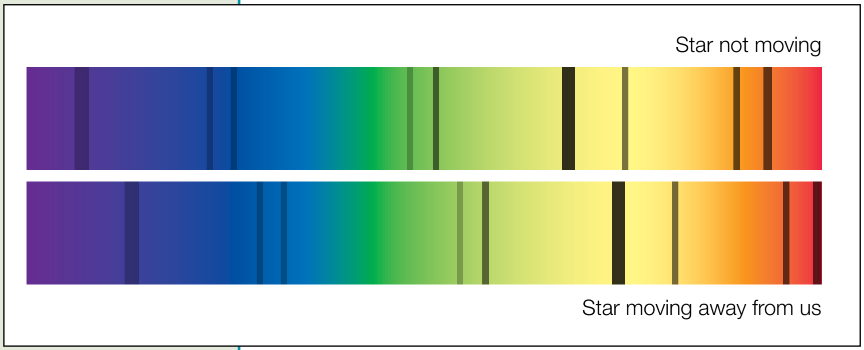
Rotational and translational velocity

The relative velocity of a star either approaching or moving away from an observer can be measured by the blue shift or red shift exhibited in the star's spectrum. The Doppler effect is the shortening of the wavelength of the light from a source that is approaching an observer and the lengthening of wavelengths from sources moving away (see Figure 24.11). Ordinarily, the Doppler effect may be noticed when an emergency vehicle passes with the siren on. The relative speed of the vehicle causes an increase in the pitch of the siren and then a decrease after it passes. This effect is also very noticeable for racing cars, as their high speed is a significant fraction (almost 1/3) of the speed of sound.

WWW→ **USEFUL WEBSITES**

A Doppler effect simulation for the effect on sound waves can be found at these two sites:
http://galileo.phys.virginia.edu/classes/109N/more_stuff/flashlets/doppler.htm
http://www.shep.net/resources/curricular/physics/java/physengl/dopplerengl.htm

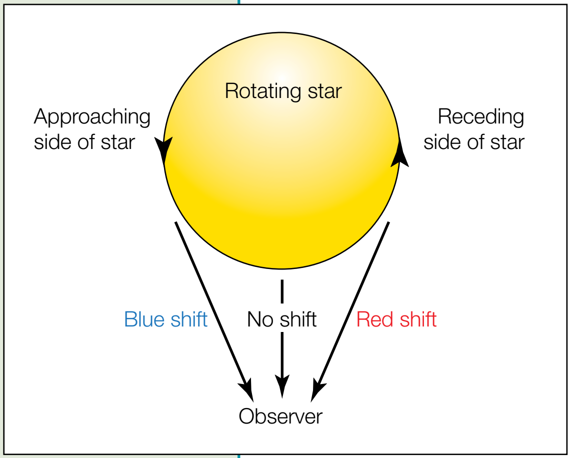
Figure 24.11 An example of red shift evident in a star's spectrum



If a star is rotating, one side is moving towards us while the other side is moving away, as shown in Figure 24.12. This results in the absorption lines within the spectrum being both red and blue shifted simultaneously, so that they appear broader than expected. Careful measurement of the amount of broadening, along with an estimation of the size of the star can lead to the calculation of the rotational velocity of the star.

If a star is moving directly towards or away from us it will not change its position relative to other stars; however, its motion can be detected by the red or blue shift of its spectral lines. Again, the amount of red or blue shift can be measured in order to calculate the star's translational velocity. Figure 24.11 shows how the spectrum of a star moving away from us would be shifted.

Figure 24.12 How a rotating star has its spectral lines broadened due to the Doppler effect



Density

It is very useful to know the density of a star's atmosphere. The largest supergiant stars have the lowest densities, while main sequence stars have higher densities. Finding the luminosity class of a star and its spectral type allows for a very good estimation of the star's absolute magnitude, from which its distance can be calculated using spectroscopic parallax. Lower density stellar atmospheres produce sharper, more narrow spectral lines. This is due to the motion of the atoms and ions, which are absorbing the radiation and producing the lines. The particles in lower density gases travel further before each collision with other particles. The absorption lines they produce are sharper. As giant stars have less gravity near their surface, the pressure is also less near the surface where the absorption spectrum is being produced, so their spectral lines are finer.

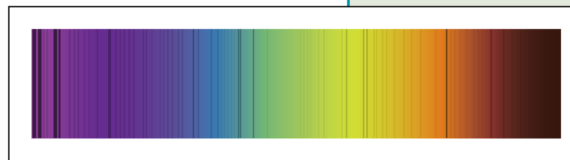


Figure 24.13 Fraunhofer lines visible in the Sun's spectrum

Chemical composition

Stars similar to the Sun have many elements in small quantities in their atmospheres. Each of these elements produces its own characteristic spectral lines. Calcium, potassium and iron are three such elements. Fraunhofer lines, named after Joseph Fraunhofer, who carefully observed the Sun's absorption lines in the 1800s, are due to the many elements absorbing radiation at particular wavelengths. Matching the absorption lines found in a star's spectrum with absorption lines produced by an element under laboratory conditions verifies the existence of that element in the star's atmosphere. The relative intensity of the absorption lines indicates the abundance of that element.

Examining spectra

FIRST-HAND INVESTIGATION

PHYSICS SKILLS

H12.1 A, B, D
H12.2 A, B
H14.1 E, F, G

- ***Perform a first-hand investigation to examine a variety of spectra produced by discharge tubes, reflected sunlight, or incandescent filaments***

This investigation is best performed using a hand-held spectroscope.

Method

1. In a darkened room, set up discharge tubes filled with a variety of different gases (sodium and mercury are two that are highly suitable.)
2. Observe the spectra produced by each discharge tube, and sketch your observations.
3. Next, observe the spectrum produced by a fluorescent light, and compare it with those previously observed from discharge tubes.
4. Observe the spectrum produced from an incandescent globe (without other sources of light present) and contrast this spectrum with those previously observed in steps 2 and 3. This should be repeated using different voltage settings on the power supply noting the effects of the change in temperature to both the intensity and the range of colour.
5. Finally, go outside and observe the spectrum from *reflected* sunlight. *Never point the spectroscope towards the sun—damage to your retina may result!* (You must ensure that the spectroscope is carefully focused for this part.) Compare and contrast this spectrum with all of those previously observed and relate the nature of each spectra to how they are produced.

TR Risk assessment matrix

Figure 24.14 An example of the emission spectrum produced by a mercury discharge tube

Predicting a star's surface temperature from its spectrum

SECONDARY SOURCE INVESTIGATION

■ *Analyse information to predict the surface temperature of a star from its intensity/wavelength graph*

An intensity versus wavelength graph such as the one shown in Figure 24.15 shows the relationship between the surface temperature of a black body and the wavelength of the peak intensity of the radiation being emitted.

WWW→

USEFUL WEBSITE

This website with user inputs for temperature shows black body radiation intensity curves:
http://webphysics.davidson.edu/Applets/java11_Archive.html

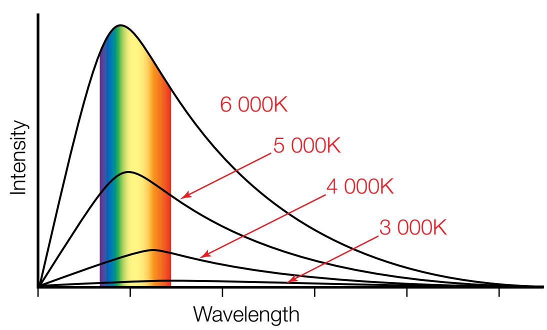


Figure 24.15 Intensity versus wavelength for black bodies at different temperatures

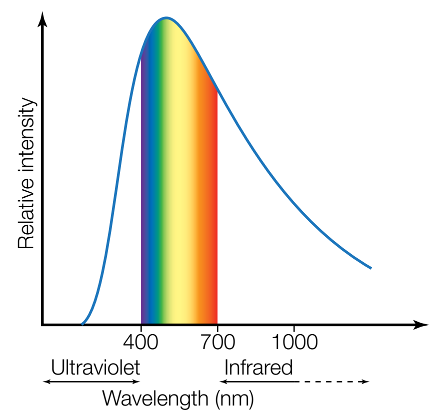


Figure 24.16 An intensity versus wavelength plot for the Sun

The intensity versus wavelength plot for a star can be compared to a given graph such as that shown in Figure 24.16. Another method is to use Wien's law, first developed in the 1890s, which is:

$$\lambda_{max} = \frac{W}{T}$$

NOTE: This equation is *not* listed in the syllabus and it is *not* necessary to memorise it.

Where:

λ_{max} = the wavelength of peak intensity

W = Wien's constant (2.898×10^{-3})

T = the star's surface temperature (in K)

The peak intensity wavelength for a star is observed and the equation applied.

Example

The peak intensity of radiation from a star being observed has a wavelength of 580 nm. What is the surface temperature of this star?

Solution

$$\lambda_{max} = \frac{W}{T}$$

$$T = \frac{W}{\lambda_{max}}$$

$$= \frac{2.898 \times 10^{-3}}{580 \times 10^{-9}}$$

$$= 5.00 \times 10^{3}\ \text{K}$$

CHAPTER REVISION QUESTIONS

1. Describe ways in which an absorption spectrum is similar to an emission spectrum and to a continuous spectrum.
2. How is a continuous spectrum produced?
3. The spectrum from a distant galaxy appears to be a continuous spectrum. Why?
4. The individual spectral lines within a star's spectrum all appear slightly shifted towards the red end. What does this tell us about the relative motion of this star?
5. Outline the information that can be found from the analysis of a star's spectrum.
6. A star, which has been observed for many years, does not seem to be moving relative to nearby stars; however, its spectral lines are shifted towards the blue end of the spectrum. What does this tell us about the motion of the star relative to us?
7. Use a diagram to explain how the spectral lines of a rotating star are red and blue shifted simultaneously.
8. How would the spectrum of a star with an atmosphere rich in metallic elements differ from a star that has a very low or non-existent abundance of metallic elements?
9. How would the peak wavelength of radiation emitted from a red star be different from the peak wavelength emitted by a white star?
10. Outline how the density of a star and hence its luminosity class can be found from its spectrum.

SR

Answers to chapter revision questions