CHAPTER 25

Photometry: measuring starlight

Photometric measurements can be used for determining distance and comparing objects

25.1 Stellar magnitude

■ *Define absolute and apparent magnitude*

The present scale of magnitude, used to measure the brightness of stars, has its origin as far back as the Greek astronomer Hipparchus (190–120 BC). Hipparchus surveyed more than 800 stars, and, based upon their apparent brightness in the night sky, assigned them a number. Number one was assigned to the brightest stars, through to number six for the faintest visible to the naked eye. It was not until the 1800s that it was realised the human eye detects light in a logarithmic fashion, and international astronomers defined a magnitude 1 star as being 100 times brighter than a magnitude 6 star. Mathematically, this results in a magnitude difference of one as being a brightness ratio of 2.512, as $\sqrt[5]{100} = 2.512$. Hipparchus's modified magnitude scale has now been extended to include the faintest objects (observed through powerful telescopes such as the Hubble Space Telescope) through to the brightest (the Sun). Some well-known objects and their magnitudes as observed from Earth are shown in Table 25.1. These magnitudes are called *apparent* as the brightness is observed from Earth. The brightness of a stellar object is dependent on its temperature, surface area and distance (inverse square law).

Definition

The **apparent magnitude** of an object is how bright it appears from the Earth using the magnitude scale.

Table 25.1 Some well-known objects and their apparent magnitudes

Object	Apparent magnitude
Sun	− 27
Venus (at its brightest)	− 4.4
Alpha Centauri	− 0.27
Titan (Saturn's largest moon)	+ 8
Faintest star visible using an Earth-based telescope	+ 26
Faintest object detected by Hubble Space Telescope	+ 30 (approx.)

A star's distance is a major factor in determining its brightness, and hence its apparent magnitude. Another magnitude, known as *absolute* magnitude is used to compare the luminosity (i.e. total light energy being emitted) of astronomical objects. To make this comparison fair, a standard distance of 10 parsecs is used.

Definition

The **absolute magnitude** of an object is how bright it would appear to be if placed at a distance of 10 parsecs using the same magnitude scale as that used for apparent magnitude.

Table 25.2 shows the apparent and absolute visual magnitudes of some stars.

Table 25.2 The apparent and absolute visual magnitudes of some stars

Star	Apparent magnitude	Absolute magnitude
Sun	– 27	+ 4.8
Sirius (next brightest star)	– 1.4	+ 1.4
Betelgeuse (a red supergiant in Orion)	+ 0.45	– 5.1
Barnard's Star	+ 9.5	+13.2

The comparison of absolute magnitudes allows the luminosities of stars to be compared.

It is noted that Betelgeuse is approximately 10 000 times more luminous than the Sun. For each five magnitudes *lower*, a star is 100 times brighter (by definition). As Betelgeuse has an absolute magnitude about 10 lower than the Sun, its luminosity is $100 \times 100 = 10\,000$ greater.

A star's luminosity is determined by two factors: the surface temperature of the star and its surface area. The laws that relate to the amount of energy emitted by a black body are closely matched by a star. Importantly, the energy radiated by a star is proportional to the temperature of the surface to the fourth power, as given by the Stefan-Boltzmann law:

$$E \propto T^4.$$

A star with a surface temperature of 7 000 K when compared to a star with a surface temperature of 3 500 K will radiate 2^4, or 16 times, more energy per surface area. A star with a surface temperature of 21 000 K is six times hotter than a star with a surface temperature of 3 500 K, and therefore emits 6^4, or 2376 times, the energy *per surface area.*

Stars are essentially spherical. The surface area of a sphere = $4\pi r^2$. A doubling in the size of a star gives it four times the surface area. A red supergiant can have a radius more than 25 000 times larger than a white dwarf, giving it 625 million times the surface area. This factor outweighs the previous temperature dependency, so that red giant stars are far more luminous than white dwarfs.

It should be remembered *why* the magnitude scale seems to be the wrong way around, that is, why *brighter* objects have a *lower* magnitude. The system in use today relates all the way back to the ancient Greek astronomers, including Hipparchus and the system he used to rank the stars from brightest to faintest using the numbers one to five.

25.2 Using magnitude to determine distance

■ *Explain how the concept of magnitude can be used to determine the distance to a celestial object.*

Only the closest stars can have their parallax angle determined and thus their distance measured directly. However, if a star's absolute magnitude can be found (methods for doing this will be discussed later) and its apparent magnitude measured, the distance to the star can be calculated. In Table 25.2, it can be seen that the Sun's apparent magnitude is a much *lower* number than its absolute magnitude. This is because the Sun is much closer than 10 parsecs away. Conversely, the apparent magnitude of Betelgeuse is *higher* than its absolute magnitude as it is about 130 pc away.

Interesting fact: The light from a star that is 10 pc away takes 32.6 years to reach us. Light from the Sun takes a little over eight minutes to reach us!

Astronomers refer to the difference between a star's apparent magnitude, m, and its absolute magnitude, M, as the star's 'distance modulus':

$m - M$ = distance modulus

Using the distance modulus, the distance to a star can be calculated using a technique called *spectroscopic parallax*.

25.3 Spectroscopic parallax

■ *Outline spectroscopic parallax*

A star closer than 10 pc will have a *negative* distance modulus, while a star further away than 10 pc will have a *positive* distance modulus.

Using this distance modulus and the definition used to determine the magnitude scale, the equation:

$$M = m - 5\log\frac{d}{10}$$

can be used to calculate the distance to the star. The distance given will be in parsecs.

Example 1

A certain star has a measured apparent magnitude of +17 (using a large telescope). This star's absolute magnitude is determined to be +3. What is the calculated distance to the star using spectroscopic parallax?

Solution

$$M = m - 5\log\frac{d}{10}$$

$$3 = 17 - 5\log\frac{d}{10}$$

$$-14 = -5\log\frac{d}{10}$$

$$\log\frac{d}{10} = 2.8$$

$$\frac{d}{10} = 10^{2.8}$$

$$d = 10^{3.8}$$

$$d = 6310 \text{ pc}$$

■ *Solve problems and analyse information using: $M = m - 5\log\left(\frac{d}{10}\right)$ and $\frac{I_A}{I_B} = 100^{(m_B - m_A)/5}$ to calculate the absolute or apparent magnitude of stars using data and a reference star*

SR

Worked examples 21, 22

The first of these two equations has been dealt with in the previous section. In order to find the absolute magnitude of a star that has a known distance (using trigonometric parallax), the star's apparent magnitude must also be measured. An example is shown below.

Example 2

A newly discovered star is in a galaxy known to be 40 000 pc away. The star's apparent magnitude is measured as +21.0. What is this star's absolute magnitude?

Solution

$$M = m - 5\log\frac{d}{10}$$

$$= 21 - 5\log\frac{40000}{10}$$

$$= 21 - 18.0$$

$$= 3.0$$

NOTE: 'Log' in physics implies $\log_{10}$.

Example 3

What is the apparent magnitude of a distant star '*Alpha*' if it is one-tenth as bright as another star '*Beta*'? The apparent magnitude of *Beta* is +8.0.

Solution

Using $\frac{I_A}{I_B} = 100^{(m_B - m_A)/5}$

where $m_B = +8.0$

and $\frac{I_A}{I_B} = \frac{1}{10}$

$= 0.1$

$0.1 = 100^{(8 - m_A)/5}$

taking the log of both sides:

so $\log 0.1 = (8 - m_A)/5\log 100$

$-1 = (8 - m_A)/5 \times 2$

$-5/2 = 8 - m_A$

$m_A = 10.5$

25.4 Colour index

■ *Explain how two-colour values (i.e. colour index, B-V) are obtained and why they are useful*

The direct observation of a star's colour is not always possible, especially if the star is faint or if there is interstellar dust or gas between Earth and the star. The human eye is insensitive to colour from faint sources, especially when the light is from point sources such as starlight. Our eyes also take a long time to adapt to darkness and we 'undersee' red light during this time. Analysis of a star's spectrum may also be difficult, so astronomers have developed an alternative way in which the colour of a star, and hence its surface temperature, can be determined.

The determination of a star's apparent magnitude (see earlier in this chapter) by comparing its brightness to a reference star's brightness is relatively straightforward. By placing a blue filter between the telescope and the camera, or using a photometric device that analyses only the blue part of the star's spectrum, an astronomer can measure the blue apparent magnitude (m_B or B) of the star. Using a yellow filter or yellow part of the star's spectrum, the yellow, or 'visual', apparent magnitude (m_V or V) of the star can also be measured. The difference between the two magnitudes, $m_B - m_V$, is usually between 0 and 1.5.

The blue filter (B), at 440 nm wavelength, is used for colour index calculations as this wavelength corresponds to the peak sensitivity of photographic film. The human eye is most sensitive to wavelengths in the yellow-green portion of the visible spectrum, at 550 nm. This wavelength is used for the visual (V) filter.

In Chapter 24, the way in which the intensity of a star's spectrum varies with wavelength was discussed. A star with a relatively low surface temperature, such as a red giant, will not emit much radiation in the shorter wavelength region of the visible spectrum as a proportion of its total radiation. This proportion will increase as the star's surface temperature increases, so that a white star will have a greater proportion of its total radiation being emitted in the blue end of the spectrum. As a consequence, a white star will have a blue magnitude very close in value to its visual (yellow) magnitude, so that its colour index, B – V, will be close to zero. However, a red star, being brighter in the yellow part of its spectrum than in the blue, will have a colour index of about 1.5. Very hot blue or blue-white stars may have a colour index slightly less than zero. Figure 25.1 shows the intensity versus wavelengths graphs of a white star and a red star with the blue and visual intensities compared. Very cool stars, such as 'brown' stars, are not usually assigned a colour index as they emit only a very small amount of blue-wavelength radiation which is often too weak to measure properly. Table 25.3 shows some examples of some colour indices.

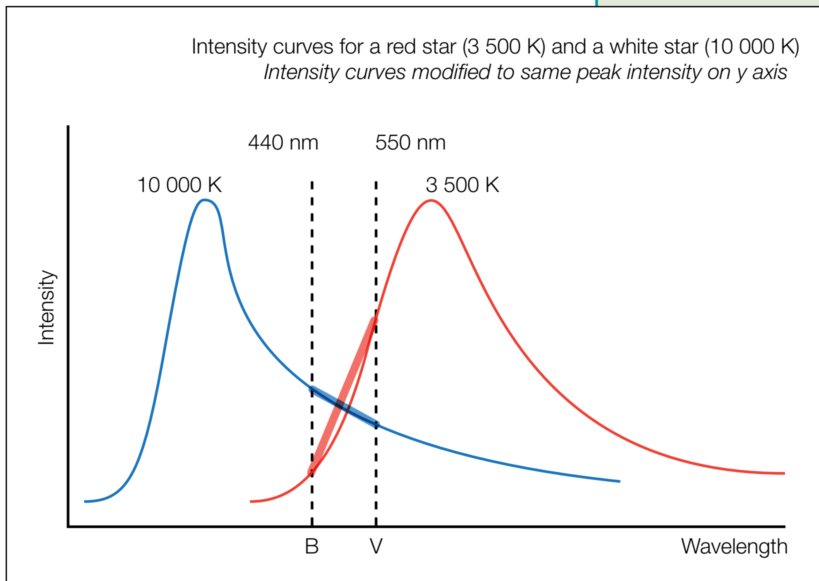


Figure 25.1 The intensity versus wavelength curves for a white star and a red star, showing how the colour index is found for both stars

Table 25.3 The colour index, $m_B - m_V$, and a star's colour and typical surface temperature

Star	Colour Index	Colour	Surface temperature (K)
Betelgeuse	+ 1.54	Red	3 400
Sun	+ 0.67	Yellow	5 850
Sirius A	– 0.06	White	9 900

Being able to obtain a star's colour index assists astronomers in determining the distance to the star using spectroscopic parallax. While spectroscopic parallax is used to find the distance to a star, it does not use parallax measurements at all. Rather, it relies on being able to find a star's absolute magnitude, M, which may include finding the star's colour index or other methods such as spectral analysis to determine the star's spectral class or surface temperature. This determines the star's horizontal position on an HR diagram. Further analysis of the star's spectrum may allow its luminosity class to be found, for example if the star is a giant or a main sequence star. This allows for the star's vertical position on a Hertzsprung-Russell (HR) diagram to be estimated which in turns reveals its absolute magnitude, M. Finally, the equation $M = m - 5\log\frac{d}{10}$ can be applied to find the distance to the star.

Using filters for photometric measurements

FIRST-HAND INVESTIGATION

PHYSICS SKILLS

H12.1A, B, C
H12.2A, B

- ***Perform an investigation to demonstrate the use of filters for photometric measurements***

Sample procedure for this investigation

Use an incandescent light (a source of a continuous spectrum) such as a light globe or the lamp in a ray box as the source. Ray box kits have coloured filters suitable for use in this investigation. Coloured cellophane will suffice as a filter too. Use either a light detector attached to a data logger, or a light meter to record the intensity of the light through various coloured filters and without the filter. If possible, change the temperature of the globe (using a ray box lamp, turn the voltage down to 10 V or 8 V) and take another set of readings.

The brightness of the light through each filter is represented by the intensity measured. It is also possible to use a hand-held spectroscope to view the spectrum of the globe through the filters to observe the effect the filter has on the different wavelengths being emitted from the globe.

Questions

1. Compare the ratio of the brightness of the light for your source through a blue or violet filter with the intensity through a red filter.
2. How does this ratio vary when the lamp is turned down (i.e. becomes cooler/redder)?
3. How does this ratio represent the 'colour index' of the globe?

25.5 Photographic versus photoelectric technology

PFA H4

'Assesses the impacts of applications of physics on society and the environment'

TR

PFA scaffold H4

- ***Describe the advantages of photoelectric technologies over photographic methods for photometry***

What are the applications of physics in this case?

Exposure to light triggers the small generation of an EMF in one of millions of miniature photocells in a CCD (charge-coupled device). The photoelectric effect is responsible for this EMF, which, when along with the millions of other EMFs in the other cells, is analysed and constructed to produce an image.

The need for sensitive CCDs to act as the 'film' in photoelectric devices with sufficient resolution to rival traditional photographic film for use by astronomers and organisations such as NASA has driven the development of this technology over the past few decades.

The advantages of photoelectric devices (digital format, better sensitivity, remote sensing, selective wavelengths, etc.) have made them essential for astronomy. This has filtered down into consumer use, where, in the space of a few years, digital cameras and videos have surpassed photographic devices with the exception of some very specialised uses.

What impacts have there been on society?

Society has benefited from photoelectric technologies in several ways. Instant viewing and transmission of photographs using digital technology (i.e. the Internet, email, etc.) is one example. A medical procedure can be viewed in real time by specialists thousands of kilometres away. The photoelectric devices in the video cameras are linked directly to the Internet, whereas photographic devices would have had to have the film developed and then transported, perhaps taking days. Remote sensing cameras onboard satellites or automatic cameras are used for weather and climate observations and in security applications.

What impacts have there been on the environment?

Large quantities of chemicals, including the element silver, were required to produce photographic film. The photos themselves were printed on paper. Many of these were subsequently discarded due to poor quality or mistakes. Digital photos still require paper and ink for printing; however, only selected good quality photos need be printed as they can be previewed using a computer or the camera itself. No silver is used in the operation.

Indirectly, the ability to monitor the environment using photoelectric devices has enabled scientists to observe the effects of pollution, land clearing and other human activity. Knowing these effects allows us to take active measures to guard against further harm. The depletion of the ozone layer is a good example of how remote sensing alerted scientists to a potential catastrophe.

The assessment of these impacts

The widespread use of photoelectric devices in today's society at the consumer as well as technical levels has made an important and significant impact. Communication, medicine, remote sensing, meteorology and climatology are a few of the important fields that have been radically changed by the adoption of technology that was originally driven by the needs of astronomy and space research.

USEFUL WEBSITES

←WWW

Interesting reading on the photoelectric effect and its applications:
http://cfcpwork.uchicago.edu/kicp-projects/nsta/2007/pdf/nsta_2007-photoeleclab.pdf

Information on charge-coupled devices:
http://www.computerworld.com/softwaretopics/software/multimedia/story/0,10801,62778,00.html

Photometry is the measurement of the brightness of astronomical objects, including stars, nebulae, asteroids and galaxies. The first photographic photometry commenced in the early 1900s. Brighter objects in a photographic exposure create larger images, despite the actual image size being a single point. Comparison of the diameter of the image made by an object against reference objects on the same exposure allowed for the accurate measurement of the brightness.

Traditional photographic techniques using light-sensitive film emulsion based on the reaction of silver salts have been used since the early 1800s. To record images seen through telescopes, astronomers have been using photography to record the spectra of stars since 1872. Photography is an inherently slow process as it is based on a chemical reaction. It requires the developing and fixing of the image onto a medium such as a glass plate or paper. It is also quite an inefficient process, capturing only a few photons out of every hundred incident photons to form an image. Photography is not suitable for remote applications such as recording images from telescopes onboard orbiting observatories.

There are three types of photoelectric technologies suitable for photometry. All utilise the photoelectric effect to produce a voltage. The first is the photomultiplier tube (see Fig. 25.2), a vacuum tube capable of multiplying the original signal by millions of times. They are accurate and sensitive, but prone to mechanical damage in harsh environments and can be destroyed by being exposed to very bright light.

Figure 25.2
A diagram of a photomultiplier

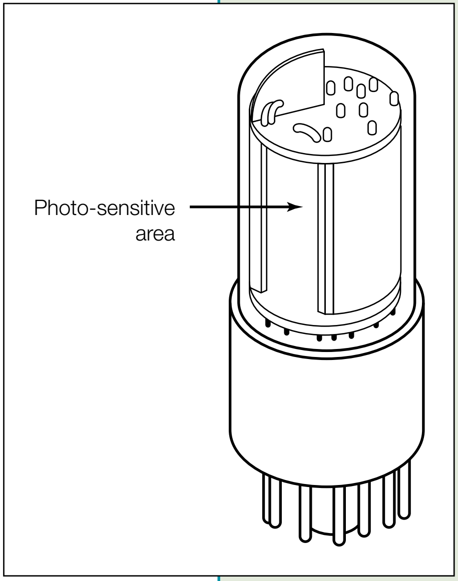
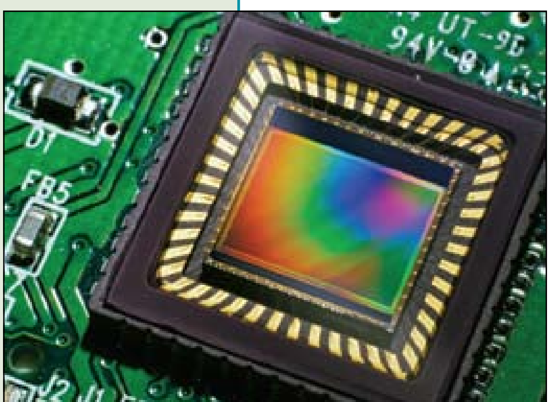


Figure 25.3
A photodiode



A typical CCD

The photodiode (see Fig. 25.3) is a solid state device used as a light detector. While not as sensitive as a photomultiplier, they are smaller and more robust, and are capable of detecting a broader range of wavelengths, from infrared through to UV.

The most popular device now used in stellar photometry is the CCD, or charge-coupled device. Modern photoelectric technologies use the photoelectric effect in tiny individual photovoltaic cells to record incident light. Millions of these cells are grouped together to act much like the rod and cone cells in a human eye. Each cell is wired to miniature capacitors to hold the charge to make CCDs. These hold the image and then deliver it in binary code to computer software, which reconstructs the code back into an image. The number of pixels in a digital camera equates to the number of individual photovoltaic cells in the CCD used to record the image. The higher the number, the better the resolution of the image, making the detail finer and the image sharper. A CCD in a typical general purpose digital camera may have many millions of these cells. The strength of the signal produced within a CCD by a particular stellar object represents that object's brightness. This analysis can be performed rapidly using computer technology.

Photoelectric technology in the form of CCDs has other distinct and important advantages over photographic methods for recording images, as well as for photometry. These are outlined below.

Sensitivity

A typical CCD will respond to over 70% of the incident light, whereas photographic film's response is only about 2–3%. For astronomy, this is a very significant advantage as exposure times necessary for photographs can be reduced by over 90% using photoelectric instruments. The sensitivity of CCDs is relatively flat over the spectrum compared to photographic film that is more sensitive to the blue end of the spectrum than the red.

Response to a range of wavelengths

CCDs are responsive to infrared wavelengths. They are used in remote-control receiving circuits for televisions and similar devices. Night vision binoculars and cameras use CCDs for military, security and search and rescue applications. In astronomy, they can be used for infrared as well as visual imaging. It is also possible to select a small range of wavelengths to analyse by subtracting unwanted wavelengths from the image.

Image manipulation and enhancement

Computer programs can be used on the digital code making up the image to enhance, enlarge, add false colour or subtract selected wavelengths to assist in identifying features in the image which may not be detected otherwise. Such manipulation of photographs is either impossible or would take a long time to prepare.

The impact of improvements in technology in astronomy

SECONDARY SOURCE INVESTIGATION

PFAs

H4, H5

PHYSICS SKILLS

H12.3A, B, C, D
H12.4F
H13.1A, B, C

- ***Identify data sources, gather, process and present information to assess the impact of improvements in measurement technologies on our understanding of celestial objects***

What you need to do

The way in which photometry has progressed, which has been outlined previously, will form the basis of your research. Further background reading, for example found at the suggested useful websites below, will assist with this. How these improvements have increased our understanding of celestial objects will centre on photoelectric applications in photometry and in image and data collection and analysis.

Specific information to gather and process for presentation

It is necessary to identify specific ways in which improvements in measurement technologies have played a part in our understanding of celestial objects. These include, but are not limited to:

- how very small variations in the brightness of a star may indicate it is in fact a multiple star system (see next chapter)
- how variable stars' light output changes over time
- how asteroids can be tracked in their orbits around the Sun
- how images obtained in the UV or infrared parts of the electromagnetic spectrum have added to our understanding

The finishing touches

As with any 'assess' investigation or question, the extent to which the improvements in measurement technologies have actually increased our understanding of celestial objects must be clearly defined. For example, it is not sufficient to simply say 'to a great extent'. Illustrate your final assessment with a few examples of what we know now as a direct result of the improvements.

SR

'Assess'

USEFUL WEBSITE

WWW

The Australia Telescope National Facility web site information:
http://outreach.atnf.csiro.au/education/senior/astrophysics/photometry_photoelectricastro.html

CHAPTER REVISION QUESTIONS

1. Outline the difference between a star's absolute magnitude and its apparent magnitude, giving definitions where appropriate.

2. Explain why a star with a larger apparent magnitude is in fact not as bright as a star with a smaller apparent magnitude.

3. A star has an apparent magnitude of +8.0 when the observer is 20.0 pc away. When the observer is 2.0 pc away from the star, what will the star's apparent magnitude be?

Answers to chapter revision questions

4. Further to question 3, calculate the star's absolute magnitude when the observer is 20.0 pc and then calculate the star's absolute magnitude when the observer is 2.0 pc away. Why are the two values equal?

5. Calculate the brightness ratio of star 'P' (apparent magnitude +4.5) with star 'Q' (apparent magnitude +7.0).

6. Explain the purpose of obtaining the colour index of a star.

7. The magnitude of a star measured through a yellow (visual) filter is +12.5. Given that it is known that this star has a surface temperature of 3500 K, what would the magnitude of the star be when taken through a blue filter?

8. In point form, list reasons why photoelectric applications have largely replaced photographic methods for measuring and recording starlight.

9. Outline some applications of photometry.