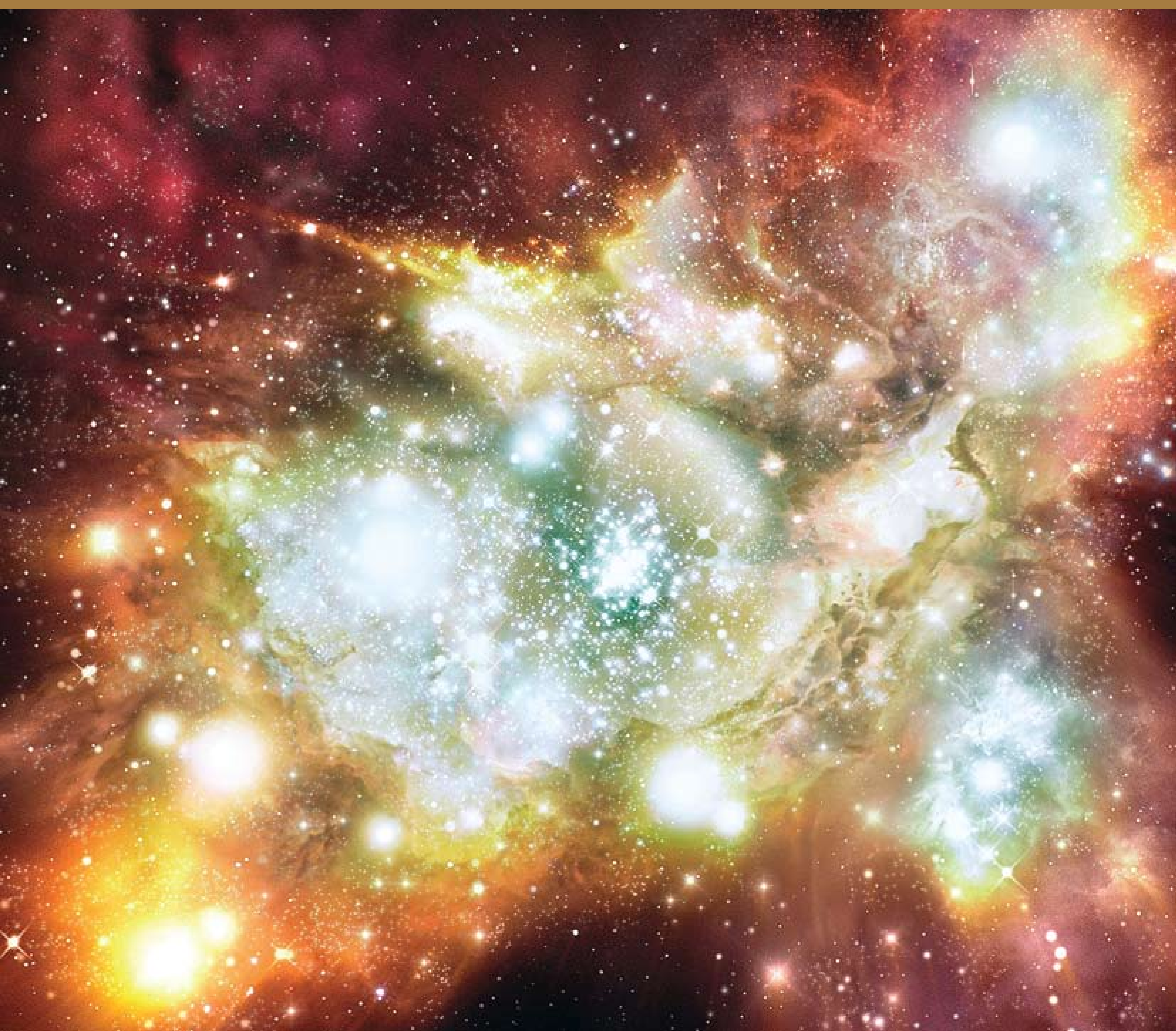
ASTROPHYSICS

Mind map



CHAPTER 22

Observing our Universe

Our understanding of celestial objects depends upon observations made from Earth or from space near the Earth

22.1 Galileo's observations of the heavens

- ***Discuss Galileo's use of the telescope to identify features of the Moon***

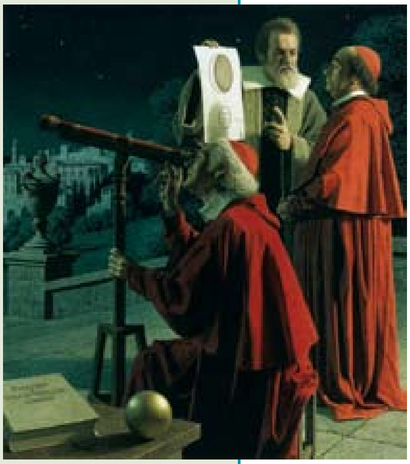


Figure 22.1 Galileo explaining Moon topography to sceptics

Galileo did not invent the telescope, but he was the first person to construct one so that it could produce a sufficiently clear image to observe features on the Moon, which today can be seen with everyday binoculars.

A crude form of telescope, known as perspicillums, made from roughly ground glass lenses placed at either end of a hollow tube, were sold as children's toys and novelty items. Believed to have been 'invented' by at least two different Dutch spectacle makers, they could make distant objects such as church steeples appear closer. Galileo improved the perspicillum. He used better quality glass from the glassblowers around Venice in Italy, which he then ground himself to produce better lenses. He called the improved the device a telescope. The result was much improved, so much so that the mountains and craters of the Moon were clearly visible to Galileo. However, in Galileo's time, all heavenly bodies were considered 'perfect'. This view had been held since Aristotle, and was incorporated into the teaching of the Catholic Church (along with the belief that the Earth was the centre of the Universe). Clearly, to Galileo, this was not the case. Using the angle of the Sun, Galileo made estimates of the heights of the lunar mountains and showed that the craters were deep with high sides around them. Vast regions of plains—'mares' (meaning oceans) were mapped by Galileo with the aid of his refined telescope.

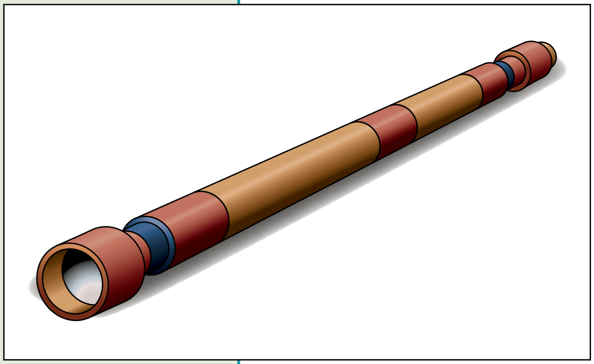


Figure 22.2 A telescope like the one used by Galileo

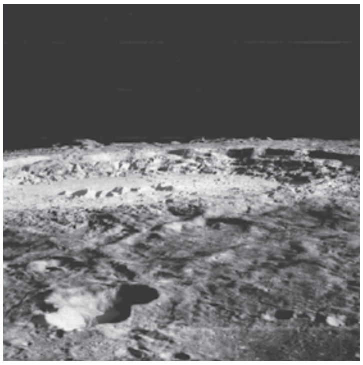


Figure 22.3 (a) The Moon, first observed through a telescope by Galileo

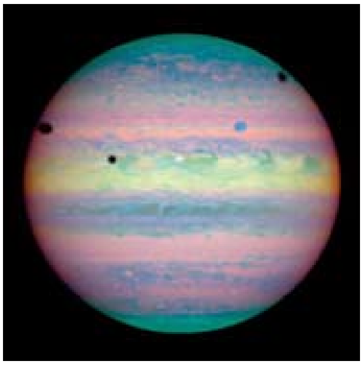


Figure 22.3 (b) Jupiter and one of its four Galilean moons, Io, as observed through a small telescope

Galileo's observations of our nearest neighbour in space, showing its imperfections for the first time, were followed by observations of Jupiter's moons orbiting their parent planet. This in turn led to Galileo's model of the solar system with the Sun, not the Earth, at its centre.

The atmosphere is a shield

22.2

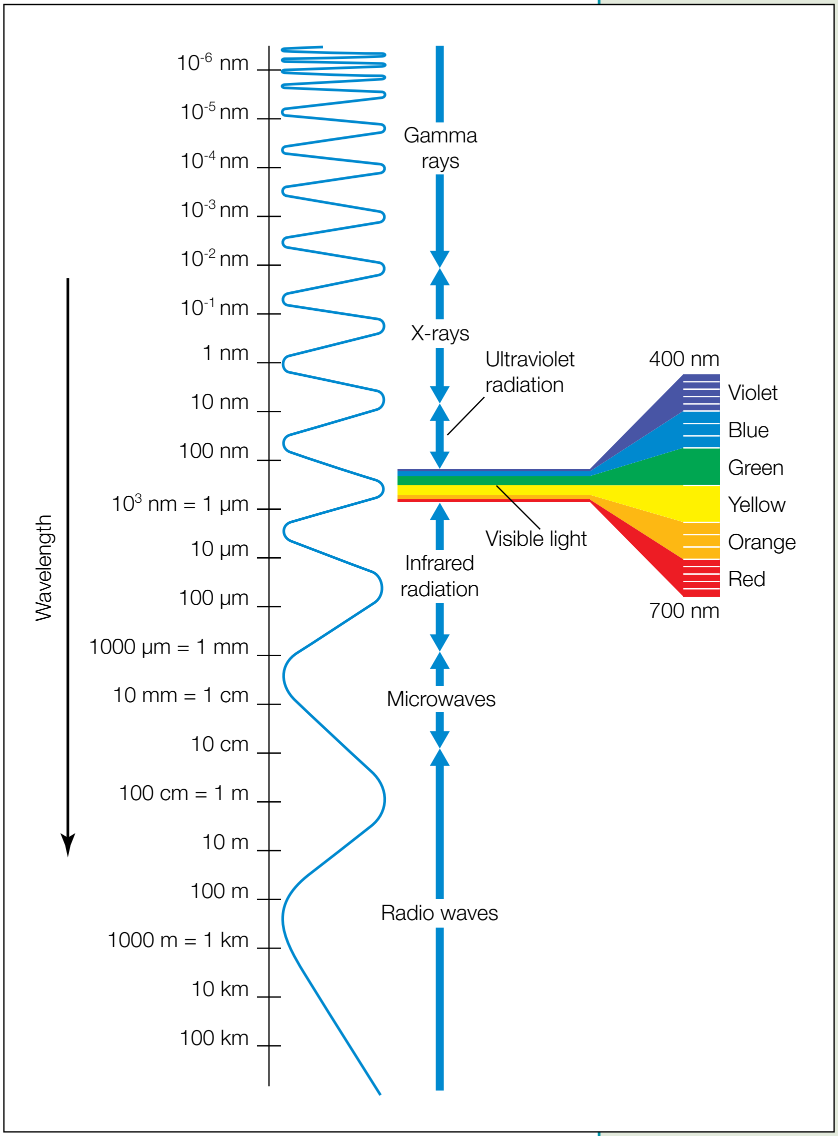
■ *Discuss why some wavebands can be more easily detected from space*

Earth's atmosphere extends above us for several hundred kilometres. Air pressure is a result of the weight of the vertical column of air above us. Composed mostly of the gases nitrogen and oxygen, the atmosphere is transparent to visible light and most radio waves. For these **wavebands**, there is little interaction with the molecules in the atmosphere. However, blue light, having a shorter wavelength in the visible spectrum, is scattered by fine particles and larger molecules in the atmosphere. The scattering is evident by the way in which the sky appears blue in all directions.

The electromagnetic spectrum is shown in Figure 22.4. The wavebands are regions within the spectrum that have common characteristics and uses.

For wavebands other than visible light and radio, the atmosphere acts as a shield, absorbing nearly all gamma and X-rays and the majority of ultraviolet (UV) rays. Gamma rays are absorbed by the atoms making up the atmosphere. UV wavelengths are absorbed by ozone gas molecules as well as by other molecules in the atmosphere. Getting a sun tan is evidence that some UV radiation penetrates the atmosphere. Infrared radiation (heat) is partially absorbed by carbon dioxide and water vapour molecules. The blue appearance of the sky is due to the scattering of short-wavelength visible light by fine particles and larger molecules, evidence that even visible light is somewhat affected by the atmosphere. At sunset and sunrise, light from the Sun has a longer path to travel through, causing the shorter wavelengths to be scattered and leaving a dominance of longer

Figure 22.4 The electromagnetic spectrum with wavebands shown



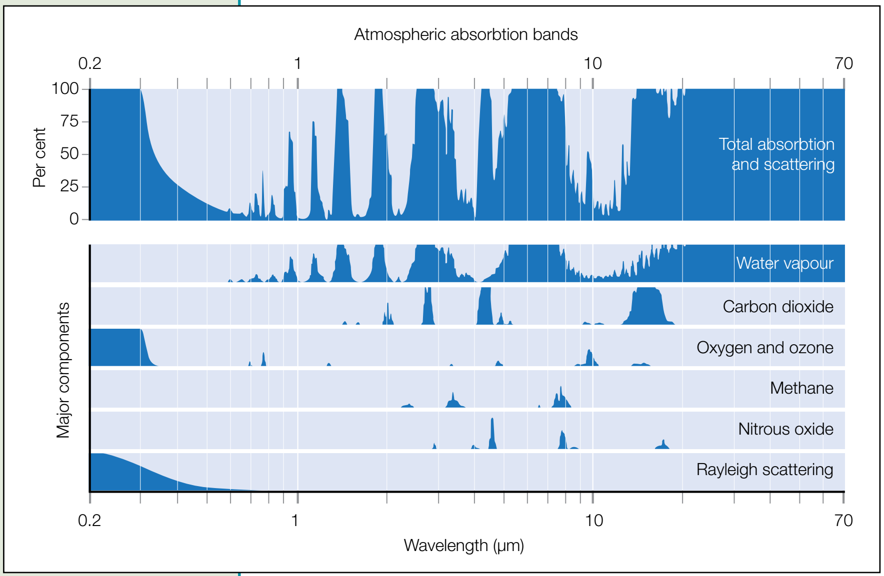


Figure 22.5 Diagram showing absorbance of wavebands by atmosphere

Figure 22.6 Mount Stromlo Observatory

wavelengths, causing the Sun to appear redder. Further to this scattering effect is the distortion, or **seeing** caused by the refraction of light as it passes through air of slightly different densities due to temperature variations. The twinkling of stars is probably the most commonly recognised effect of seeing. The stars are so distant that they approximate mathematical points to our eyes. Refraction (seeing) causes minute shifts in position resulting in apparently larger and flickering dots.

A mirage seen on a hot road in summer is an extreme case of the refraction of light due to the difference in the density of hot air and cooler air. Very hot air near the road's surface is less dense and allows light to travel through it faster than the cooler air above. When viewing at very shallow angles, the road appears to shimmer as the observer is actually viewing a distorted image of the sky just above the road. See Figures 22.7 (a) and 22.7 (b). The same refractive effect, although less pronounced, causes the twinkling of stars—an astronomer's worst nightmare after clouds.

Wavebands absorbed by the atmosphere are more easily detected from space, above any atmospheric effects. This is why many hundreds of millions of dollars have been spent in recent years in placing instruments on satellites to detect all but radio waves for use in astronomical observations. The Compton Gamma Ray Observatory, the Chandra X-ray Observatory, the Hubble Space Telescope and the Spitzer

Figure 22.7 (a) How a mirage forms over a hot road

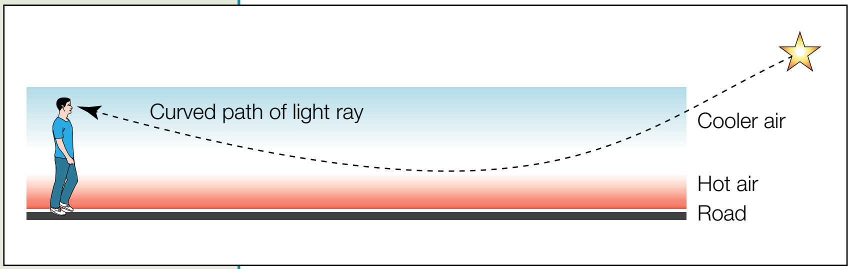


Figure 22.7 (b) A mirage

(infrared) Space Telescope all orbit the Earth and are controlled remotely from ground-based centres.

For ground-based instruments, astronomers have been limited to gathering information primarily in the visible light and radio wavebands. The reception of radio waves from deep space using instruments on satellites is not feasible due to the very large dishes used in radio astronomy. The main dish on the Parkes radio telescope has a diameter of 64 m.

Figure 22.8 The Compton Gamma Ray Observatory

Figure 22.9 The Parkes radio telescope

Resolution and sensitivity

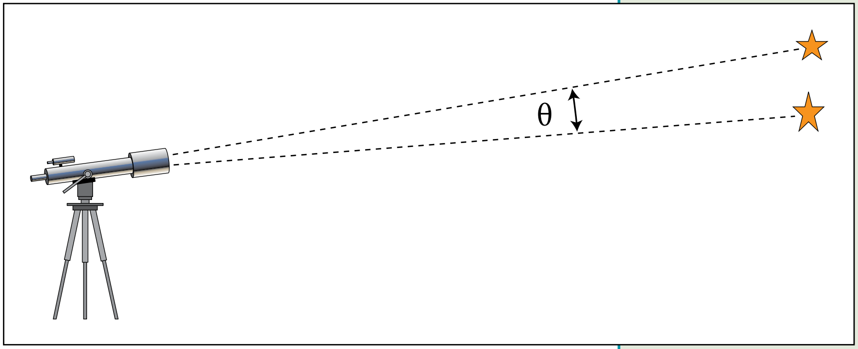
22.3

■ *Define the terms 'resolution' and 'sensitivity' of telescopes*

Any device designed to capture an image must resolve the information in a similar way to how a camera focuses. The **resolving power** of a telescope is its ability to make distinct images of objects, which are close to each other in **angular separation**. Our eyesight cannot resolve the distant headlights of a car into two separate sources of light until the approaching car is sufficiently close for the angular separation of the headlights to be greater than the resolving power of our eyes. Figure 22.10 shows how angular separation is defined by the angle two objects make with the observer.

In the case of an astronomical telescope, two stars with a small angular separation may appear as one. A larger telescope with better resolving power may make the two stars become distinctly separate. This is because the larger the diameter of the primary light gathering lens or mirror, the better the resolving power of the telescope. The resolving power, wavelength of light and diameter of the primary lens or mirror are related by the equation:

Figure 22.10 Angular separation diagram



$$R = \frac{2.1 \times 10^5 \lambda}{D}$$

Where:

R = the minimum angle of resolution (seconds of arc)

λ = the wavelength (m)

D = diameter of the telescope's primary mirror or lens (m)

(a)

(b)

Figure 22.11 Sensitivity comparison photograph: (a) less sensitivity, (b) more sensitivity

As the wavelength of the observed light increases, the minimum angle of resolution for that instrument increases. As a consequence, blue light has a smaller angle of resolution than red light using the same telescope. Radio telescopes have a relatively poor resolving power compared to light telescopes. The introduction of interferometry, which links radio telescopes hundreds of kilometres apart, has increased the resolution of radio astronomy. Visible light wavelengths to which the human eye responds range from 380 nm to about 750 nm (i.e. 3.8×10^{-7} m to 7.5×10^{-7} m). Radio telescopes typically observe electromagnetic radiation with wavelengths of the order of millimetres to centimetres.

The **sensitivity** of a telescope is a measurement of its light gathering ability. This is directly proportional to the surface area used to collect the incoming light, either the objective lens for a refracting telescope or the primary mirror for a reflecting telescope. For radio telescopes, the area of the dish, which is used to reflect the radio signals onto the receiver, is proportional to the sensitivity. As most mirrors and lenses are circular, a doubling of their diameter results in a four-fold increase in their surface area, and therefore in the sensitivity of the telescope. For any circle, $A = \pi r^2$. It follows that the sensitivity of a telescope is proportional to the square of the diameter of its primary lens or mirror. Figure 22.11 shows images taken through telescopes with different sensitivities. A more sensitive telescope will reveal stars with less brightness.

22.4 Earth's atmosphere limits ground-based astronomy

- ***Discuss the problems associated with ground-based astronomy in terms of resolution and absorption of radiation and atmospheric distortion***

Ground-based astronomy has a number of limitations imposed by the effects of the atmosphere on observations, as discussed in previous sections. The wavebands that can be detected from the ground, radio and visible light, had been the traditional types of astronomy until the advent of satellite-based instruments. The remaining wavebands, gamma rays, X-rays, UV and infrared are all extremely useful to astronomers, as they can reveal information and detail hidden from the radio and visible light wavebands.

Seeing, the term for atmospheric distortion, limits the practical resolution possible for any telescope, no matter how large. A number of techniques are used to reduce this limitation (see the next section) but they are expensive and available only by utilising considerable computing power. Placing the telescope as high as possible, on a mountain, reduces atmospheric distortion in a number of ways. Having less atmosphere to penetrate by being placed at altitude results in less haze, pollution and water vapour (most of which is found in the lower few kilometres), which absorb light and infrared wavelengths. Often the site is above the clouds and it is affected by fog far less frequently than at lower altitudes. Also, the temperature tends to be more uniform in the atmosphere at higher altitudes, resulting in less seeing. Seeing is the result of warmer air pockets with a lower refractive index in surrounding cooler air (or vice versa). Another effect of the atmosphere for ground-based astronomy is distortion of the colour of the light passing through it. At sunrise and sunset, sunlight must follow a longer path through the atmosphere (see Fig. 22.12). This effect is seen in an exaggerated form as the blue light (shorter wavelengths) is scattered by the atmosphere so that the longer wavelengths (i.e. red) dominate. Ground-based astronomers must take this into account when making observations, even when the subject is at a relatively high elevation.

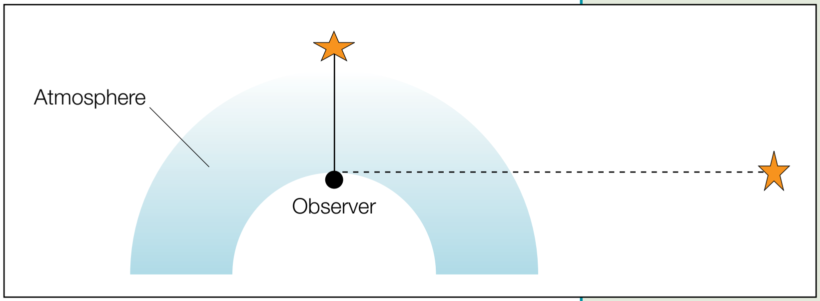


Figure 22.12 How light from a low elevation source passes through more of the atmosphere

Improving resolution

22.5

- ***Outline methods by which the resolution and/or sensitivity of ground-based systems can be improved, including adaptive optics, interferometry and active optics***

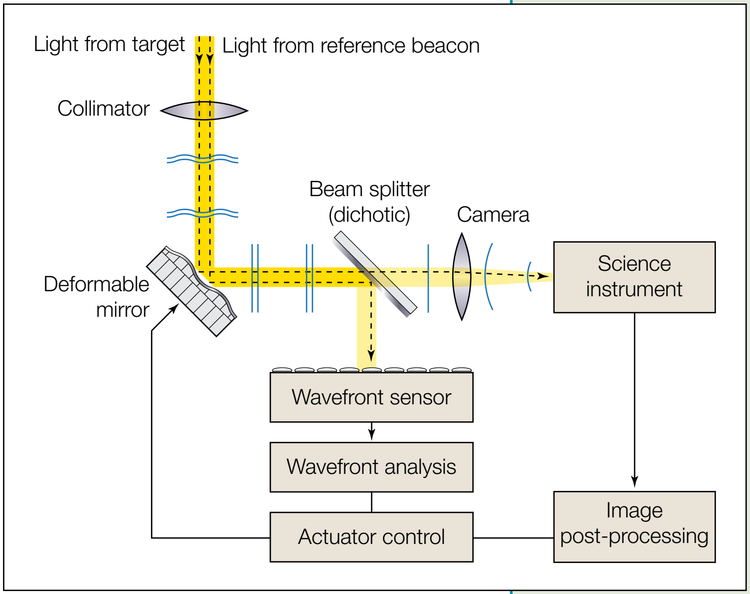
The limit of the resolving power of a standard ground-based telescope is about one arc second. This can be achieved with a relatively small mirror. Simply using larger mirrors improves sensitivity but not resolution.

The problems associated with ground-based systems, referred to previously, can be reduced using methods that utilise computerised control of mirror shape, or computerised wavefront correction or extended baseline by utilising separate telescopes, or by simply placing the telescope at high-altitude locations. The details of these methods are outlined below.

Adaptive optics uses a brighter light source from either a nearby star or a laser beam. The way in which the atmosphere affects this bright light source is analysed in real time by a wavefront sensor. Corrections to the distortions are fed into the telescope's rapidly adaptable mirror so that the observed image has the distortion caused by the atmosphere largely eliminated. As the corrections are made at around 1000 times per second, considerable computing power is required. In addition, expensive technology is needed to make the changes in the adaptable mirror.

Active optics has some similarities with adaptive optics in that it too employs a wavefront sensor to detect distortion in the collected light. However, unlike adaptive optics, active optics uses a slower feedback system that corrects deformities in the primary mirror of the telescope. These deformities can be caused by sagging under its own weight as it is moved to different positions and by differences in temperature,

Figure 22.13 Adaptive optics applied to an optical system



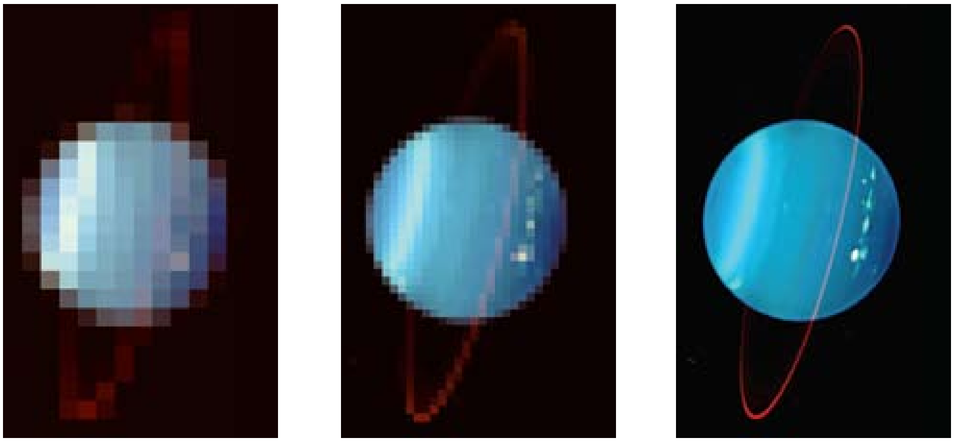


Figure 22.14 The enhanced effect of adaptive optics (simulated)
(a) View of Uranus through a conventional Earth-based telescope; **(b)** the Hubble Space Telescope; **(c)** the Hawaiian Keck Telescope fitted with adaptive optics

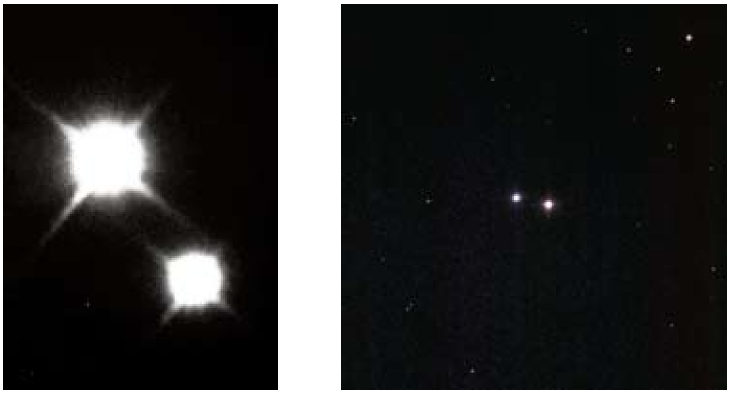


Figure 22.15 An example of an image of a double star taken without adaptive optics (left image) and through the same telescope using adaptive optics (right image)

causing expansion and contraction in the mirror itself. Prior to active optics, mirrors were constructed using thick glass to avoid deforming, but this added to their weight and to the cost of the mounting and the mirror itself. Such thick mirrors were limited to about 5 to 6 m in diameter. With active optics, thinner, cheaper and lighter mirrors can be used, typically 8 m or more in diameter. Active optics is now used in most new telescope mirrors, such as the 10 m Keck telescopes in Hawaii.

Interferometry is a technique applied to radio astronomy. The wavelength of radio waves (typically from 1 mm to several hundred kilometres) is many times greater than visible light (400 to 800 nm). This means that radio telescopes would need to have dishes hundreds of kilometres in diameter to match the resolution of large optical telescopes. This is clearly not practical. In order to overcome this limitation, two or more radio telescopes are linked by computers, which combine the incoming signals from the separate telescopes to produce an interference pattern. This is then analysed further and is converted into an image with a resolution approaching those of the largest optical telescopes. The Square Kilometre Array (SKA) is a system of about 80–100 separate radio telescopes, costing approximately AU$1.8 billion. It is planned to be built either in Australia or South Africa. Interferometry will enable the SKA to have the equivalent resolution of a single dish hundreds of kilometres in diameter by placing several receivers hundreds of kilometres from the main group. Its sensitivity will be 100 times greater than any other radio telescope due to the total receiving area being about 1 million square metres (1 square kilometre).

Figure 22.16 The twin Keck telescopes in Hawaii

The relationship between the size of the instrument and sensitivity

■ *Identify data sources, plan, choose equipment or resources for, and perform, an investigation to demonstrate why it is desirable for telescopes to have a large diameter objective lens or mirror in terms of both sensitivity and resolution*

This investigation can be performed in several ways. If two telescopes with considerably different objective lens or mirror diameters are available, viewing the same region of the night sky (if possible) will reveal far more stars through the larger telescope due to its greater sensitivity. Viewing a planet that has observable detail (Jupiter with its red spot or Saturn with its rings) will reveal greater detail through the larger telescope due to its better resolution.

A second way avoids the need for a night excursion. It would require an observer to compare the clarity of detail of objects in the far distance viewed through two binoculars of different sizes. This method only provides a qualitative comparison of resolution.

In a third method, the resolving power of a small telescope, binoculars and the unaided eye are compared. This is done using a chart with two black rectangles close together. The distances at which the gap between the rectangles on the chart can be discerned when viewed through each device or unaided eyes represents the difference in the resolving powers.

Yet another way in which this investigation can be approached is by using Internet search engines to obtain images of the same region of the sky taken through telescopes with different diameters. Search terms 'resolution', 'objective lens size', 'telescope mirror diameter', etc. are starting points. These would become the resources used in the investigation.

FIRST-HAND INVESTIGATION

PFAs

H1

SKILLS OUTCOMES

H11.1B, E
H11.2B, C, D, E
H11.3A, B, C
H12.1A, B, D
H12.2A, B
H12.4A
H14.1A, C

TR

Risk assessment matrix

USEFUL WEBSITES

WWW

NASA's deep space tracking facility in Canberra with links to many space observatories and probes:
http://www.cdscc.nasa.gov/Pages/pg03_trackingtoday.html

Use of radio frequencies in radio astronomy:
http://www.nfra.nl/craf/freq.htm

The Narrabri radio telescope facility:
http://www.narrabri.atnf.csiro.au/public/atca_live/atca_live.html

CHAPTER REVISION QUESTIONS

1. (a) Outline the adverse effects that the Earth's atmosphere has on astronomical observations made in wavebands other than light.
   (b) Outline how these adverse effects are overcome or avoided in modern astronomy.
2. Describe quantitatively the changes in a telescope's resolution and in its sensitivity when its 20 cm diameter objective lens is upgraded to a 40 cm diameter lens.
3. Explain the purpose of adaptive optics and how it overcomes some of the problems caused by the atmosphere.

4. Compare the techniques of adaptive optics and active optics in improving astronomical observations.
5. Give reasons why interferometry is widely used in the field of radio astronomy.
6. Undertake further research into future developments regarding interferometry and its application in astronomy.
7. Research several orbiting satellites and for each, describe the waveband being observed, its purpose, current status and achievements.
8. Discuss the costs involved in making modern astronomical observations against the benefits to society (knowledge, technological gains, etc).

SR

Answers to chapter revision questions