1) Description of stelar - systems
2) Nature of Stars (chemical composure)
3) Paralax Method (angles mainly and distances)
4) Luminosity and Brightness - Problems with distance

globular = old stars (larger numbers)
open = younger stars (hotter) (smaller)

Option D Astrophysics

D1 Stellar quantities

This section begins with a brief description of the various objects that comprise the universe, especially stars. We discuss astronomical distances and the main characteristics of stars: their luminosity and apparent brightness. Table **D.1** presents a summary of key terms.

Learning objectives

- Describe the main objects comprising the universe.
- Describe the nature of stars.
- Understand astronomical distances.
- Work with the method of parallax.
- Define luminosity and apparent brightness and solve problems with these quantities and distance.

D1.1 Objects in the universe

We live in a part of space called the **solar system**: a collection of eight major planets (Mercury, Venus, the Earth, Mars, Jupiter, Saturn, Uranus and Neptune) bound in elliptical orbits around a star we call the Sun. Pluto has been stripped of its status as a major planet and is now called a 'dwarf planet'. The orbit of the Earth is almost circular; that of Mercury is the most elliptical. All planets revolve around the Sun in the same direction. This is also true of the comets, with a few exceptions, the most famous being Halley's comet. All the planets except Mercury and Venus have moons orbiting them.

Leaving the solar system behind, we enter interstellar space, the space between stars. At a distance of 4.2 light years (a light year is the distance travelled by light in one year) we find Proxima Centauri, the nearest star to us after the Sun. Many stars find themselves in **stellar clusters**, groupings of large numbers of stars that attract each other gravitationally and are relatively close to one another. Stellar clusters are divided into two groups: **globular clusters**, containing large numbers of mainly old, evolved stars, and **open clusters**, containing smaller numbers of young stars (some are very hot) that are further apart, Figure **D.1**.

Very large numbers of stars and stellar clusters (about 200 billion of them) make up our **galaxy**, the Milky Way, a huge assembly of stars that are kept together by gravity. A galaxy with spiral arms (similar to the one in Figure **D.2a**), it is about 120 000 light years across; the arm in which our solar system is located can be seen on a clear dark night as the spectacular 'milky' glow of millions of stars stretching in a band across the sky.

As we leave our galaxy behind and enter intergalactic space, we find that our galaxy is part of a group of galaxies – a **cluster** (such as the one shown in Figure **D.2b**), known as the Local Group. There are about 30 galaxies in the Local Group, the nearest being the Large Magellanic

open

globular

Figure D.1 **a** The open cluster M36; **b** the globular cluster M13.

Option D

16

Astrophysics

galaxy:
A large number of stelar and open cluster

ESSENTIAL IDEAS

- ✓ One of the most difficult problems in astronomy is coming to terms with the vast distances between stars and galaxies and devising accurate methods for measuring them.
- ✓ A simple diagram that plots the luminosity versus the surface temperature of stars reveals unusually detailed patterns that help understand the inner workings of stars. Stars follow well-defined patterns from the moment they are created to their eventual death.
- ✓ The Hot Big Bang model is a theory that describes the origin and expansion of the universe and is supported by extensive experimental evidence.
- (chem) ✓ The laws of nuclear physics applied to nuclear fusion processes inside stars determine the production of all the elements up to iron.
- The modern field of cosmology uses advanced experimental and observational techniques to collect data with an unprecedented degree of precision, and as a result very surprising and detailed conclusions about the structure of the universe have been reached.

16.1 (D1: Core) Stellar quantities

– one of the most difficult problems in astronomy is coming to terms with the vast distances between stars and galaxies and devising accurate methods for measuring them

SOS

Nature of Science

A topic without practical investigations

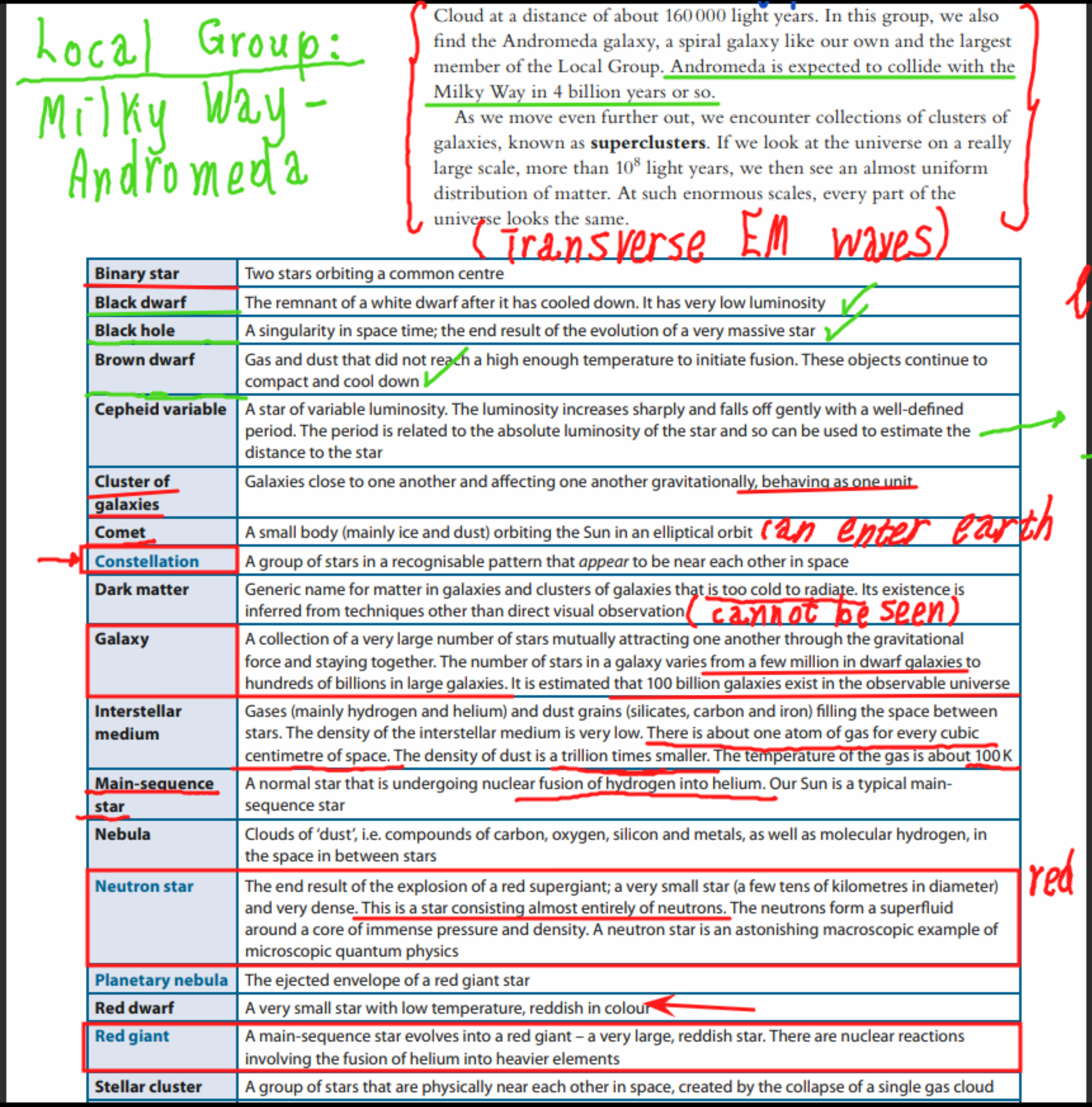
Astronomy is an unusual topic within the study of physics because the standard 'scientific method' is not so obvious. There are no controlled experiments designed to investigate a theory. Instead astronomers make observations and collect data. One consequence of this is that the growth of knowledge in astronomy is very much dependent on the latest technology available to aid observations.

No student studying astronomy can fail to be impressed by the depth of knowledge about the universe that astronomers have gained from apparently so little evidence – just the radiation received from outer space!

Galaxies can also be packed in groups

In the first section of this chapter we will begin by summarising what we can see in the night sky and then outline the essential features of stars and stellar systems, before explaining the scale of the universe and the units astronomers use to measure such large distances. Finally we will establish the important relationship between the power emitted from a star and the intensity received here on Earth.

1) Description of stelar - systems
2) Nature of Stars (chemical composure)
3) Paralax Method (angles mainly and distances)
4) Luminosity and Brightness - Problems with distance



Local Group:
Milky Way - Andromeda

Cloud at a distance of about 160 000 light years. In this group, we also find the Andromeda galaxy, a spiral galaxy like our own and the largest member of the Local Group. Andromeda is expected to collide with the Milky Way in 4 billion years or so.

As we move even further out, we encounter collections of clusters of galaxies, known as **superclusters**. If we look at the universe on a really large scale, more than 10^8 light years, we then see an almost uniform distribution of matter. At such enormous scales, every part of the universe looks the same.

(Transverse EM waves)

Binary star	Two stars orbiting a common centre
Black dwarf	The remnant of a white dwarf after it has cooled down. It has very low luminosity ✓
Black hole	A singularity in space time; the end result of the evolution of a very massive star ✓
Brown dwarf	Gas and dust that did not reach a high enough temperature to initiate fusion. These objects continue to compact and cool down ✓
Cepheid variable	A star of variable luminosity. The luminosity increases sharply and falls off gently with a well-defined period. The period is related to the absolute luminosity of the star and so can be used to estimate the distance to the star
Cluster of galaxies	Galaxies close to one another and affecting one another gravitationally, behaving as one unit
Comet	A small body (mainly ice and dust) orbiting the Sun in an elliptical orbit can enter earth
Constellation	A group of stars in a recognisable pattern that *appear* to be near each other in space
Dark matter	Generic name for matter in galaxies and clusters of galaxies that is too cold to radiate. Its existence is inferred from techniques other than direct visual observation (cannot be seen)
Galaxy	A collection of a very large number of stars mutually attracting one another through the gravitational force and staying together. The number of stars in a galaxy varies from a few million in dwarf galaxies to hundreds of billions in large galaxies. It is estimated that 100 billion galaxies exist in the observable universe
Interstellar medium	Gases (mainly hydrogen and helium) and dust grains (silicates, carbon and iron) filling the space between stars. The density of the interstellar medium is very low. There is about one atom of gas for every cubic centimetre of space. The density of dust is a trillion times smaller. The temperature of the gas is about 100 K
Main-sequence star	A normal star that is undergoing nuclear fusion of hydrogen into helium. Our Sun is a typical main-sequence star
Nebula	Clouds of 'dust', i.e. compounds of carbon, oxygen, silicon and metals, as well as molecular hydrogen, in the space in between stars
Neutron star	The end result of the explosion of a red supergiant; a very small star (a few tens of kilometres in diameter) and very dense. This is a star consisting almost entirely of neutrons. The neutrons form a superfluid around a core of immense pressure and density. A neutron star is an astonishing macroscopic example of microscopic quantum physics
Planetary nebula	The ejected envelope of a red giant star
Red dwarf	A very small star with low temperature, reddish in colour
Red giant	A main-sequence star evolves into a red giant – a very large, reddish star. There are nuclear reactions involving the fusion of helium into heavier elements
Stellar cluster	A group of stars that are physically near each other in space, created by the collapse of a single gas cloud

ℓ
cepheid variable
T(y)

red supernova

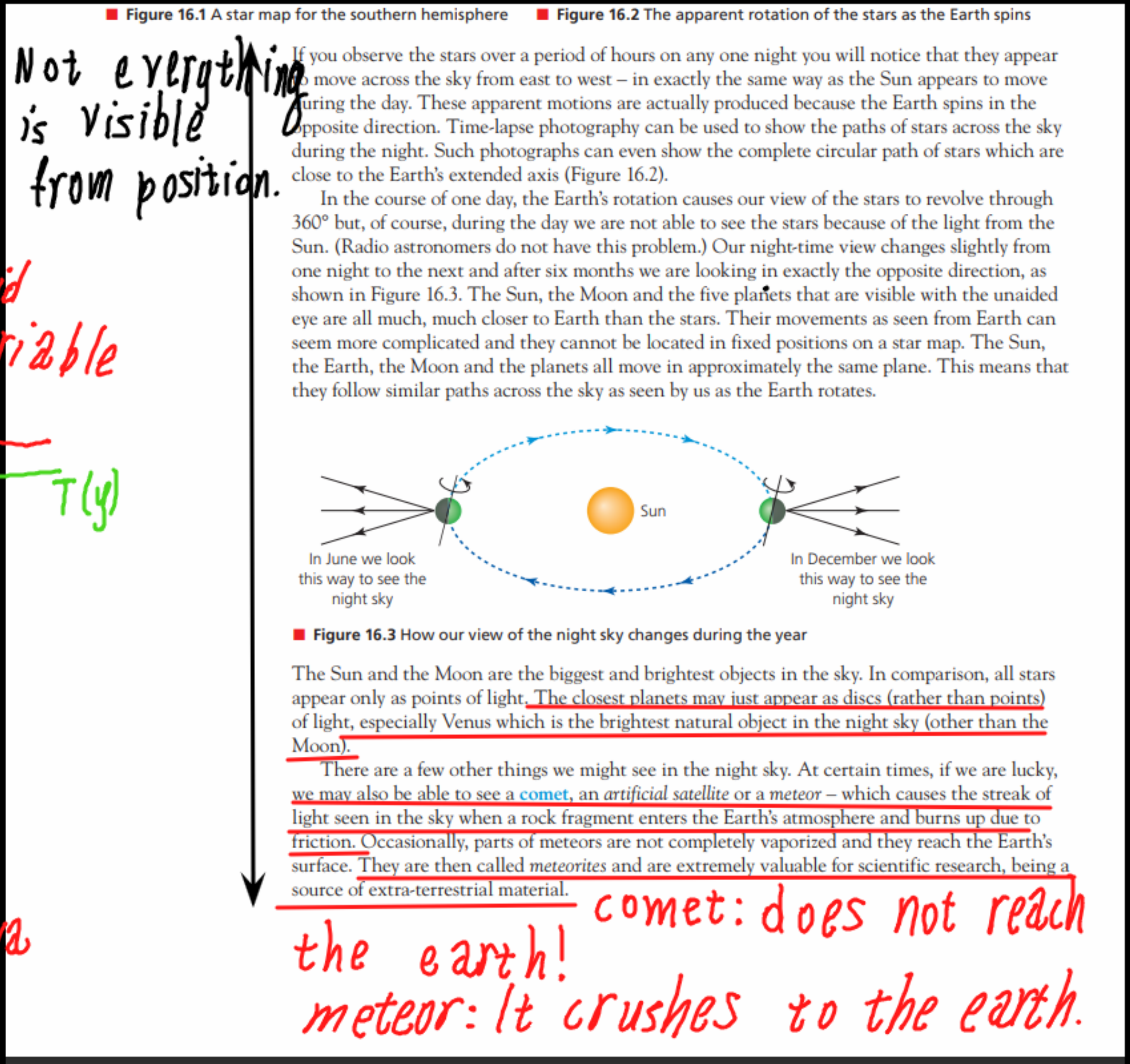


Figure 16.1 A star map for the southern hemisphere

Figure 16.2 The apparent rotation of the stars as the Earth spins

Not everything is visible from position.

If you observe the stars over a period of hours on any one night you will notice that they appear to move across the sky from east to west – in exactly the same way as the Sun appears to move during the day. These apparent motions are actually produced because the Earth spins in the opposite direction. Time-lapse photography can be used to show the paths of stars across the sky during the night. Such photographs can even show the complete circular path of stars which are close to the Earth's extended axis (Figure 16.2).

In the course of one day, the Earth's rotation causes our view of the stars to revolve through 360° but, of course, during the day we are not able to see the stars because of the light from the Sun. (Radio astronomers do not have this problem.) Our night-time view changes slightly from one night to the next and after six months we are looking in exactly the opposite direction, as shown in Figure 16.3. The Sun, the Moon and the five planets that are visible with the unaided eye are all much, much closer to Earth than the stars. Their movements as seen from Earth can seem more complicated and they cannot be located in fixed positions on a star map. The Sun, the Earth, the Moon and the planets all move in approximately the same plane. This means that they follow similar paths across the sky as seen by us as the Earth rotates.

Figure 16.3 How our view of the night sky changes during the year

The Sun and the Moon are the biggest and brightest objects in the sky. In comparison, all stars appear only as points of light. The closest planets may just appear as discs (rather than points) of light, especially Venus which is the brightest natural object in the night sky (other than the Moon).

There are a few other things we might see in the night sky. At certain times, if we are lucky, we may also be able to see a comet, an *artificial satellite* or a *meteor* – which causes the streak of light seen in the sky when a rock fragment enters the Earth's atmosphere and burns up due to friction. Occasionally, parts of meteors are not completely vaporized and they reach the Earth's surface. They are then called *meteorites* and are extremely valuable for scientific research, being a source of extra-terrestrial material.

comet: does not reach the earth!
meteor: It crushes to the earth.

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Supernova (Type Ia)	The explosion of a white dwarf that has accreted mass from a companion star exceeding its stability limit
Supernova (Type II)	The explosion of a red supergiant star: The amount of energy emitted in a supernova explosion can be staggering – comparable to the total energy radiated by our Sun in its entire lifetime!
White dwarf	The end result of the explosion of a red giant. A small, dense star (about the size of the Earth), in which no nuclear reactions take place. It is very hot but its small size gives it a very low luminosity

Table D.1 Definitions of terms.

$\boxed{x = 10^{27}\ \text{atoms}}$

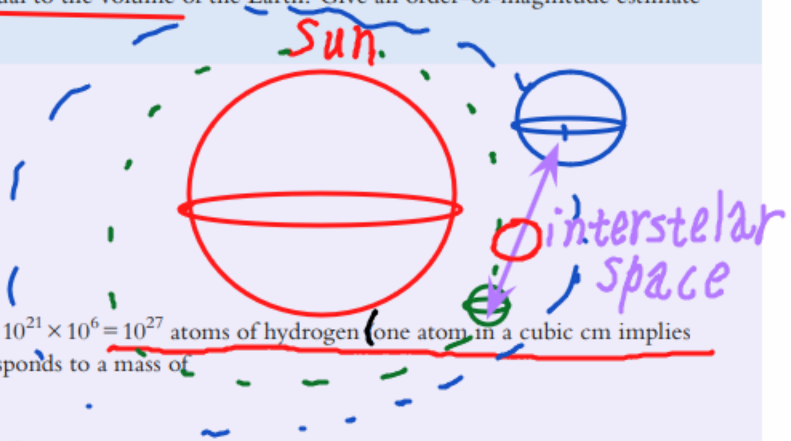
1 atom of hydrogen 1 one cm^3
10^6 atom → $1\ m^3$
Apa x → 10^{21}

$\boxed{R = 6 \cdot 10^6\ m}$

How much mass is there in a volume comparable to the size of earth?
1a.h./cm³

Worked example

D.1 Take the density of interstellar space to be one atom of hydrogen per cm³ of space. How much mass is there in a volume of interstellar space equal to the volume of the Earth? Give an order-of-magnitude estimate without using a calculator.



The volume of the Earth is

$$V \approx \tfrac{4}{3}\pi R^3$$
$$\approx \tfrac{4}{3} \times 3 \times (6 \times 10^6)^3\ \text{m}^3$$
$$\approx 4 \times 200 \times 10^{18}$$
$$\approx 10^{21}\ \text{m}^3$$

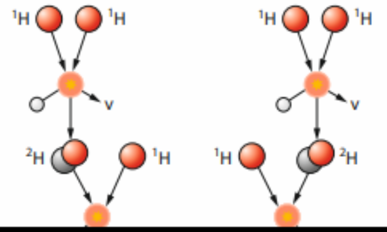
The number of atoms in this volume is $10^{21} \times 10^6 = 10^{27}$ atoms of hydrogen (one atom in a cubic cm implies 10^6 atoms in a cubic metre). This corresponds to a mass of

$$10^{27} \times 10^{-27}\ \text{kg} \approx 1\ \text{kg}.$$

$M_{hydrogen} = 10^{-27}\ Kg$

D1.2 The nature of stars

A star such as our own Sun radiates an enormous amount of power into space – about $10^{26}\ \text{J s}^{-1}$. The source of this energy is nuclear fusion in the interior of the star, in which nuclei of hydrogen fuse to produce helium and energy. Because of the **high temperatures** in the interior



■ **Figure 16.1** A star map for the southern hemisphere ■ **Figure 16.2** The apparent rotation of the stars as the Earth spins

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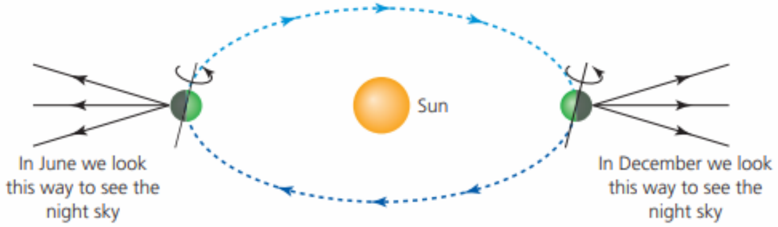

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Several Kinds of Nebula

How is a star kept in equilibrium ???

Άρα οι βαρυτικές δυνάμεις κάνουν το αστέρι να θέλει να συνθλιβεί (να μειωθεί το μέγεθός του) και η "πίεση ακτινοβολίας" κάνει το αστέρι να θέλει να επεκταθεί (tends to expand)

proton-proton

Source of radiation: nuclear fusion

D1.2 The nature of stars

A star such as our own Sun radiates an enormous amount of power into space – about $10^{26}\,\mathrm{J\,s^{-1}}$. The source of this energy is nuclear fusion in the interior of the star, in which nuclei of hydrogen fuse to produce helium and energy. Because of the **high temperatures** in the interior of the star, the electrostatic repulsion between protons can be overcome, (coulomb force) allowing hydrogen nuclei to come close enough to each other to fuse. Because of the **high pressure** in stellar interiors, the nuclei are sufficiently close to each other to give a high probability of collision and hence fusion. The sequence of nuclear fusion reactions that take place is called the **proton–proton cycle** (Figure **D.3**):

collision → fusion

×2

$${}^{1}_{1}\mathrm{H}+{}^{1}_{1}\mathrm{H}\rightarrow{}^{2}_{1}\mathrm{H}+{}^{0}_{1}\mathrm{e}^{+}+\nu$$

$${}^{1}_{1}\mathrm{H}+{}^{2}_{1}\mathrm{H}\rightarrow{}^{3}_{2}\mathrm{He}+\gamma \quad +$$

$${}^{3}_{2}\mathrm{He}+{}^{3}_{2}\mathrm{He}\rightarrow{}^{4}_{2}\mathrm{He}+2{}^{1}_{1}\mathrm{H}$$

The net result of these reactions is that four hydrogen nuclei turn into one helium nucleus (to see this multiply the first two reactions by 2 and add side by side). Energy is released at each stage of the cycle, but most of it is released in the third and final stage. The energy produced is carried away by the photons (and neutrinos) produced in the reactions. As the photons move outwards they collide with the surrounding material, creating a **radiation pressure** that opposes the gravitational pressure * arising from the mass of the star. In the outer layers, convection currents also carry the energy outwards. In this way, the balance between radiation and gravitational pressures keeps the star in equilibrium (Figure **D.4**).

Nuclear fusion provides the energy that is needed to keep the star hot, so that the radiation pressure is high enough to oppose further gravitational contraction, and at the same time to provide the energy that the star is radiating into space. SOS

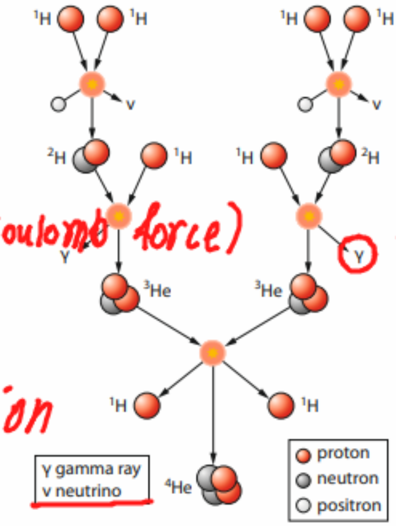


Figure D.3 The proton–proton cycle of fusion reactions.

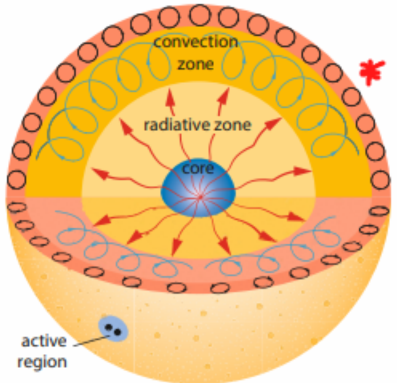


Figure D.4 The stability of a star depends on equilibrium between two opposing forces: gravitation, which tends to collapse the star, and radiation pressure, which tends to make it expand.

convection = ελαγωγη-

Many of the details of nuclear fusion reactions in stars were worked out

---

extremely high coulomb (SOS) force

$$F=K\cdot\frac{q_1\cdot q_2}{r^2}$$

Coulomb Law

Stars

Within part of a nebula, over a very long period of time, gravity pulls atoms closer together and they can gain very high kinetic energies (that is, the temperature is extremely high – millions of kelvin) if the overall mass is large. The hydrogen nuclei (protons) can then have enough kinetic energy to overcome the very high electric forces of repulsion between them and fuse together to make helium nuclei. This process, known as nuclear fusion, can be simplified to:

reactants $4{}^{1}_{1}\mathrm{H}\rightarrow{}^{4}_{2}\mathrm{He}+2{}^{0}_{1}\mathrm{e}$ + neutrinos and photons (SOS)

products

Nuclear fusion happens in all stars (until near the end of their 'lifetimes') and is their dominant energy transformation.

Each completed nuclear fusion of helium from four hydrogen nuclei (protons) is accompanied by a decrease in mass and an equivalent release of energy amounting to about 27 MeV (Chapter 12). The fusion of heavier elements occurs later in the lifetime of stars.

When nuclear fusion begins on a large scale it is commonly described as the *birth* of a star. The contraction of the material in the forming star creates a thermal gas pressure and the emitted radiation also creates a radiation pressure outwards in opposition to the gravitational pressure inwards. These pressures remain equal and opposite for a very long time, during which the star will remain the same size, stable and unchanging. It will be in stellar equilibrium (Figure 16.5). It may be helpful to compare this to a balloon in equilibrium under the action of the gas pressure outwards and the pull of the elastic inwards. There is also a balance between energy transferred from fusions and energy radiated from the surface.

*

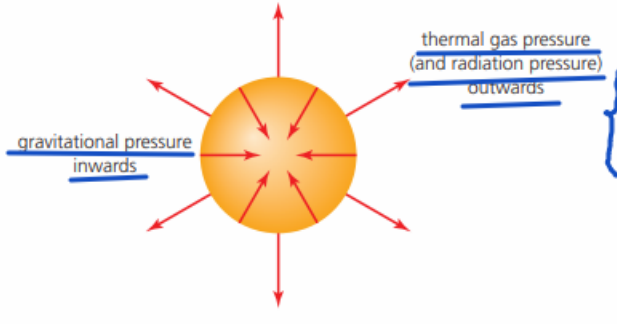


Figure 16.5 A stable star in equilibrium

κύρια ακολουθία

During this period the star is known as a main sequence star. The only fundamental difference between these stars is their masses. Eventually the supply of hydrogen will be used up and the star will no longer be in equilibrium. This will be the beginning of the end of the 'lifetime' of a main sequence star. What happens then depends on the mass of the star (explained later in this chapter). Our Sun is approximately halfway through its lifetime as a main sequence star.

Figure 16.6 An artist's impression of a visual binary star system

Binary stars

It is estimated that around half of all stars are in fact two (or more) stars orbiting around their common centre of mass with a constant period. Stars in a two-star system are described as binary stars (see Figure 16.6). Binary stars that are not too far away from Earth may be seen through a telescope as two separate stars, but most binary stars are further away and appear as a single point of light.

Binary star systems are important in astronomy because the period of their orbital motion is

directly related to their mass.

Figure D.5 Hans Bethe, who unravelled the secrets of energy production in stars.

Exam tip
1 AU = 1.5×10^{11} m
1 ly = 9.46×10^{15} m
1 pc = 3.09×10^{16} m = 3.26 ly

D1.3 Astronomical distances

In astrophysics, it is useful to have a more convenient unit of distance than the metre!

> A **light year** (ly) is the distance travelled by light in one year. Thus:
>
> $$1\text{ ly} = 3\times10^{8}\times365\times24\times60\times60\text{ m}$$
> $$= 9.46\times10^{15}\text{ m}$$
>
> Also convenient for measuring large distances is the **parsec** (pc), a unit that will be properly defined in Section **D1.4**:
>
> $$1\text{ pc} = 3.26\text{ ly} = 3.09\times10^{16}\text{ m}$$
>
> Yet another convenient unit is the **astronomical unit** (AU), which is the average radius of the Earth's orbit around the Sun:
>
> $$1\text{ AU} = 1.5\times10^{11}\text{ m}$$

The average distance between stars in a galaxy is about 1 pc. The distance to the nearest star (Proxima Centauri) is approximately 4.2 ly = 1.3 pc. A simple message sent to a civilisation on Proxima Centauri would thus take 4.2 yr to reach it and an answer would arrive on Earth another 4.2 yr later.

The average distance between galaxies varies from about 100 kiloparsecs (kpc) for galaxies within the same cluster to a few megaparsecs (Mpc) for galaxies belonging to different clusters.

Worked examples

D.2 The Local Group is a cluster of some 30 galaxies, including our own Milky Way and the Andromeda galaxy. It extends over a distance of about 1 Mpc. Estimate the average distance between the galaxies of the Local Group.

Assume that a volume of

$$V = \tfrac{4}{3}\pi R^3$$
$$= \tfrac{4}{3}\times3\times(0.5)^3\text{ Mpc}^3$$
$$\approx 0.5\text{ Mpc}^3$$

is uniformly shared by the 30 galaxies. Then to each there corresponds a volume of

$$\frac{0.5}{30}\text{Mpc}^3 = 0.017\text{ Mpc}^3$$

The linear size of each volume is thus

$$\sqrt[3]{0.017\text{ Mpc}^3} \approx 0.3\text{ Mpc}$$
$$= 300\text{ kpc}$$

so we may take the average separation of the galaxies to be about 300 kpc.

---

dark matter
"
bodies that
no longer
radiate

cluster = σμήνος / super clusters:
υπερ σμήνη

Groups of stars

Galaxies

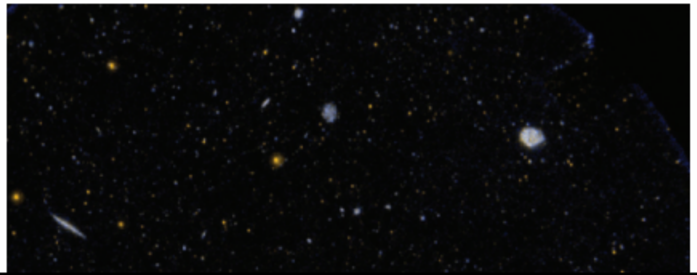
When we look at the stars in the night sky, they seem to be distributed almost randomly, but we are only looking at a tiny part of an enormous universe. The force ① of gravity causes billions of stars to collect into groups, all orbiting the same centre of mass. These groups are known as **galaxies**. Some of the spots of light we see in the night sky ③ are distant galaxies (rather ② than individual stars). Billions of galaxies have been observed using astronomical telescopes. The Earth, the Sun and all the other stars that we can see with the unaided eye are in a galaxy called the **Milky Way**.

Figure 16.7 Spiral galaxy M81

Galaxies are commonly described by their shape as being *spiral* (Figure 16.7), *elliptical* or *irregular*.

Galaxies are distributed throughout space, but not in a completely random way. For example, the Milky Way is one of a group of about 50 galaxies known as the 'Local group'. Larger groups of galaxies, called **clusters of galaxies**, are bound together by gravitational forces. (See Figure 16.8 for an example.) Clusters may contain thousands of galaxies and much intergalactic gas along with undetected 'dark matter'. (The term 'galactic cluster' is commonly used for a group of *stars* within a galaxy.)

Clusters of galaxies are not distributed evenly throughout space, but are themselves grouped together in what are known as **super clusters**. Super clusters of galaxies may be the largest 'structures' in the universe.



Stellar clusters

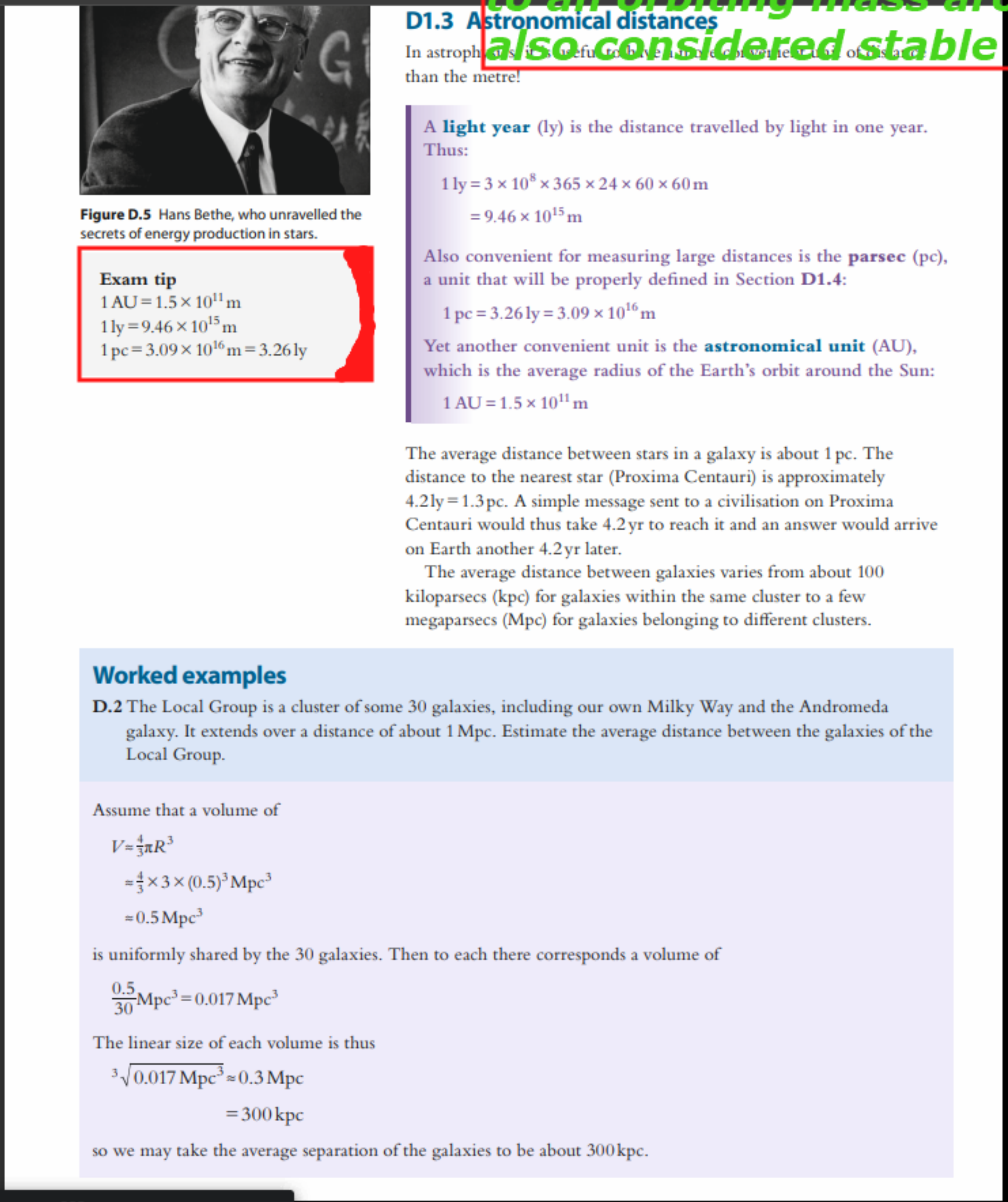
Some stars within a galaxy are close enough to each other that they become gravitationally bound together and rather than move independently, they move as a group called a **stellar cluster**. All the stars within a particular cluster were formed from the same nebula. There are two principal types of stellar cluster:

- **Globular clusters** are old and contain many thousands of stars in roughly spherical shapes that are typically about

1) Two-Dimensional Patterns of Visible Stars are called Constellations (no apparent similarities between the stars forming them)

2) Planetary Systems: Collection of (non-stellar) masses orbiting a star. Same formation processes as the formation of the stars.

Nuclear Fusion cannot occur because they are not "heavy" enough, however compared to an orbiting mass around a star, planets have cleared their surroundings and they are also considered stable



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so we may take the average separation of the galaxies to be about 300 kpc.

Earth-Like Planet: 186f

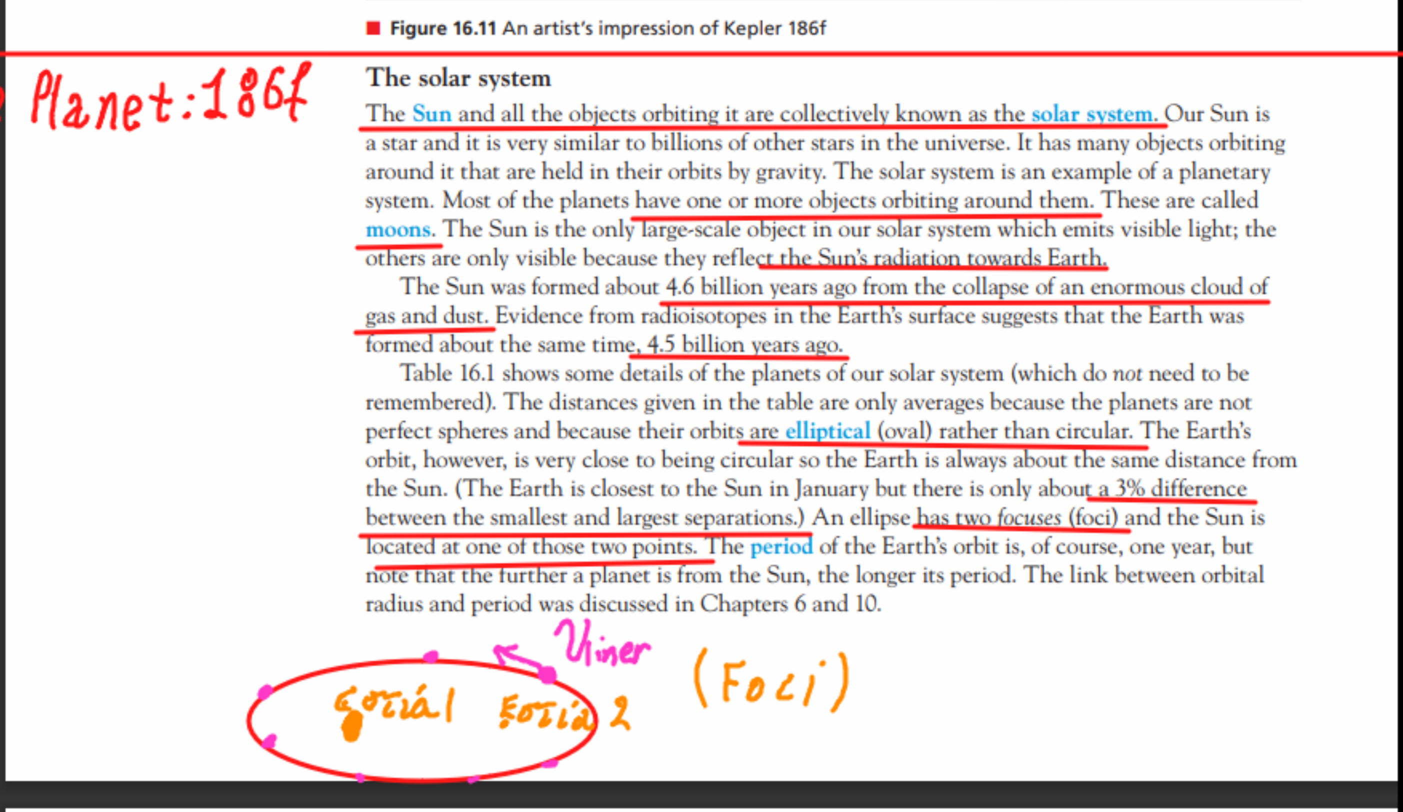


Figure 16.11 An artist's impression of Kepler 186f

The solar system

The Sun and all the objects orbiting it are collectively known as the solar system. Our Sun is a star and it is very similar to billions of other stars in the universe. It has many objects orbiting around it that are held in their orbits by gravity. The solar system is an example of a planetary system. Most of the planets have one or more objects orbiting around them. These are called moons. The Sun is the only large-scale object in our solar system which emits visible light; the others are only visible because they reflect the Sun's radiation towards Earth.

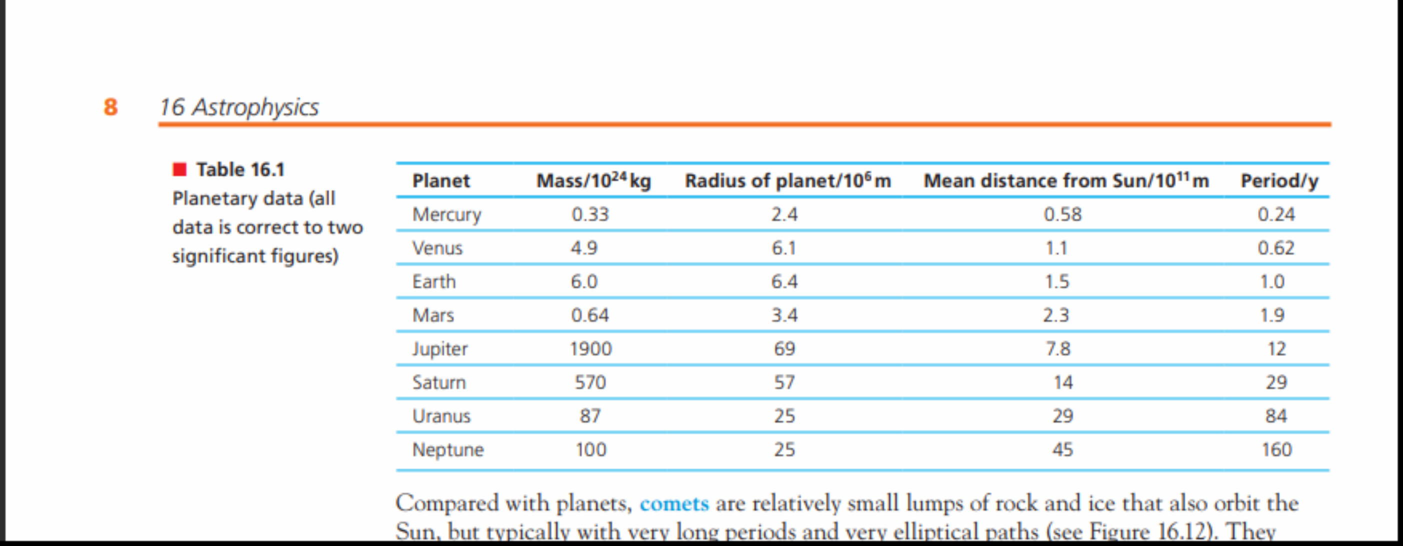
The Sun was formed about 4.6 billion years ago from the collapse of an enormous cloud of gas and dust. Evidence from radioisotopes in the Earth's surface suggests that the Earth was formed about the same time, 4.5 billion years ago.

Table 16.1 shows some details of the planets of our solar system (which do *not* need to be remembered). The distances given in the table are only averages because the planets are not perfect spheres and because their orbits are elliptical (oval) rather than circular. The Earth's orbit, however, is very close to being circular so the Earth is always about the same distance from the Sun. (The Earth is closest to the Sun in January but there is only about a 3% difference between the smallest and largest separations.) An ellipse has two *focuses* (foci) and the Sun is located at one of those two points. The period of the Earth's orbit is, of course, one year, but note that the further a planet is from the Sun, the longer its period. The link between orbital radius and period was discussed in Chapters 6 and 10.

Uiner

Εστία 1 Εστία 2

(Foci)



8 *16 Astrophysics*

Table 16.1 Planetary data (all data is correct to two significant figures)

Planet	Mass/10^{24} kg	Radius of planet/10^6 m	Mean distance from Sun/10^{11} m	Period/y
Mercury	0.33	2.4	0.58	0.24
Venus	4.9	6.1	1.1	0.62
Earth	6.0	6.4	1.5	1.0
Mars	0.64	3.4	2.3	1.9
Jupiter	1900	69	7.8	12
Saturn	570	57	14	29
Uranus	87	25	29	84
Neptune	100	25	45	160

Compared with planets, comets are relatively small lumps of rock and ice that also orbit the Sun, but typically with very long periods and very elliptical paths (see Figure 16.12). They

Figure D.5 Hans Bethe, who unravelled the secrets of energy production in stars.

Exam tip

1 AU = 1.5 × 10^{11} m
1 ly = 9.46 × 10^{15} m
1 pc = 3.09 × 10^{16} m = 3.26 ly

*The volume off all the local group of galaxies

D1.3 Astronomical distances

In astrophysics, it is useful to have a more convenient unit of distance than the metre!

A **light year** (ly) is the distance travelled by light in one year. Thus:

$$1\,\text{ly} = 3\times10^{8}\times365\times24\times60\times60\,\text{m}$$
$$=9.46\times10^{15}\,\text{m}$$

} 1 ly = light · 1 year
d = v·t

Also convenient for measuring large distances is the **parsec** (pc), a unit that will be properly defined in Section **D1.4**:

$$1\,\text{pc} = 3.26\,\text{ly} = 3.09\times10^{16}\,\text{m}$$

Yet another convenient unit is the **astronomical unit** (AU), which is the average radius of the Earth's orbit around the Sun:

$$1\,\text{AU} = 1.5\times10^{11}\,\text{m}$$

The average distance between stars in a galaxy is about 1 pc. The distance to the nearest star (Proxima Centauri) is approximately 4.2 ly = 1.3 pc. A simple message sent to a civilisation on Proxima Centauri would thus take 4.2 yr to reach it and an answer would arrive on Earth another 4.2 yr later.

The average distance between galaxies varies from about 100 kiloparsecs (kpc) for galaxies within the same cluster to a few megaparsecs (Mpc) for galaxies belonging to different clusters.

Worked examples

D.2 The Local Group is a cluster of some 30 galaxies, including our own Milky Way and the Andromeda galaxy. It extends over a distance of about 1 Mpc. Estimate the average distance between the galaxies of the Local Group.

diameter

Assume that a volume of

$$V=\tfrac{4}{3}\pi R^{3}$$

radius

$$=\tfrac{4}{3}\times3\times(0.5)^{3}\,\text{Mpc}^{3}$$

$$* \boxed{=0.5\,\text{Mpc}^{3}}$$

} Assumption that the cluster of galaxies is considered a perfect sphere

is uniformly shared by the 30 galaxies. Then to each there corresponds a volume of

$$\frac{0.5}{30}\,\text{Mpc}^{3}=0.017\,\text{Mpc}^{3}$$ (average volume of each galaxy)

The linear size of each volume is thus

$$\sqrt[3]{0.017\,\text{Mpc}^{3}}\approx0.3\,\text{Mpc}$$
$$=300\,\text{kpc}$$

so we may take the average separation of the galaxies to be about 300 kpc.

$$V_{galaxy}=\frac{4}{3}\pi\cdot r_{galaxy}^{3} \Rightarrow r_{galaxy}=\sqrt[3]{\frac{3}{4\pi}\cdot V_g}$$

---

1 AU = 1.5·10^{11} m
Earth-Sun

1 pc = 3.26 ly

Astronomical distances

The universe is enormous! Rather than use metres (or km) to measure distances, astronomers usually prefer to deal with smaller numbers and have introduced alternative units for distance.

The light year, ly, is defined as the *distance* travelled by light in a vacuum in one year.

At a light speed of 2.998 × 10^{8} m s^{-1} and 365.25 days, a light year is easily shown to be 9.46 × 10^{15} m. This value is provided in the *Physics data booklet*.

The astronomical unit, AU, is equivalent to the mean distance between the Earth and the Sun, 1.50 × 10^{11} m.

This value is provided in the *Physics data booklet*. (Although the actual distance varies, the value of 1 AU is *defined* to be 1.495 978 707 × 10^{11} m.)

One parsec, pc, is equal to 3.26 ly. This value is provided in the *Physics data booklet*. The parsec is the preferred unit of measurement in astronomy because it is closely related to parallax angles – the way in which the distances to 'nearby' stars are measured (this will be explained later).

One parsec is defined as the distance to a star that has a parallax angle of one arc-second.

While distances to 'nearby' stars are commonly measured in parsecs, the more distant stars in a galaxy are kpc away and distances to the most distant galaxies will be recorded in Mpc and Gpc.

Table 16.2 Summary of distance units commonly used in astronomy

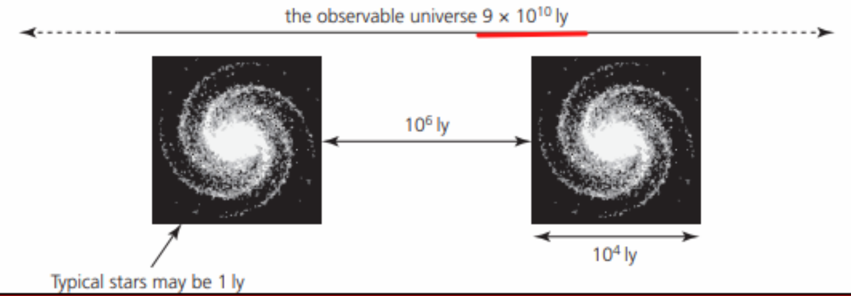
Unit	Metres/m	Astronomical units/AU	Light years/ly
1 AU =	1.50 × 10^{11}	–	–
1 ly =	9.46 × 10^{15}	6.30 × 10^{4}	–
1 pc =	3.09 × 10^{16}	2.06 × 10^{5}	3.26

30.9×10^{15}

The scale of the universe

The diameter of the observable universe is about 9 × 10^{10} ly. The speed of light limits the amount of the universe that we can, in principle, 'observe'. The distance to the edge of the observable universe is equal to the speed of light multiplied by the age of the universe (but the expansion of space itself must be considered, which will be discussed later in the chapter).

Distances between stars and between galaxies vary considerably. As a *very approximate* guide there might be 10^{12} stars in a big galaxy. A typical separation of stars within it may be about 1 ly, with a typical total diameter of a galaxy being about 10^{4} ly (Figure 16.15). The billions of galaxies are separated from each other by vast distances, maybe 10^{7} ly or more.



D1.4 Stellar parallax and its limitations

The **parallax** method is a means of measuring astronomical distances. It takes advantage of the fact that, when an object is viewed from two different positions, it appears displaced relative to a fixed background. If we measure the angular position of a star and then repeat the measurement some time later, the two positions will be different relative to a background of very distant stars, because in the intervening time the Earth has moved in its orbit around the Sun. We make two measurements of the angular position of the star six months apart; see Figure **D.6**.

The distance between the two positions of the Earth is $D = 2R$, the diameter of the Earth's orbit around the Sun ($R = 1.5 \times 10^{11}$ m). The distance d to the star is given by

arcsecond: $\frac{1}{100} \cdot 1^\circ$

$$\tan p = \frac{R}{d} \Rightarrow d = \frac{R}{\tan p}$$

Since the parallax angle is very small, $\tan p \approx p$, where the parallax p is measured in radians, and so $d = \frac{R}{p}$.

The parallax angle (shown in Figure **D.6**) is the angle, at the position of the star, that is subtended by a distance equal to the radius of the Earth's orbit around the Sun (1 AU).

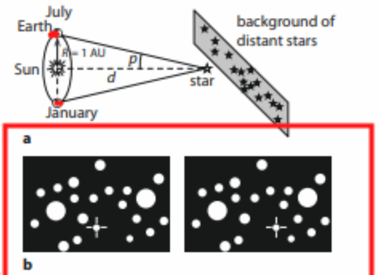


Figure D.6 **a** The parallax of a star. **b** Two 'photographs' of the same region of the sky taken six months apart. The position of the star (indicated by a cross) has shifted, relative to the background stars, in the intervening six months.

The parallax method can be used to define a common unit of distance in astronomy, the **parsec**. One parsec (from **par**allax **sec**ond) is the distance to a star whose parallax is 1 arc second, as shown in Figure **D.7**. An arc second is 1/3600 of a degree.

In conventional units,

$$1\,\text{pc} = \frac{1\,\text{AU}}{1''} = \frac{1.5 \times 10^{11}}{\left(\frac{2\pi}{360}\right)\left(\frac{1}{3600}\right)}\,\text{m} = 3.09 \times 10^{16}\,\text{m}$$

(The factor of $\frac{2\pi}{360}$ converts degrees to radians.)

If the parallax of a star is known to be p arc seconds, its distance is

$$d\ (\text{in parsecs}) = \frac{1}{p}\ (\text{in arc seconds}).$$

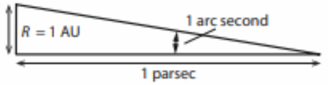


Figure D.7 Definition of a parsec: 1 parsec is the distance at which 1 AU subtends an angle of 1 arc second.

Exam tip
You will not be asked to provide these derivations in an exam. You should just know that d (in parsecs) $= \frac{1}{p}$ (in arc seconds).

You must also understand the limitations of this method.

Ancient methods are still useful!

---

6 Use Table 16.1 to determine the mean distance (in AU) from the Sun to the planets Mercury and Uranus.

7 What is the approximate size of the observable universe in:
- a km
- b pc?

8 Proxima Centauri is the nearest star to Earth at a distance of 4.0×10^{16} m.
- a How many light years is this?
- b If the Earth was scaled down from a diameter of 1.3×10^7 m to the size of a pin head (1 mm diameter), how far away would this star be on the same scale?

9 Our solar system has an approximate size of at least 10^{11} km.
- a How many light years is that?
- b If you were making a model of our solar system using a ball of diameter 10 cm to represent the Sun, how far away would the 'edge' of the solar system be? (The Sun's diameter = 1.4×10^6 km.)
- c Research into how the edge of the solar system can be defined and what objects in the solar system are the most distant from the Sun.

10 Calculate the time for light to reach Earth from the Sun.

11 a Estimate how long would it take a spacecraft travelling away from Earth at an average speed of 4 km s^{-1} to reach:
  - i Mars
  - ii Proxima Centauri.
- b Find out the highest recorded speed of a spacecraft.

12 Use the data from Figure 16.15 to make a very rough estimate of the number of stars in the observable universe.

13 Research the diameter of our galaxy, the Milky Way, in parsecs.

14 Explain why it would be unusual to quote a distance between stars in AU.

ToK Link

Imagination

The vast distances between stars and galaxies are difficult to comprehend or imagine. Are other ways of knowing more useful than imagination for gaining knowledge in astronomy?

Imagining the vast distances in the universe may be considered to be similar to imagining the number of molecules in a grain of salt – the numbers are so large that they are almost meaningless to us. There is no doubt that it does help us to make comparisons like 'it would take more than a billion years to walk to the nearest star', but then we realise that this is an incredibly *small* distance in the universe!

■ Determining the distances to the stars and distant galaxies

The measurement of astronomical distances is a key issue in the study of astronomy. However, determining the distance from Earth to a star or galaxy accurately is not easy and a variety of methods have been developed.

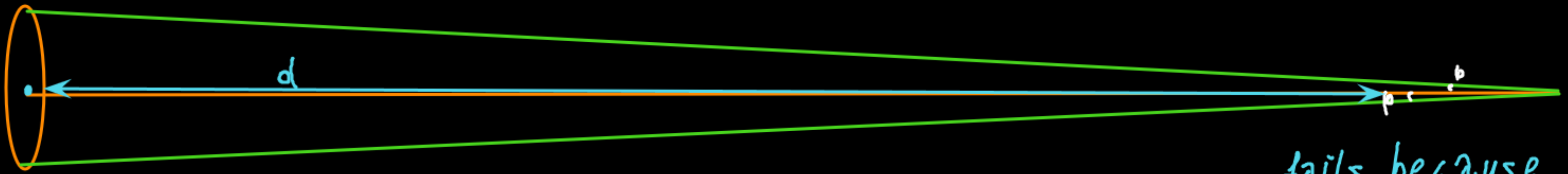
In this course we will consider three different ways in which the distance to a star or distant galaxy may be determined:
- stellar parallax ①
- use of Cepheid variable stars ②
- use of supernovae ③

ways to meausure distance

The use of stellar parallax for 'nearby' stars is the most direct and easily understood method. The other two methods are used for distant galaxies. They will be discussed later in the chapter.

Stellar parallax and its limitations

This method is similar in principle to one that we might use on Earth to determine the distance to an inaccessible object, such as a boat or a plane. If the object can be observed from two different places, then its distance away can be calculated using trigonometry. An example of this *triangulation* method is shown in Figure 16.16.



$d = \frac{R}{p}$, when $p \approx 0$
parallax method
fails, because $d \to +\infty$

R = radius of the

100pc = 326 ly.

If the star is too far away, however, the parallax angle is too small to be measured and this method fails. Typically, measurements from observatories on Earth allow distances up to 100 pc to be determined by the parallax method, which is therefore mainly used for nearby stars. Using measurements from satellites without the distortions caused by the Earth's atmosphere (turbulence, and variations in temperature and refractive index), much larger distances can be determined using the parallax method. The Hipparcos satellite (launched by ESA, the European Space Agency, in 1989) measured distances to stars 1000 pc away; Gaia, launched by ESA in December 2013, is expected to do even better, extending the parallax method to distances beyond 100 000 pc!

error

because they get out of the atmosphere.

Table **D.2** shows the five nearest stars (excluding the Sun).

Star	Distance/ly
Proxima Centauri	4.3
Barnard's Star	5.9
Wolf 359	7.7
Lalande 21185	8.2
Sirius	8.6

Table D.2 Distances to the five nearest stars.

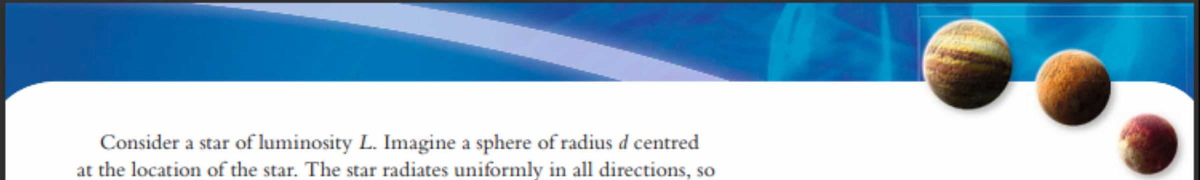
D1.5 Luminosity and apparent brightness

Stars are assumed to radiate like black bodies. For a star of surface area A and absolute surface temperature T, we saw in Topic **8** that the power radiated is

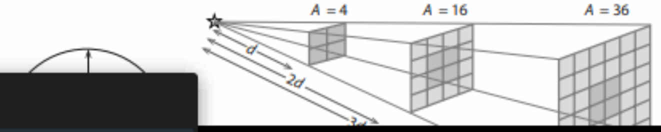
$$L = \sigma A T^4$$

where the constant σ is the Stefan–Boltzmann constant ($\sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$).

> The power radiated by a star is known in astrophysics as the **luminosity**. It is measured in watts.



Consider a star of luminosity L. Imagine a sphere of radius d centred at the location of the star. The star radiates uniformly in all directions, so the energy radiated in 1 s can be thought of as distributed over the surface of this imaginary sphere. A detector of area a placed somewhere on this sphere will receive a small fraction of this total energy (see Figure **D.8a**).



Exam tip
In many problems you will need to know that the surface

Stellar parallax and its limitations

This method is similar in principle to one that we might use on Earth to determine the distance to an inaccessible object, such as a boat or a plane. If the object can be observed from two different places, then its distance away can be calculated using trigonometry. An example of this *triangulation* method is shown in Figure 16.16.

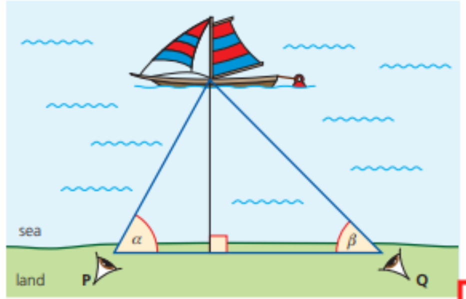


Figure 16.16 Determining the distance to a ship at sea using triangulation

An observer on land sees the boat from position P and then moves to position Q. If the angles α and β are measured and the distance PQ is known, then the other distances can be calculated. When astronomers want to locate a star, they can try to observe it from two different places, but the distance between two different locations on Earth is far too small compared with the distance between the Earth and the star. Therefore, astronomers observe the star from the same telescope at the same location, but at two different places in the Earth's orbit; in other words, at different times of the year. To get the longest difference they usually take two measurements separated in time by six months.

The triangulation method described above to locate a boat would be much more difficult if the observer was in a *moving* boat at sea and this is similar to the difficulty faced by astronomers locating stars from Earth. The problem can be overcome by comparing the position of the star to other stars much further away (in the 'background'). This is known as a **parallax** method.

least square method (linear regression)

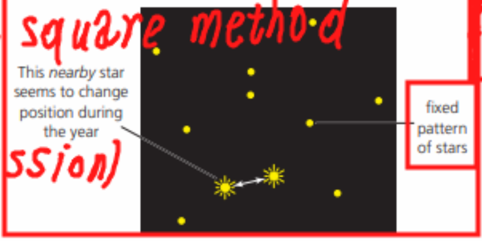


Figure 16.17 A nearby star's apparent movement due to parallax

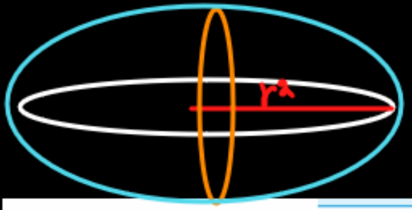
Parallax is the visual effect of a nearby object appearing to move its position, as compared to more distant objects (behind it), when viewed from different positions. A simple example is easily observed by looking at one finger held in front of your face and the background behind it, first with one eye and then the other. In the same way, a 'nearby' star can appear to *very slightly* change its position during the year compared to other stars much further away (although, as we have noted before, stars generally appear to remain in fixed patterns over very long periods of times).

Stellar parallax (Figure 16.17) was first confirmed in 1838. Many astronomers had tried to detect it before (without success) because the existence of stellar parallax provides evidence for the motion of the Earth around the Sun.

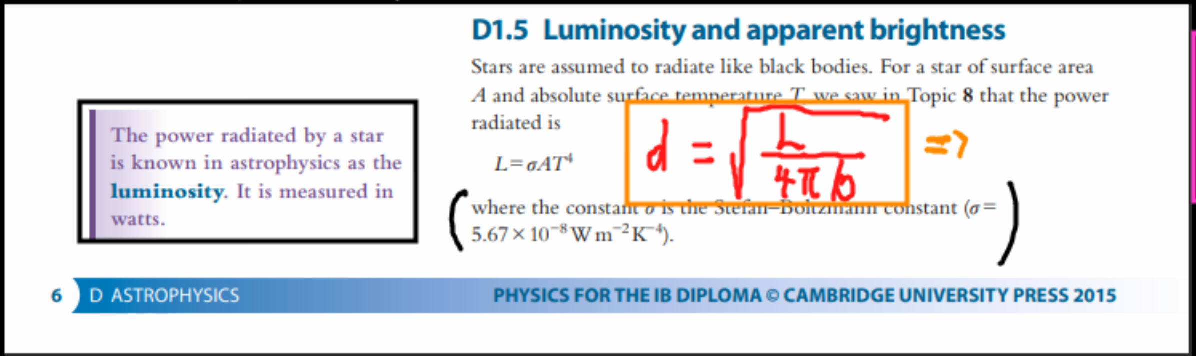
Using telescopes, astronomers measure the **parallax angle**, *p*, between, for example, observations of the star made in December and June. Figure 16.18 shows the angular positions of a nearby star in December and June. (In Figures 16.18 and 16.19 the size of the parallax angle has been *much* exaggerated for the sake of clarity.)

Figure 16.18 Measuring the parallax angle six

b : What WE receive : $b = \frac{L}{4\pi d^2}$ (in m^2)



Surface of a sphere: $4\pi d^2$.



D1.5 Luminosity and apparent brightness

The power radiated by a star is known in astrophysics as the **luminosity**. It is measured in watts.

Stars are assumed to radiate like black bodies. For a star of surface area A and absolute surface temperature T, we saw in Topic **8** that the power radiated is

$$L = \sigma A T^4$$

$$d = \sqrt{\frac{L}{4\pi b}} \Rightarrow$$

(where the constant σ is the Stefan–Boltzmann constant ($\sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$).)

$$d = \sqrt{\frac{\sigma \cdot A \cdot T^4}{4\pi b}}$$

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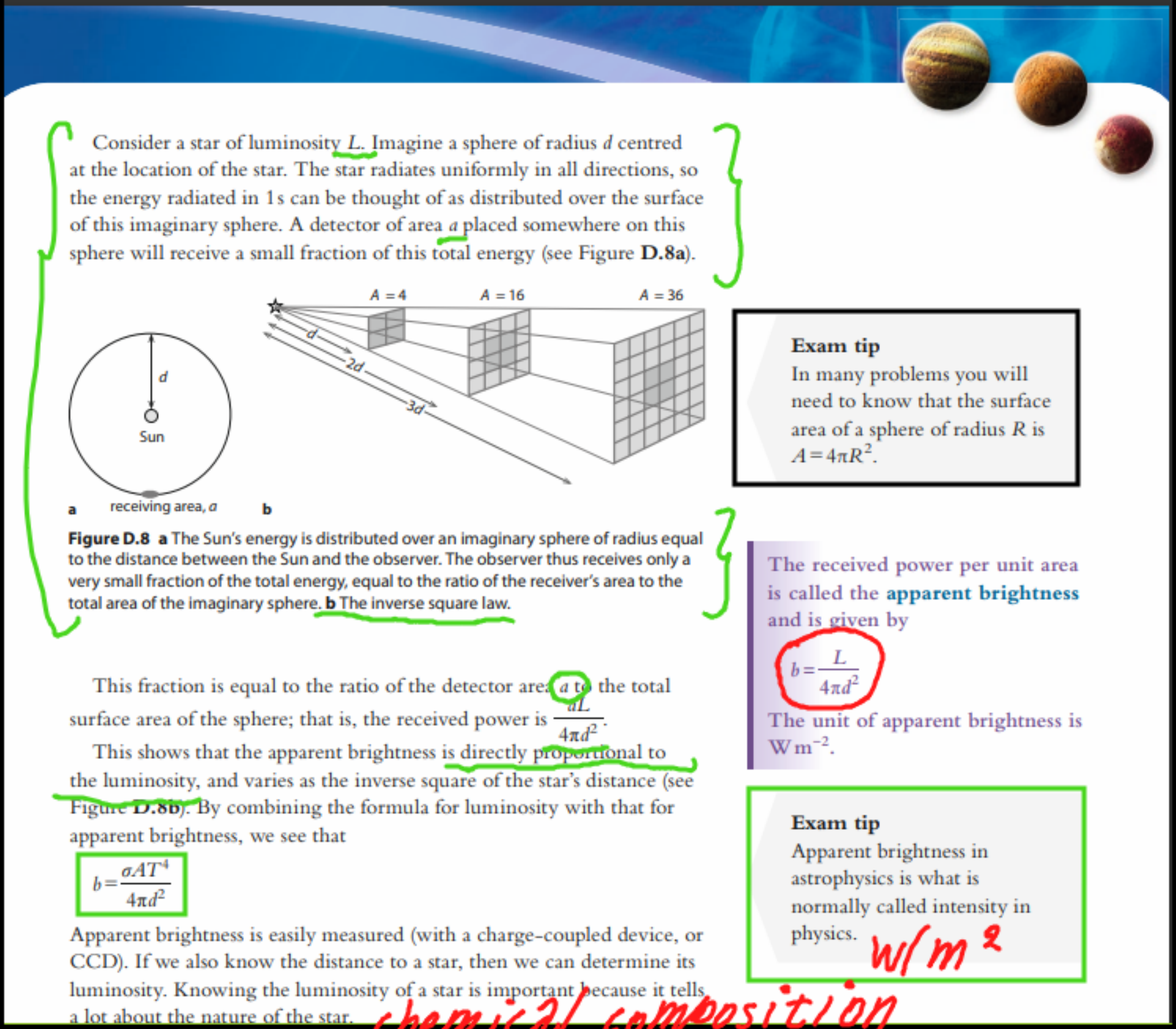


Consider a star of luminosity L. Imagine a sphere of radius d centred at the location of the star. The star radiates uniformly in all directions, so the energy radiated in 1 s can be thought of as distributed over the surface of this imaginary sphere. A detector of area a placed somewhere on this sphere will receive a small fraction of this total energy (see Figure **D.8a**).

Figure D.8 **a** The Sun's energy is distributed over an imaginary sphere of radius equal to the distance between the Sun and the observer. The observer thus receives only a very small fraction of the total energy, equal to the ratio of the receiver's area to the total area of the imaginary sphere. **b** The inverse square law.

Exam tip
In many problems you will need to know that the surface area of a sphere of radius R is $A = 4\pi R^2$.

This fraction is equal to the ratio of the detector area a to the total surface area of the sphere; that is, the received power is $\frac{aL}{4\pi d^2}$.

This shows that the apparent brightness is directly proportional to the luminosity, and varies as the inverse square of the star's distance (see Figure **D.8b**). By combining the formula for luminosity with that for apparent brightness, we see that

$$\boxed{b = \frac{\sigma A T^4}{4\pi d^2}}$$

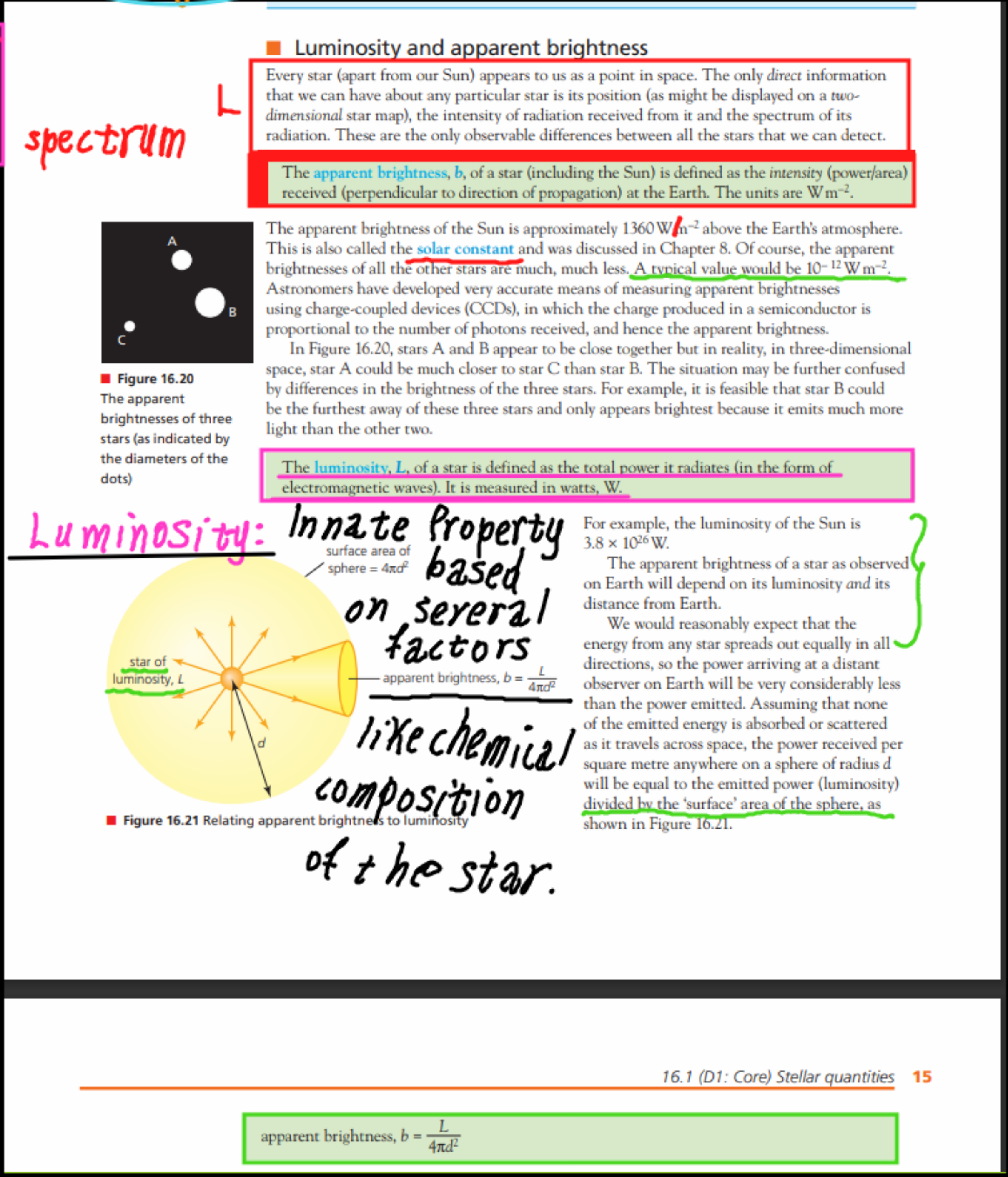
Apparent brightness is easily measured (with a charge-coupled device, or CCD). If we also know the distance to a star, then we can determine its luminosity. Knowing the luminosity of a star is important because it tells a lot about the nature of the star. chemical composition

The received power per unit area is called the **apparent brightness** and is given by

$$b = \frac{L}{4\pi d^2}$$

The unit of apparent brightness is $\mathrm{W\,m^{-2}}$.

Exam tip
Apparent brightness in astrophysics is what is normally called intensity in physics. W/m²



Luminosity and apparent brightness

spectrum L

Every star (apart from our Sun) appears to us as a point in space. The only *direct* information that we can have about any particular star is its position (as might be displayed on a *two-dimensional* star map), the intensity of radiation received from it and the spectrum of its radiation. These are the only observable differences between all the stars that we can detect.

The apparent brightness, b, of a star (including the Sun) is defined as the *intensity* (power/area) received (perpendicular to direction of propagation) at the Earth. The units are $\mathrm{W\,m^{-2}}$.

Figure 16.20 The apparent brightnesses of three stars (as indicated by the diameters of the dots)

The apparent brightness of the Sun is approximately $1360\,\mathrm{W\,m^{-2}}$ above the Earth's atmosphere. This is also called the solar constant and was discussed in Chapter 8. Of course, the apparent brightnesses of all the other stars are much, much less. A typical value would be $10^{-12}\,\mathrm{W\,m^{-2}}$. Astronomers have developed very accurate means of measuring apparent brightnesses using charge-coupled devices (CCDs), in which the charge produced in a semiconductor is proportional to the number of photons received, and hence the apparent brightness.

In Figure 16.20, stars A and B appear to be close together but in reality, in three-dimensional space, star A could be much closer to star C than star B. The situation may be further confused by differences in the brightness of the three stars. For example, it is feasible that star B could be the furthest away of these three stars and only appears brightest because it emits much more light than the other two.

The luminosity, L, of a star is defined as the total power it radiates (in the form of electromagnetic waves). It is measured in watts, W.

Luminosity: Innate Property based on several factors like chemical composition of the star.

Figure 16.21 Relating apparent brightness to luminosity

For example, the luminosity of the Sun is 3.8×10^{26} W.

The apparent brightness of a star as observed on Earth will depend on its luminosity *and* its distance from Earth.

We would reasonably expect that the energy from any star spreads out equally in all directions, so the power arriving at a distant observer on Earth will be very considerably less than the power emitted. Assuming that none of the emitted energy is absorbed or scattered as it travels across space, the power received per square metre anywhere on a sphere of radius d will be equal to the emitted power (luminosity) divided by the 'surface' area of the sphere, as shown in Figure 16.21.

16.1 (D1: Core) Stellar quantities 15

apparent brightness, $b = \frac{L}{4\pi d^2}$

✓ **12.** A distant galaxy emits light of wavelength 486 nm. The light received on Earth has wavelength 512 nm.

✓ (a) Determine the recession speed of the galaxy.

$$\frac{\Delta\lambda}{\lambda_0} \approx \frac{v}{c} \Rightarrow \frac{512-486}{486} \approx \frac{v}{3\cdot10^{8}\,m/s}$$

$$v = \frac{26\cdot\cancel{10^{-9}}\,\cancel{m}}{486\cdot\cancel{10^{-9}}\,\cancel{m}}\cdot 3\cdot10^{8}\,\frac{m}{s} \Rightarrow v = \frac{78\cdot}{486}\,10^{8}\,\frac{m}{s}$$

$$\boxed{v = 1.6\cdot10^{7}\,m/s}$$

✓ (b) Estimate the distance to the galaxy in pc. Take the Hubble constant as 72 km s^{-1} Mpc^{-1}.

$$H_0 = 72{,}000\,m\,s^{-1}\,Mpc^{-1}$$

$$d = \frac{v}{H_0} = \frac{1.6\cdot\cancel{10^{7}}^{4}\,\cancel{m\,s^{-1}}}{72\cdot\cancel{10^{3}}\,\cancel{m\,s^{-1}}}\cdot10^{6}\,pc = \frac{160}{72}\cdot10^{8}$$

$$d = 2.2\times10^{8}\,pc$$

(c) Astrophysicists continue to seek an accurate value of the Hubble constant. State the importance of this constant for cosmology.

- It is important because it is related to the age of the universe
- It is important in testing models of the universe