An introduction to exoplanets

About this free course

This version of the content may include video, images and interactive content that may not be optimised for your device.

You can experience this free course as it was originally designed on OpenLearn, the home of free learning from The Open University – https://www.open.edu/openlearn/science-maths-technology/introduction-exoplanets/content-section-overview

There you'll also be able to track your progress via your activity record, which you can use to demonstrate your learning.

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Welcome to this free course, *An introduction to exoplanets*.

The course lasts 8 weeks with approximately 3 hours of study time each week. You can work through the course at your own pace, so if you have more time one week there is no problem with pushing on to complete another week.

The course introduces our Galaxy's population of planets, and some of their many surprises. It explains the methods used by astronomers to study exoplanets, and provides a general introduction to the methods of scientific inquiry. The course culminates in discussion of life elsewhere in our Galaxy.

After completing this course, you will be able to:

- discuss planets, exoplanets, stars, galaxies and the Universe
- describe the various types of planets in terms of their mass, radius and density, and know which types are most common within our Galaxy
- understand how astronomers detect and study exoplanets, and appreciate the limitations to the knowledge we have
- describe the characteristics of some particularly interesting exoplanets, and know a little about the Galaxy's history of planet formation
- summarise the current ideas about the likelihood of life and complex life elsewhere in the Galaxy.

Moving around the course

In the 'Summary' at the end of each week, you can find a link to the next one. If at any time you want to return to the start of the course, click on 'Course content'. From here you can navigate to any part of the course. Alternatively, use the week links at the top of every page of the course.

It's also good practice, if you access a link from within a course page (including links to the quizzes), to open it in a new window or tab. That way you can easily return to where you've come from without having to use the back button on your browser.

The Open University would really appreciate a few minutes of your time to tell us about yourself and your expectations for the course before you begin, in our optional start-of-course survey. Participation will be completely confidential and we will not pass on your details to others.

Maths help

Some parts of this course are quite mathematical. To help with this, here are some direct links to maths OpenLearn courses. Open the link in a new tab or window by holding down Ctrl (or Cmd on a Mac) when you click on the link. Remember to return here when you have finished. Alternatively you may just want to bear these links in mind, and return to this page later, if you come across an activity that you need extra help with.

everyday maths
- decimals
- percentages
- ratios

squares, roots and powers
- squares
- square roots
- cubes

using a scientific calculator
- doing longer calculations using your calculator
- using roots on your calculator

In addition to this, for some of the calculations in this course, you might want to acquire a scientific calculator if you don't already have one. A web search for 'scientific calculator' should quickly help. There are also free web applets available.

What is a badged course?

While studying *An introduction to exoplanets* you have the option to work towards gaining a digital badge.

Badged courses are a key part of The Open University's mission *to promote the educational well-being of the community*. The courses also provide another way of helping you to progress from informal to formal learning.

To complete a course you need to be able to find about 24 hours of study time, over a period of about 8 weeks. However, it is possible to study the course at any time, and at a pace to suit you.

Badged courses are all available on The Open University's OpenLearn website and do not cost anything to study. They differ from Open University courses because you do not receive support from a tutor. But you do get useful feedback from the interactive quizzes.

What is a badge?

Digital badges are a new way of demonstrating online that you have gained a skill. Schools, colleges and universities are working with employers and other organisations to develop open badges that help learners gain recognition for their skills, and support employers to identify the right candidate for a job.

Badges demonstrate your work and achievement on the course. You can share your achievement with friends, family and employers, and on social media. Badges are a great

Introduction and guidance

motivation, helping you to reach the end of the course. Gaining a badge often boosts confidence in the skills and abilities that underpin successful study. So, completing this course should encourage you to think about taking other courses.

How to get a badge

Getting a badge is straightforward! Here's what you have to do:

- read each week of the course
- score 50% or more in the two badge quizzes in Week 4 and Week 8.

For all the quizzes, you can have three attempts at most of the questions (for true or false type questions you usually only get one attempt). If you get the answer right first time you will get more marks than for a correct answer the second or third time. Therefore, please be aware that for the two badge quizzes it is possible to get all the questions right but not score 50% and be eligible for the badge on that attempt. If one of your answers is incorrect you will often receive helpful feedback and suggestions about how to work out the correct answer.

For the badge quizzes, if you're not successful in getting 50% the first time, after 24 hours you can attempt the whole quiz, and come back as many times as you like.

We hope that as many people as possible will gain an Open University badge – so you should see getting a badge as an opportunity to reflect on what you have learned rather than as a test.

If you need more guidance on getting a badge and what you can do with it, take a look at the OpenLearn FAQs. When you gain your badge you will receive an email to notify you and you will be able to view and manage all your badges in My OpenLearn within 24 hours of completing the criteria to gain a badge.

Get started with Week 1.

Introduction and guidance

Week 1: Planets and the Solar System

Introduction

What is an exoplanet? Put simply, an exoplanet is a planet that orbits a star other than our own Sun. Until the final years of the twentieth century the only planets we knew of in the entire Universe were the eight planets orbiting our Sun. We could only speculate as to what might lie ‘out there’ among the other stars. Could our own Solar System be unique? The historic discovery of the first exoplanet completely changed our perspective – we are at the dawn of an entirely new branch of astronomy.

During this course you will learn about this fascinating subject. First, in Week 1, you’ll start by looking at the ‘building blocks’ of the Universe: stars, planets, planetary systems and galaxies, and how they relate to each other. You will understand the location within the Universe of our own planet Earth and our Solar System, along with the thousands of planets orbiting other stars that have been discovered since 1995.

Watch the following video in which Carole Haswell talks more about this.

Video content is not available in this format.

By the end of this week, you will be able to:

- recognise the International Astronomical Union (IAU) definition of a planet
- understand the difference between planets and dwarf planets
- describe the other objects in our Solar System
- define the term ‘exoplanet’
- describe each of the following building blocks of the Universe: stars, planets, planetary systems and galaxies
- identify objects and constellations in the night sky.

The Open University would really appreciate a few minutes of your time to tell us about yourself and your expectations for the course before you begin, in our optional start-of-course survey. Participation will be completely confidential and we will not pass on your details to others.

1 What is a planet?

What is a planet? Most people, if asked, can name at least one planet: the Earth (Figure 1).

Figure 1 The Earth as seen from the Apollo 17 spacecraft

The word ‘planet’ comes from the ancient Greeks who observed ‘wanderers’ in the night sky – bright star-like objects which gradually moved against the background pattern of stars. We now have the ability to view them as much more than just points of light.

Occasionally, the media showcases stunning photographs of planets, such as the one of Saturn, taken by a spacecraft (Figure 2).

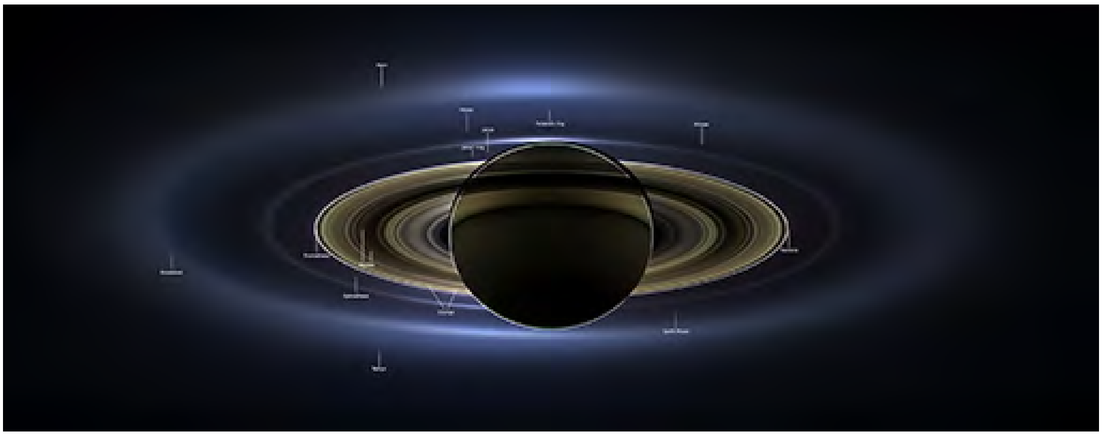


Figure 2 ‘The Day the Earth Smiled’. This is an annotated image of the planet Saturn and its rings taken by the NASA Cassini spacecraft in 2013. The rings are backlit by sunlight, and the Earth is just visible, appearing between two of the rings in the bottom right corner, you will need to click to view a larger version of the image to see it.

Some of us were lucky enough to catch one of the recent ‘transits’ of the planets Venus and Mercury. In a transit, a planet passes directly between the Earth and Sun, appearing as a dark spot silhouetted against the Sun’s bright surface.

Figure 3 shows the latest transit of Venus across the Sun, which took place in 2012. Venus can be seen as a round black spot towards the top right on the Sun. This image was taken by the NASA Solar Dynamics Observatory with a particular colour filter that is sensitive to the Sun’s outer atmosphere.

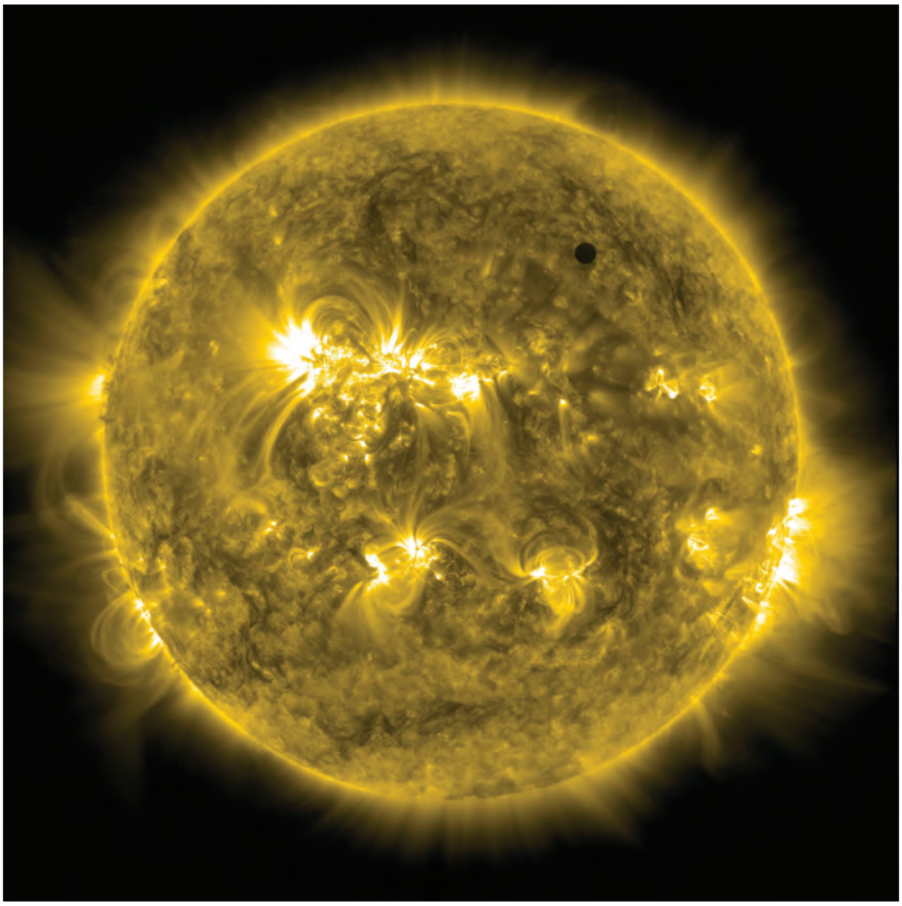


Figure 3 Transit of Venus

1.1 Phases

During a transit, Venus and Mercury appear completely dark against the bright Sun. At other times they appear bright against the night sky – Venus is so bright it is easily visible even in the twilight of morning or evening. With only the naked eye Mercury is a bit more challenging to spot. When viewed through a telescope, it becomes evident that Venus and Mercury have *phases*, similar to the phases of the Moon (Figure 4).

Figure 4 This composite of photographs, taken over a lunar month, shows the changing shape, or phase, of the Moon, growing from a thin crescent to full moon and back again

Figure 5 explains how the phases of the Moon change as the Moon orbits around the Earth each month, according to how much we see of the half that is illuminated by the Sun. At full moon, the Moon is opposite the Sun as viewed from Earth, so we are looking at the entire illuminated half of the Moon, and it appears to be a complete circle. At other phases, some of the illuminated half of the Moon is on its far side as viewed from the Earth, so we see a partially lit object.

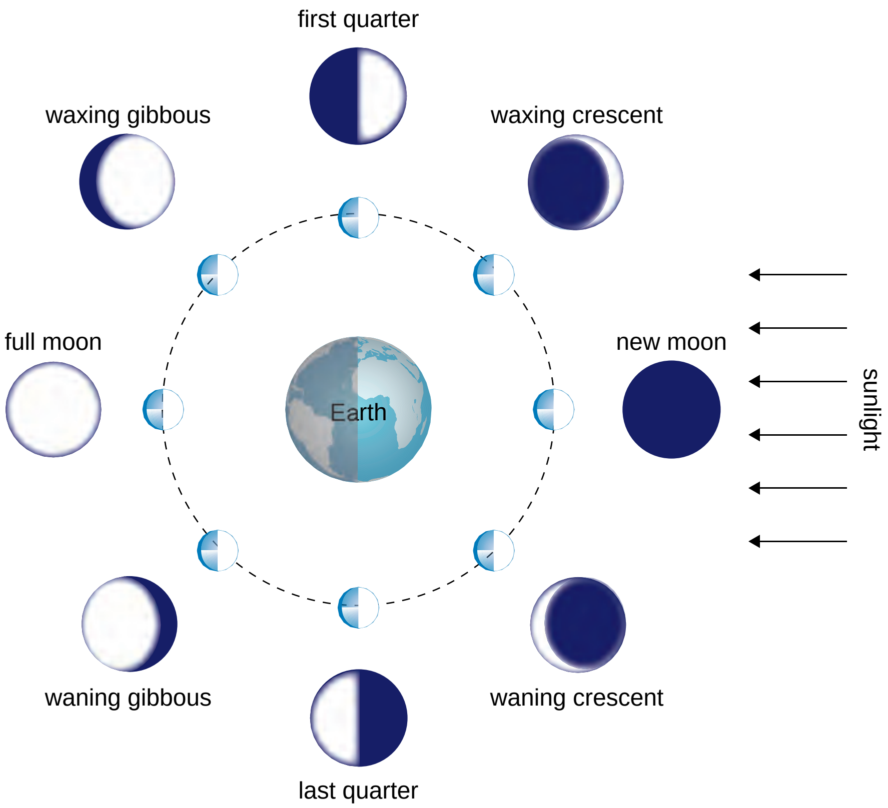


Figure 5 Phases of the Moon. The inner dashed circle represents the Moon's orbit around the Earth. At each position half of the Moon is illuminated by sunlight. The outer images show how the half-lit Moon would appear to someone on Earth.

We see something very similar with Venus, as Figure 6 shows. With the naked eye Venus looks like a bright star, but even with just binoculars it's possible to discern some change in shape.

Figure 6 Phases of Venus. This composite of photographs taken through a telescope shows Venus narrowing to a thin crescent over the course of a couple of months.

1.2 Two characteristics of planets

The observations of phases, as covered in Section 1.1 and explained in Figure 7 below, indicate two characteristics of planets: they orbit the Sun and they don't produce light of their own. The light we see from planets is reflected light from the Sun. Because of this, planets are much dimmer than the Sun, and so we can see them easily only at night.

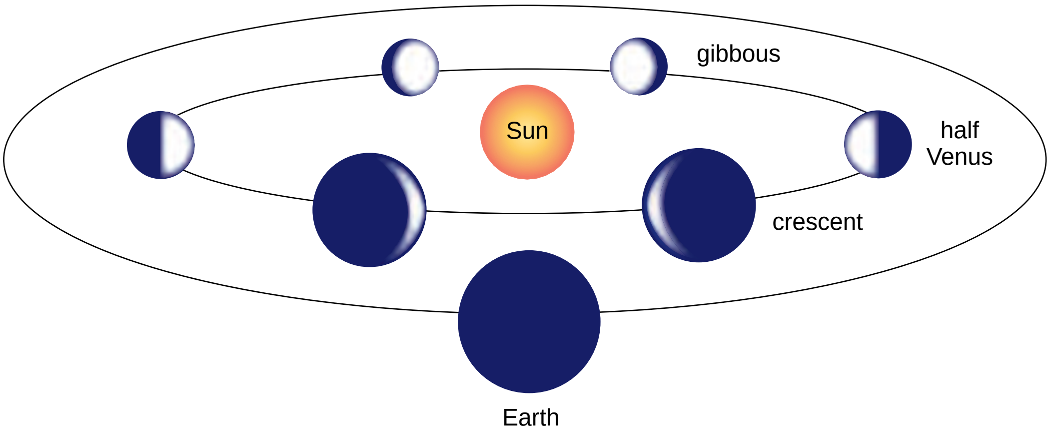


Figure 7 The phases of Venus are caused by the changing relative positions of the Earth, Venus and the Sun, as Venus orbits around the Sun. Our view of the half of Venus that is reflecting the Sun's light consequently changes, in an analogous way to the lunar phases.

Another effect that Figures 6 and 7 show is the change in apparent size of Venus, due to the changing distance between the Earth and Venus during their orbits. Exactly the same effects happen with Mercury: it shows phases and changes in apparent size. The reasons are also the same: Mercury reflects the Sun's light, and Mercury orbits the Sun.

Some planets orbit closer to the Sun than the Earth does, and some orbit at greater distances. For a transit to occur, the planet in question has to be on an orbit that is inside the Earth's orbit. In the Solar System we can only ever see transits of Venus and Mercury because the other planets never pass directly between the Earth and the Sun.

Collectively, the Sun, its planets, together with other smaller objects, are known as the Solar System (Figure 8).

Figure 8 The main bodies of the Solar System – the Sun and its eight planets

Activity 1 Distance from the Sun

Allow about 10 minutes

Using the internet to find information, arrange the following ten objects in order of their distance from the Sun (Hint: My Very Easy Method Just Speeds Up Naming Planets):

(1 = nearest, 10 = furthest)

- Mercury
- Venus
- Earth
- Mars
- asteroid belt
- Jupiter
- Saturn
- Uranus
- Neptune
- Pluto

Match each of the items above to an item below.

- 1
- 2
- 3
- 4
- 5
- 6

7
8
9
10

In Activity 1 you arranged objects in our Solar System in order of their distance from the Sun. While considering the information needed to complete this activity, you might have noticed that our nearest neighbour planets, Venus and Mars, are quite similar to the Earth in size and mass. In contrast, the outer Solar System contains some much bigger and more massive planets. You will learn more about the different types of planet in Week 2.

Before 1995, astronomers assumed that if other planetary systems existed outside our Solar System, they were probably similar to our own. As you learn about exoplanets, it will become clear that this is not always true. It is useful, however, to be able to compare exoplanets with the more familiar planets of our own Solar System. If you used the internet to find or check the information needed for Activity 1, you probably found some beautiful images of the Solar System. You are encouraged to seek out images like this: astronomy explores a spectacular Universe!

1.3 Planets and dwarf planets

In Section 1.2 you looked at ten objects in our Solar System. How many of these objects do you think are planets? In 2015 one of the objects made the headlines. After a journey that lasted a decade, the NASA New Horizons spacecraft finally got up close and personal with Pluto, sending back striking images of its surface, including a huge, heart-shaped area (Figure 9). But, despite all the fuss, Pluto hasn't been considered to be a planet since 2006. So what is it that makes a planet, and why did Pluto lose that status?

Figure 9 An image of the surface of Pluto from NASA's New Horizons probe. The heart-shaped region was named Tombaugh Regio by the mission scientists in honour of Clyde Tombaugh, who discovered Pluto in 1930.

In 2005, another object was discovered similar in size to Pluto but much further away. It was named Eris (Figure 10) after the Greek goddess of discord. Eris and several other objects found at the same time encouraged astronomers to rethink the definition of a planet.

Figure 10 Eris and its moon, Dysnomia; image taken by the Hubble Space Telescope

1.4 What defines a planet?

Video 1 shows some of the key differences between planets and dwarf planets.

View at: youtube:RQU2Q-CU6lY

Video 1 What is a planet?

As you have just seen, in 2006 the International Astronomical Union (IAU) met to decide what the definition of a planet in our Solar System should be. They came up with three criteria:

1. A planet must orbit the Sun.
2. A planet must have enough mass for its own gravity to cause it to be round, rather than being an irregularly-shaped large rock.
3. A planet must have cleared the neighbourhood around its orbit.

The second and third points relate to the gravity that an object must have to be considered a planet. Planets have enough mass for their own gravity to be the strongest force acting on them, which pulls them into roughly a sphere shape. Smaller objects – rocky asteroids and icy comets – are often a variety of weird and wonderful shapes because they don't have much mass and become distorted as a result of other forces acting on them.

The third point means that a planet must gravitationally dominate its own orbit. Large objects would either consume smaller bodies, capture them as moons or send them into different orbits. Only the most massive objects can 'clear their neighbourhood'. This means that there shouldn't be other independent objects of comparable size that also orbit the Sun in the same region of space as a planet. Moons don't count because they orbit a planet rather than the Sun – they are controlled by the planet's gravity. This definition also allows for other objects such as so-called Trojan asteroids, which are small clumps of asteroids pushed along or 'shepherded' by a planet's gravity.

Point number three is where Pluto lost out. As you saw in Video 1, Pluto shares its orbit with many other objects. Pluto is now defined as a dwarf planet – an object that ticks points one and two of the planet definition, but not point three. Eris, and the largest object in the asteroid belt, Ceres, have also joined this new group.

Activity 2 Is the neighbourhood clear?

Allow about 5 minutes

Based on what you have just learned, which of the following planet candidates would astronomers say satisfy the third planet criterium?

- ☐ a lone planet candidate
- ☐ a planet candidate orbiting within the asteroid belt
- ☐ a planet candidate with Trojan asteroids sharing its orbit
- ☐ a planet candidate which shares the orbit of another, larger planet

1.5 Other objects in the Solar System

There are plenty of objects in the Solar System that are neither planets nor dwarf planets. Objects that orbit a planet rather than the Sun are called moons, or satellites. Mercury and Venus are the only planets in our Solar System that don't have satellites, while the giant planets – Jupiter, Saturn, Uranus and Neptune – have over 150 between them.

The montage in Figure 11 shows Jupiter's Great Red Spot and its four largest moons, the Galilean moons. From top to bottom, these are Io, Europa, Ganymede and Callisto. Their relative sizes and the size of the Great Red Spot are accurate.

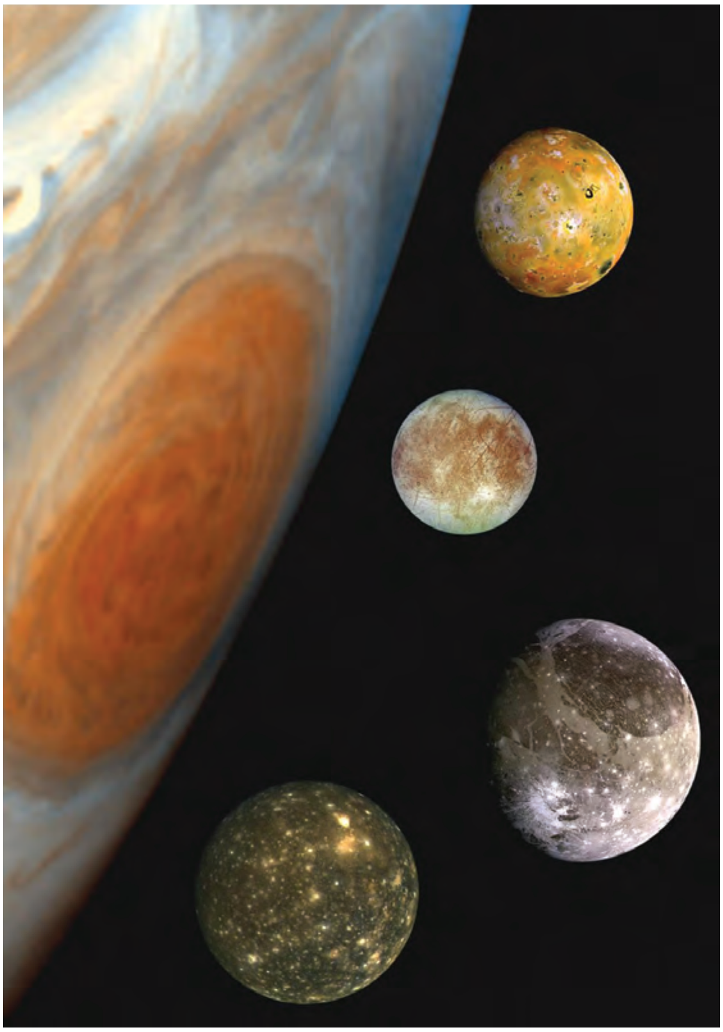


Figure 11 Jupiter and the Galilean moons

Dwarf planet Pluto has five moons, of which the largest, Charon, is almost as large as Pluto itself (Figure 12).

Figure 12 Colour-enhanced images of Pluto (bottom) and Charon (top)

The rest of the Solar System is far from empty. Apart from the planets and moons, the Solar System contains asteroids (smaller, irregular lumps of rock) and comets (irregular lumps of ice and dust). Asteroids mostly congregate in the region between Mars and Jupiter known as the ‘asteroid belt’. Comets tend to have very stretched, or elliptical, orbits around the Sun, often coming from regions beyond Pluto to pass close to the Sun. The most famous of these, Halley’s comet, returns to the inner Solar System about once every 75 years – it will visit us again in 2061.

When a comet approaches the Sun, the heat and radiation destroys some of the ice, creating a huge cloud of gas and dust, called a ‘coma’, which surrounds the comet. Some of the material streams out in a long tail behind the comet, giving the comet its distinctive appearance. Some comets return after hundreds of years, but some never come back at all. The unlucky ones, such as comet ISON in 2013, fail to survive their encounter with the Sun (Figure 13).

Figure 13 Comet ISON on 24 September 2013

Activity 3 Planet, dwarf planet, moon, or something else?

Allow about 5 minutes

Using the internet to help where necessary, identify each of the following objects as either a planet, dwarf planet, moon or something else.

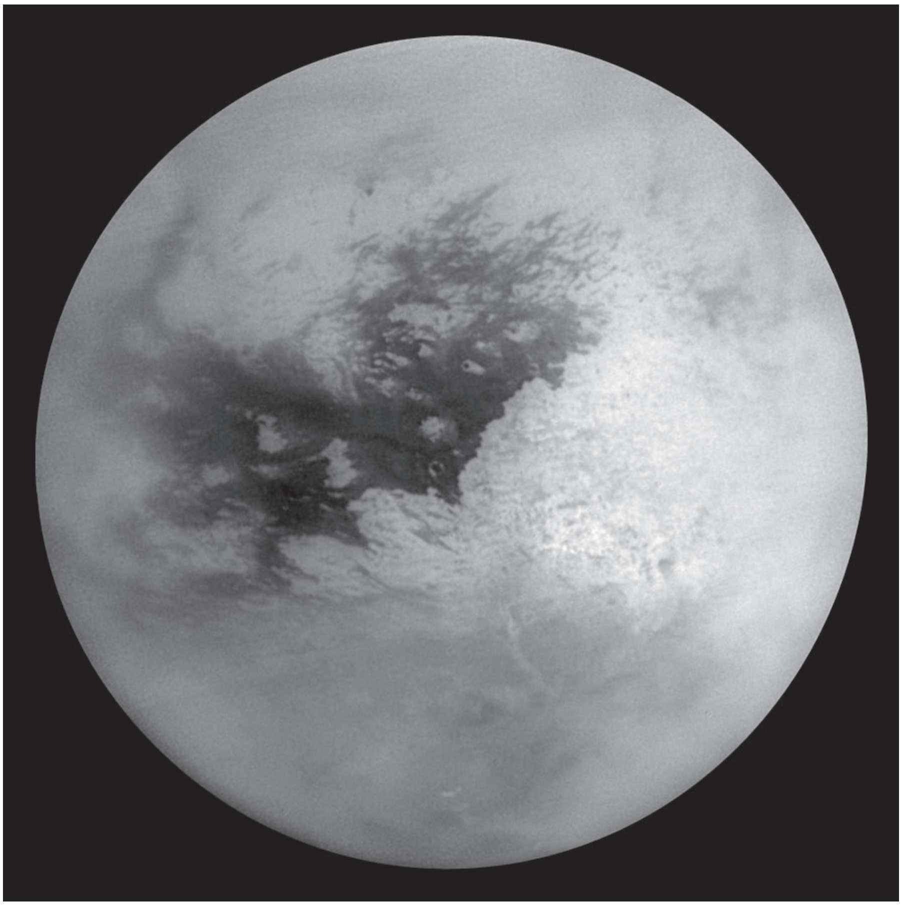


Figure 14

1. Vital statistics: approximately half the size of Earth, rocky, round, orbits Saturn.

Provide your answer...

Answer

Titan, Saturn’s largest moon.

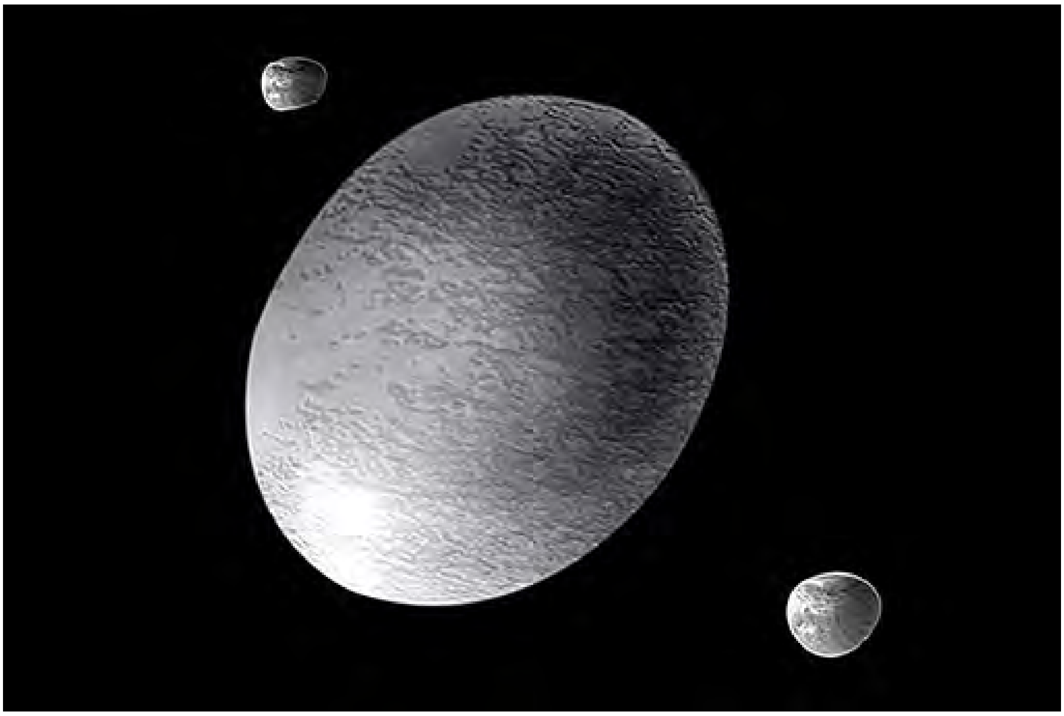


Figure 15

2. Vital statistics: approximately one-third the size of Earth, rocky, orbits the Sun, found in the distant region of the Solar System called the Kuiper Belt (like Eris).

Provide your answer...

Answer

Haumea, a dwarf planet. Although Haumea is rounded it is less spherical than other dwarf planets because it is rapidly spinning.

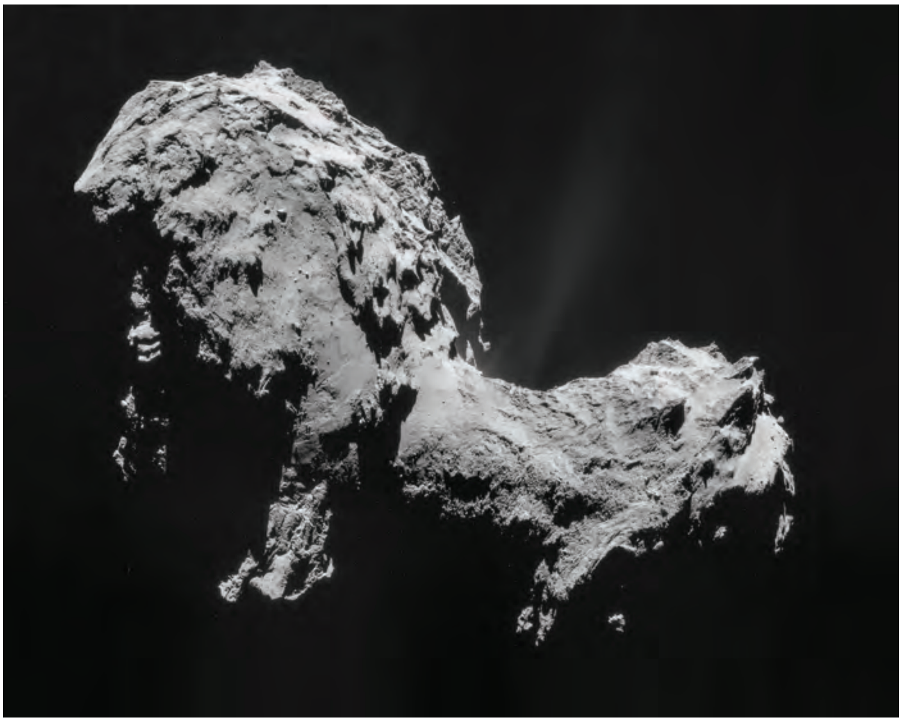


Figure 16

3. Vital statistics: a few kilometres across, icy, orbits the Sun.

Provide your answer...

Answer

Comet 67P, on which the Philae spacecraft landed in 2014.

Figure 17

4. Vital statistics: a few tens of kilometres across, rocky, orbits the Sun.

Provide your answer...

Answer

Ida, an asteroid (larger body) and Dactyl, a baby asteroid that orbits the larger body like a mini-moon (smaller body).

The planets in our Solar System vary greatly in size, although they are generally much smaller and fainter than stars, as Video 2 shows.

View at: youtube:RePa0VqIs8s

Video 2 The Solar System planets, Pluto, the Sun, Vega (a bright star visible to the human eye) and a giant star (please note this video has no spoken audio)

2 Stars and galaxies

The Sun is just one of billions of stars in our Galaxy, the Milky Way. Like all stars, the Sun is a large ball of gas, mostly hydrogen, which is so massive that its centre has become a nuclear reactor. The weight of all the layers of the star pressing inwards creates huge temperatures and pressures at the centre. Under these conditions hydrogen undergoes nuclear fusion, creating helium. All of the energy that the Sun produces comes from this conversion of hydrogen gas into helium gas.

Our Sun is about 4.5 billion years old. 4.5 billion can also be written as 4500 000 000 or 4.5×10^9. The Sun is middle-aged: halfway through its lifetime as a 'normal' star, which we call a 'main sequence' star. More massive main sequence stars than the Sun are bigger, bluer and hotter (Figure 18). These stars burn through their resources of hydrogen relatively rapidly, after which they evolve into other types of stars and eventually 'die'. Less massive stars are smaller, redder, cooler and burn hydrogen more slowly. Less massive stars therefore have longer lifetimes.

Figure 18 Normal main sequence stars have different sizes, colours and temperatures depending on how massive they are

When the Sun runs out of its hydrogen supply in about another 4.5 billion years it will become a 'red giant'. Its outer layers will expand, possibly reaching as far as the Earth's orbit. Mercury and Venus will certainly be swallowed up. Eventually, these outer layers will be shed and just a dense core will be left where the Sun used to be. A remnant star like this is called a 'white dwarf'.

Many stars will end their lives in the same way as the Sun, but others will have more dramatic deaths. More massive stars can explode as supernovas, and their leftover cores form extremely dense objects called neutron stars, or even black holes.

Maths help

The following OpenLearn resources may help with the maths in this section. Open the link in a new tab or window by holding down Ctrl (or Cmd on a Mac) when you click on the link. Remember to return here when you have finished.

- power notation (hundred, thousand, million in powers of ten) (Sections 2.2 and 2.2.1)
- scientific notation (for large numbers) (Sections 3.1 and 3.1.1, Activities 33 and 34 – positive powers)

2.1 Exoplanets

You might have noticed that the IAU definition of a planet doesn't seem to account for planets orbiting stars other than the Sun. These planets are called exoplanets. The first planet orbiting another Sun-like star was discovered in 1995, and since then astronomers have found over 4000 of these exoplanets. A star along with its exoplanets is known as a planetary system. We now know that our own Solar System is not unique: it is one planetary system among a very large number of others.

You'll be finding out more about exoplanets over the weeks to come, but first you'll get to know the Universe beyond our Solar System.

2.2 The Milky Way and other galaxies

Groups of stars congregate due to the force of gravity between them, forming galaxies.

Video 3 shows the structure of the Milky Way, the Galaxy that contains our Solar System. Our most precise knowledge of the distances to the stars comes from the space missions that used the satellites Hipparcos and Gaia, whose ranges are indicated towards the end of the video.

View at: youtube:G5AdrupH788

Video 3 Guide to our Galaxy (please note this video has no spoken audio)

Astronomers are not completely sure how many stars the Milky Way contains, with 400 billion being their best estimate. It is now known that many of these stars have their own systems of planets. Based on the number of planets astronomers have found so far, it is thought that there are even more planets in the Galaxy than stars. Just how numerous planets are will become clearer in the near future, as astronomers work on trying to find as many planets as possible around the stars closest to the Sun.

Galaxies tend to fall into two groups:

1. spiral galaxies (Figure 19), such as the Milky Way, which contain stars of a variety of ages, including young stars that are still forming
2. elliptical galaxies (Figure 20), which contain mostly older stars and look like fuzzy blobs.

Spiral galaxies are prettier (at least in common belief!).

Figure 19 M101, a spiral galaxy

Figure 20 NGC 4150, an elliptical galaxy

Activity 4 Hierarchy of the Universe

Allow about 5 minutes

Put the following in order of the hierarchy, from smallest (1) to largest (3):

Star

Planetary system

Galaxy

Match each of the items above to an item below.

1

2

3

Answer

1. Star
2. Planetary system
3. Galaxy

Galaxies themselves congregate in groups, clusters and superclusters. Astronomers' best estimate is that there are over 100 billion galaxies (that is 100 000 000 000 galaxies) in the observable Universe. It is daunting to think that the Sun is only one star among something like 400 000 000 000 × 100 000 000 000 in the observable Universe! But fear not! In this course you will focus only on exoplanets and stars in the Milky Way: galaxies beyond our own and the possibly infinite Universe are covered elsewhere.

3 The sky

This course will acquaint you with one of the most active research areas in astronomy: exoplanets. It would be a shame to study astronomy without sharing the primal and universal experience of viewing the night sky directly with your own eyes.

If you have time, on any suitable night, try the following (you'll need about an hour).

Box 1 Stargazing

Go outside on a clear night, preferably away from city lights. If you have them, take a pair of binoculars with you. If you have a smartphone with GPS you can download an app that shows the positions of stars in the night sky wherever you are (free app for iPhone: SkyView; free app for Android: Sky Map). Alternatively, the website of *Sky and Telescope* magazine has a very useful 'This week's sky at a glance' feature, which includes diagrams of what to look for each week.

Wait at least 15 minutes for your eyes to become adjusted to the dark. Is the Moon up? If it is, you may want to look in the opposite direction as it will be easier to see fainter objects if the Moon isn't in your field of vision. You could try to spot a planet – if it is dawn or dusk and you see what looks like a very bright star close to the eastern (dawn) or western (dusk) horizon, you have probably seen Venus. Jupiter is also often clearly visible and is usually higher in the sky than Venus. You can identify planets because, as well as being very bright, they do not appear to twinkle, as stars do.

Stars are grouped into patterns on the sky, or constellations, many of which are traditionally imagined as mythological figures.

Good features to look for associated with some constellations include:

- The Plough (a distinctive pattern that makes up part of the constellation of Ursa Major, the Great Bear) and Polaris (the Pole Star, a bright star in the constellation of Ursa Minor, the Little Bear) (Figure 21).

Figure 21 The Plough and Polaris (the Pole Star)

- Cygnus (The Swan) (Figure 22) – believe it or not, most of the exoplanets we know of are in a tiny patch of sky in this constellation.

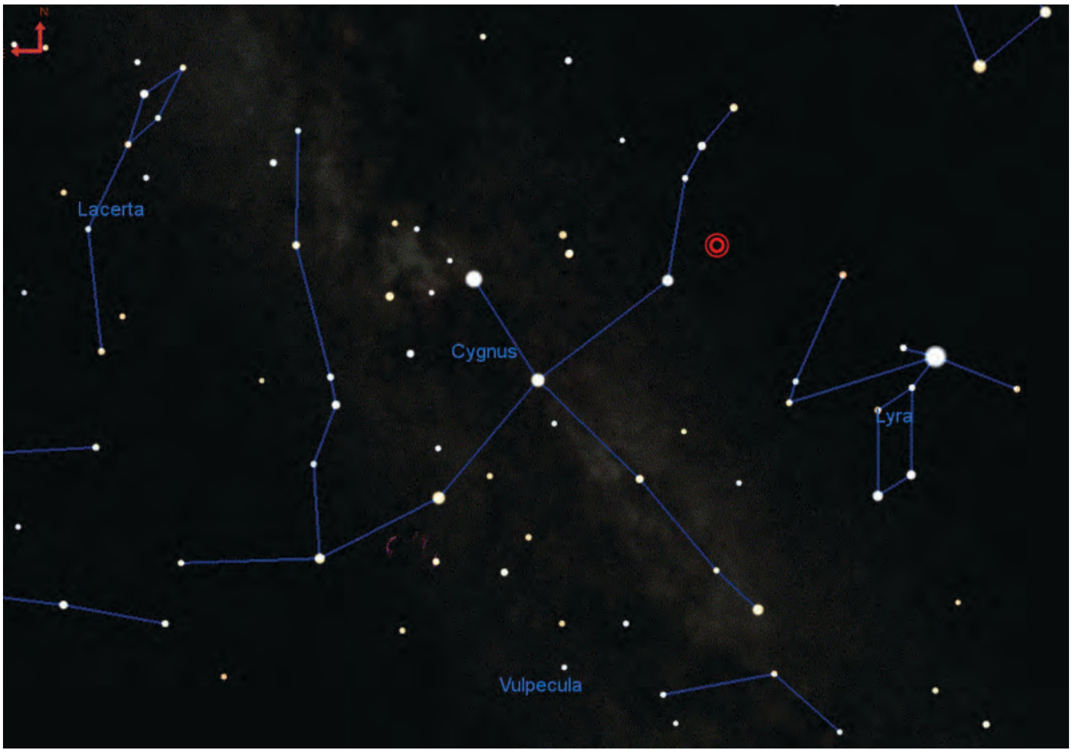


Figure 22 The constellation Cygnus

- Orion (winter months in the Northern Hemisphere and summer in the Southern Hemisphere) and Sirius, the brightest star in the night sky (Figure 23). Sirius is a binary star: two stars in orbit around each other. But all you see is light from one star – the other is a white dwarf and is very faint.

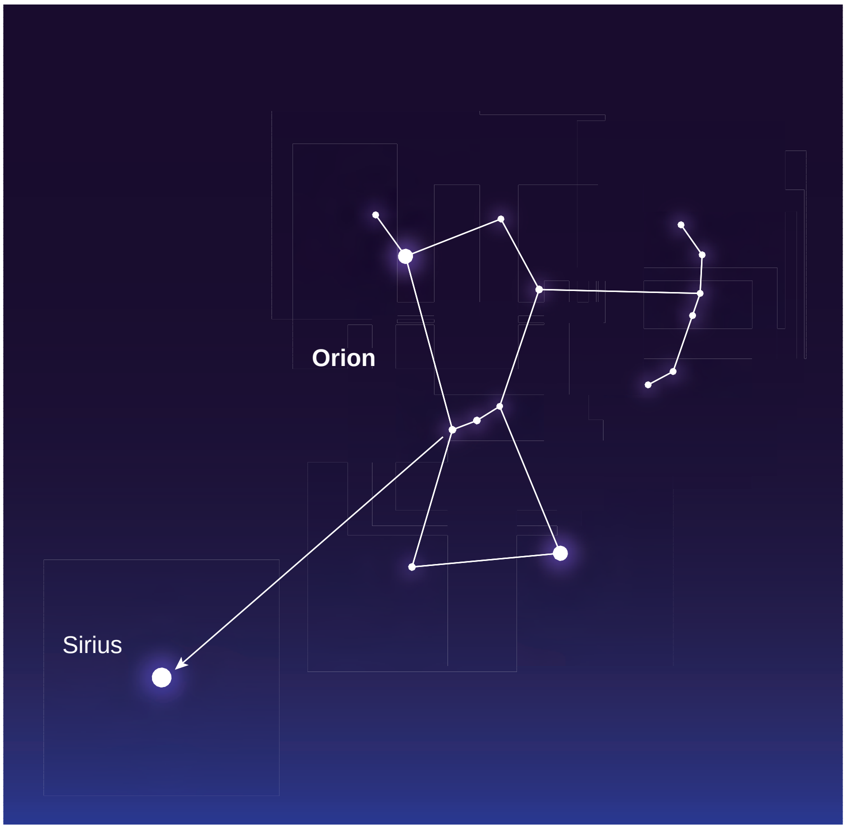


Figure 23 Orion and Sirius

From a dark site, it is possible to see the Milky Way. It appears as a faint cloudy band across the sky. If you have a pair of binoculars, use them to scan along the Milky Way – the number of stars that can be discerned dramatically increases and you may spot beautiful ‘open clusters’ of bright young stars.

Video 4 shows a short time-lapse sequence of the night sky from the Canary Islands. In the video, the Milky Way moves from being roughly horizontal to roughly diagonal. You can see dark clouds of interstellar dust obscuring the light of billions of stars. Because your eyes’ pupils are smaller than the aperture of the camera used to make this film, you are unlikely to ever see this much detail with the naked eye.

4 This week's quiz

Well done – you have reached the end of Week 1 and can now take the weekly quiz to test your understanding.

Week 1 practice quiz

Open the quiz in a new tab or window (by holding down Ctrl [or Cmd on a Mac] when you click the link).

5 Summary of Week 1

This week you have learned about what makes a planet a planet. You've covered the planets in our Solar System and have learned about how planetary systems and galaxies are structured. You should be able to confidently use the words star, planet, planetary system and galaxy, and be able to describe the relationships between them. Learning about how our Solar System works provides a great starting point for exploring planets around other stars, which you will be doing over the weeks to come.

You should now be able to:

- recognise the International Astronomical Union (IAU) definition of a planet
- understand the difference between planets and dwarf planets
- describe the other objects in our Solar System
- define the term 'exoplanet'
- describe each of the following building blocks of the Universe: stars, planets, planetary systems and galaxies
- identify some objects and constellations in the night sky.

Next week you will be looking at the properties of individual planets in the Solar System in more detail.

You can now go to Week 2.

Week 2: Planets, large and small

Introduction

Last week you learned about the Solar System and the planets within it. Those planets come in a range of sizes and they have very different conditions. Now that astronomers are discovering planets around other stars too, they are finding that planets are even more varied than the examples in our Solar System led us to believe. In Week 2, you'll learn about the different classes of planet and their basic characteristics.

Watch the following video in which Carole Haswell talks about what you'll be doing in the course this week.

Video content is not available in this format.

By the end of this week, you will be able to:

- describe what is meant by a terrestrial planet and a giant planet, and the differences between these two planet types
- understand the scale of the Solar System and use the astronomical unit to measure it
- classify the planets Jupiter, Saturn, Uranus and Neptune as gas giants or ice giants
- describe what is meant by mass, radius, volume and density, and how these terms are used within astronomy
- understand the meaning of the symbols AU, M_J, R_J, M_E, R_E, $M_\oplus$, $R_\oplus$, M_{Sun}, R_{Sun}, $M_\odot$ and $R_\odot$.

1 Terrestrial and giant planets

The eight planets in our Solar System can be split into two main categories.

The four inner planets, of which Earth is the largest, are all rocky planets. Because they are like the Earth, we call them the terrestrial planets. Mars is the outermost terrestrial planet, about one and a half times as far from the Sun as the Earth is. Beyond Mars is the asteroid belt.

On the other side of the asteroid belt, things are very different. The next planet, Jupiter, is about five times the Earth's distance from the Sun. The four large outer planets, Jupiter, Saturn, Uranus and Neptune, aren't made of rock – instead, they are large balls of gas held together by gravity. Collectively, they are referred to as the giant planets. Jupiter and Saturn are called the gas giants. Because Uranus and Neptune are even further from the Sun than Jupiter and Saturn are and are extremely cold, they are referred to as the ice giants.

Terrestrial planets and giant planets have very different structures (Figure 1). Planets like Earth are mostly made of rock, possibly with an iron core. Planets like Jupiter are made almost entirely of hydrogen. Astronomers are not absolutely sure what goes on in the interior of the gas planets, but they think that at very high pressures the hydrogen gas may start to behave like a metal. A big question is whether Jupiter has a small rocky core or not. New results from NASA's Juno spacecraft orbiting Jupiter since 2016 may soon answer this.

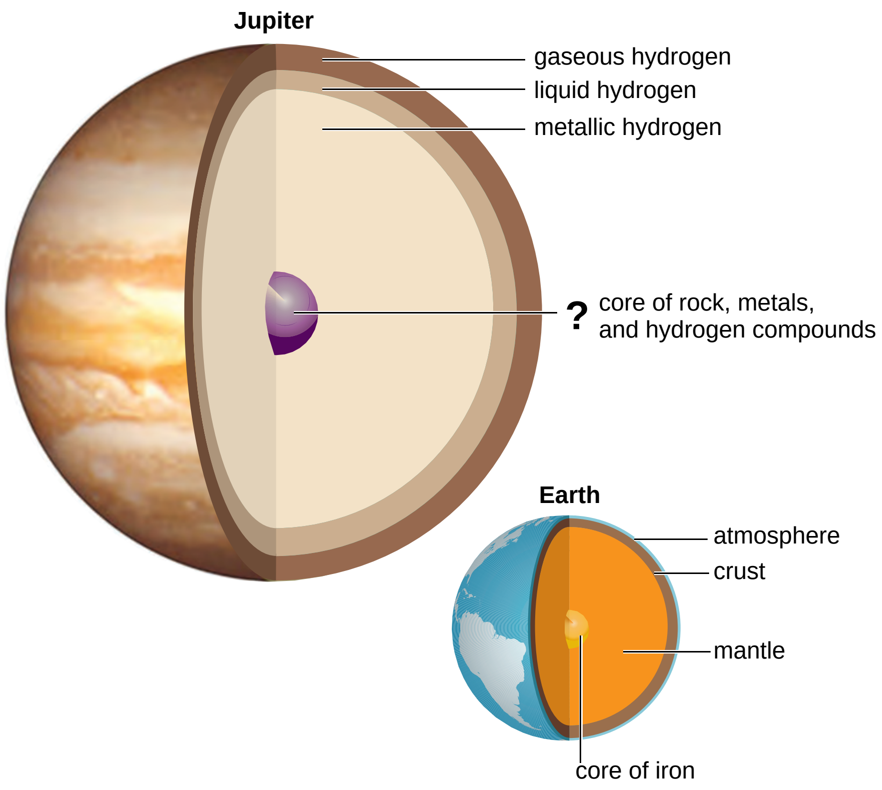


Figure 1 Cutaways showing the interiors of Jupiter and Earth. Note that different scales have been used for Earth and Jupiter so the Earth's structure is clear.

2 The scale of the Solar System: everything is big!

Probably the most obvious difference between a gas giant planet such as Jupiter and a terrestrial planet such as Earth is their size. Jupiter, the largest planet in our Solar System, is around ten times the size of Earth. In Week 1 you learned that stars are much bigger than planets; for instance, the Sun is nearly ten times the size of Jupiter and therefore about one hundred times the size of the Earth! When referring to the 'size' of a planet or star we could think of its diameter, measured through the middle from one side across to the other. Astronomers usually use the 'radius' though, which is the distance between the centre and the surface, and so is half the diameter.

Because everything is so big, it can be very difficult to picture the differences in size between the Solar System planets, and to imagine the vast distances that separate them. The next two activities should help you to do this.

Big numbers!

We said that the lifetime of the Sun is about 9 billion years. A billion is clearly a huge number but it's very difficult to get a feel for just how big it is.

How long do you think it would take to count to one thousand if you say one number each second? And what about one million? Does it take much longer to count to one billion in this way?

You might be surprised by the answer:

One thousand seconds is 17 minutes, one million seconds is nearly 12 days, and one billion seconds is nearly 32 years! It's easy to forget just how much bigger billions are than millions.

Incidentally, one trillion seconds is nearly 32 000 years!

2.1 Sizes of the Solar System planets

Activity 1 will help you to visualise the relative sizes of the planets in our Solar System.

Activity 1 DIY edible Solar System

Allow about 10 minutes, plus time for shopping (and eating)

You need:

1 watermelon or similar large melon
1 large grapefruit
1 dessert apple
1 lime
2 gooseberries
1 blueberry

1 white/red/black currant (or peppercorn).

You can substitute any of these for fruit/vegetables of a similar size.

Using information from the internet, try to match each piece of fruit with the correct planet. (Hint: which is the largest planet? Which two planets are almost identical in size?)

When you think you've got it right you can check your answer here:

Answer

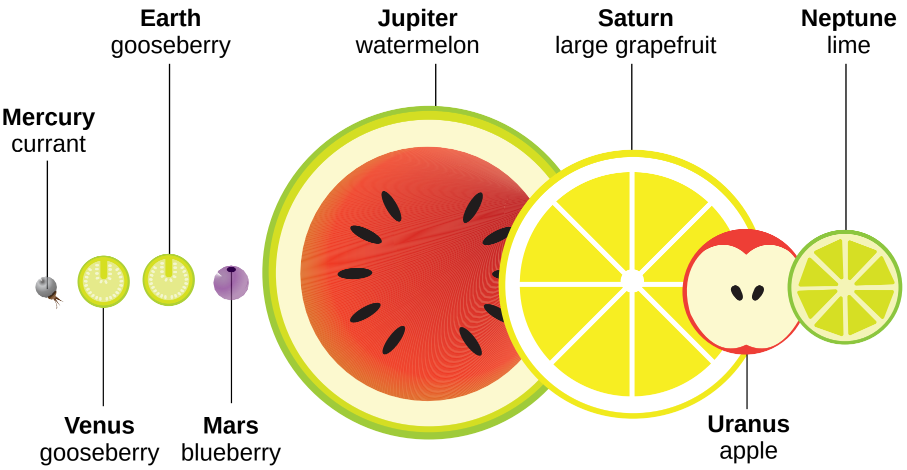


Figure 2 A fruit salad Solar System showing the approximate relative sizes of the planets

2.2 Distances between the Solar System planets

Activity 2 will help you to visualise the distances between the planets in our Solar System.

Activity 2 Toilet roll Solar System distances

Allow about 20 minutes

You need:

a new roll of toilet paper (preferably strong)

a felt-tip pen.

Open the roll and unroll the first few sheets. Place a mark on the seam in between the first two sheets and label this as the Sun. Then count the following numbers of sheets and make a mark for each of the Solar System planets (if you want to be very accurate, use fractions of a sheet as indicated by the numbers in brackets).

Table 1 Solar System distances with toilet paper

Planet	Number of sheets from previous planet
Mercury	1
Venus	1 (0.9)

Earth	1	(0.7)
Mars	1	(1.3)
Jupiter	9	(9.5)
Saturn	12	(11.3)
Uranus	25	(24.9)
Neptune	28	(28.0)

Notice that as you go further out the planets generally become more distant from each other. The Sun would look much smaller and its light and heat would seem much weaker from the outer Solar System planets (Figure 3 below).

Mercury is about 58 million kilometres from the centre of the Sun, so in this activity one sheet of toilet paper represents this distance. This is similar to the way that a map gives a scaled-down picture of an area on the Earth. The scale of a map is usually represented as a ratio such as 1 : 50 000. This means that 50 000 cm on the ground is represented on the map by 1 cm. As 50 000 cm is the same as 500 m, a kilometre (2 × 500 m) would be represented by 2 cm on such a map.

We can work out the scale of your toilet paper Solar System. Don't worry if you don't understand this immediately – read through it slowly to give yourself a fair chance. It's not the end of the world if you don't get the hang of it!

One sheet represents the distance between the Sun and Mercury, 58 million kilometres. Assuming your toilet paper has sheets which are about 15 cm long, this is a scale of

1 sheet : 58 million km

so 15 cm : 58 million km

Converting the right-hand side first to metres and then to centimetres to match the units on the left-hand side, this is

15 cm : 58 billion m

15 cm : 5800 billion cm

Dividing both sides of the scale by 15, this becomes about

1 cm : 387 billion cm

So we can say that the approximate scale is 1 : 400 billion or 1 : 400 000 000 000, which is quite a bit more compressed than the 1 : 50 000 maps which tourists often use to explore. The Solar System is really big!

Figure 3 shows the relative approximate size of the Sun as seen from the other planets in the Solar System. It is very small and faint when seen from Uranus and Neptune.

Figure 3 The Sun from other planets

Maths help

The following OpenLearn resources may help with the maths in this section. Open the link in a new tab or window by holding down Ctrl (or Cmd on a Mac) when you click on the link. Remember to return here when you have finished.

- changing units (Section 1.1)
- converting units (Sections 2.2, 2.2.1 and 2.4)

2.3 The astronomical unit: a convenient way to measure distances in the Solar System

Distances in the Solar System are easiest to describe in terms of the distance between the Sun and the Earth. This distance is called 1 astronomical unit, or 1 AU for convenience. 1 AU is roughly equivalent to 150 million kilometres (150 000 000 km) (1.5×10^8 km). This is about 93 million miles – a number which may be more familiar to some.

Using this unit you can rewrite what was explained in Section 1: Mars's distance from the Sun is about 1.5 AU, while Jupiter's is about 5 AU. This unit helps to appreciate the vast scale of the Solar System: Neptune and Pluto are approximately 30 AU and 40 AU from the Sun, respectively. Eris, which until 2018 was the most distant known natural object in the Solar System, has a maximum distance from the Sun of 98 AU. Eris's record was recently displaced by an object nicknamed 'Farout', observed in 2018 at a distance of around 120 AU (18 billion kilometres just sounds like another very big number which is difficult to mentally compare with other distances in the Solar System!).

In all sciences it is extremely important to state the units of any quantity. This is particularly true in astronomy, where the numbers can be very different if expressed in everyday units.

3 Gas giants and ice giants

The outer regions of the four giant planets in the Solar System are pretty similar – their atmospheres are all mostly made of hydrogen and helium gas. However, if you look at their interiors, you can start to see some differences between them.

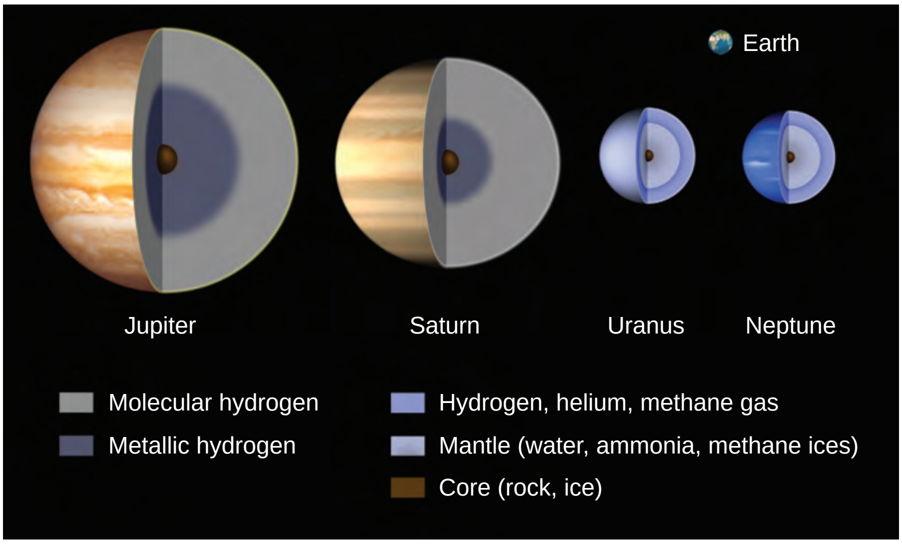


Figure 4 Gas and ice giant interiors

Jupiter and Saturn are made predominantly of hydrogen, with some helium. However, the cooler planets, Uranus and Neptune, are thought to have mantles made of water, ammonia and methane underneath their atmospheres. You may know methane better as the natural gas that powers your gas boiler if you have one in your house.

It's hard to tell for certain because Uranus and Neptune are shrouded in a shell of hydrogen and helium, but astronomers think the water, ammonia and methane in their mantles are in the form of fluids under very high pressure – so not really ices. Uranus and Neptune are actually called ice giants because scientists think the water, ammonia and methane were all ices when the planets were formed. Uranus and Neptune formed in extremely cold conditions – methane freezes at −182 °C!

Uranus and Neptune are the only planets in the Solar System that have not had a dedicated mission sent to observe them, so these are probably the most mysterious of the eight planets. They were briefly studied by the Voyager 2 spacecraft in 1986 (Uranus) and 1989 (Neptune). Beautiful images like the one shown in Figure 5 of Neptune's Great Dark Spot make them a very attractive target for future space missions, but because they are so far away it would take years to get there.

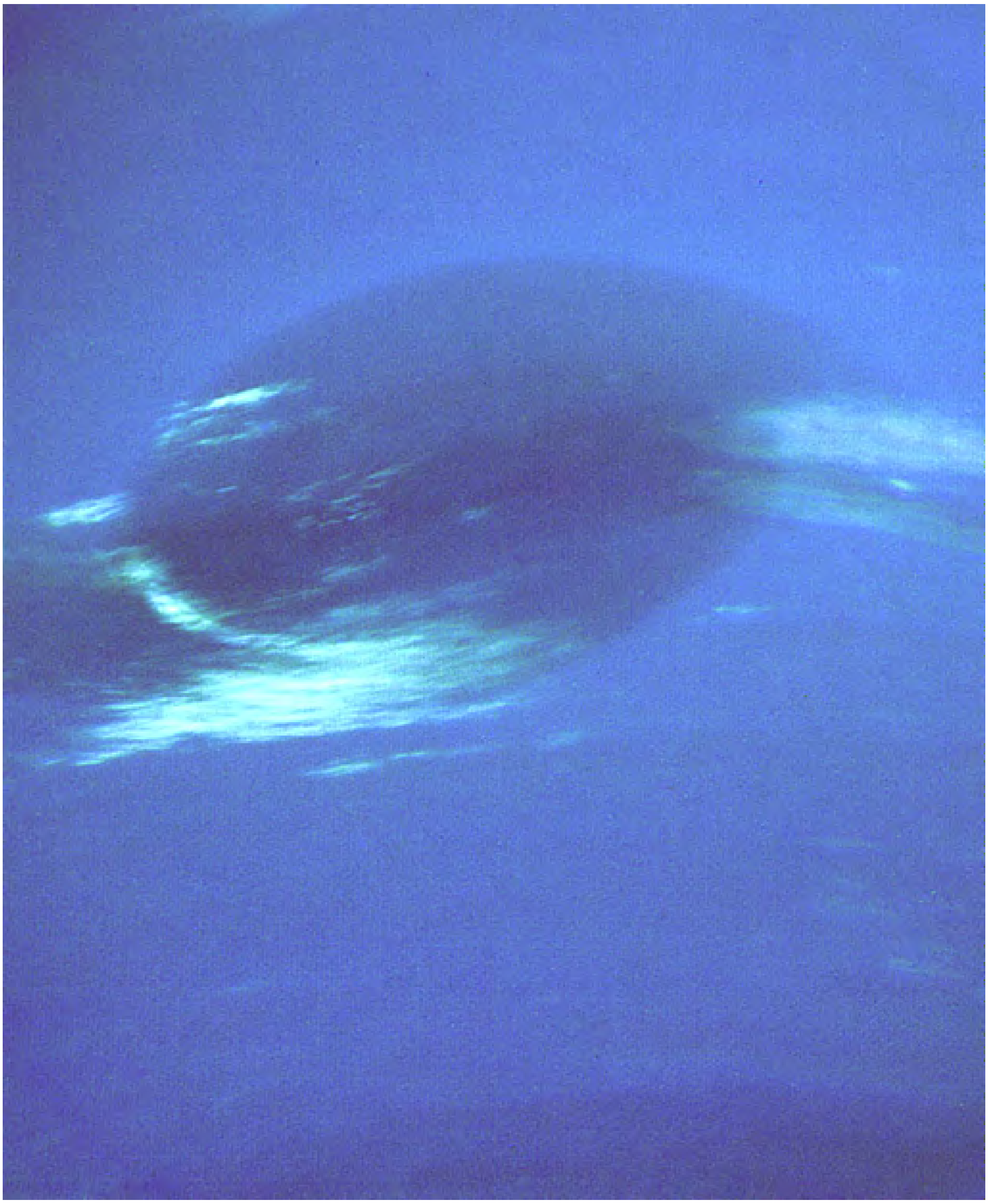


Figure 5 Neptune's Great Dark Spot, a feature similar to Jupiter's Great Red Spot. This image was taken by the Voyager 2 spacecraft on its way past Neptune.

4 Planet vital statistics

In previous sections you have covered sizes and distances in the Solar System; now you will look at how astronomers measure and discuss the properties of planets.

If you've ever taken a long-haul flight, you will know that the Earth is big. The usual terminology for measuring size and mass was designed for talking about things we usually deal with on Earth, like the distance of a car journey or weighing out ingredients for a cake. These measures quickly become inadequate when talking about astronomy.

You've already seen how astronomers use the distance between the Earth and Sun when discussing distances within the Solar System. Similarly, it is very convenient to measure all rocky planets in terms of 'Earths' and all gas giants and ice giants in terms of 'Jupiters'. With this trick, instead of trying to quote a planet's mass in billions of billions of kilograms, you can simply say it is a certain number of Jupiter masses. In the case of our Solar System this number will be a fraction of course, but this will become particularly useful when we encounter exoplanets that are even more massive than Jupiter!

4.1 Planet sizes

Earlier this week, you learned that the radius is used as a measurement of size in planets. Generally, if people need to calculate something that depends on a radius, they use the letter *r* to stand for the radius. For the purpose of this course, we will use a capital *R* for a planet's radius (Figure 6) and a lower case *r* for other radii. The radius of the Earth is 6378 km.

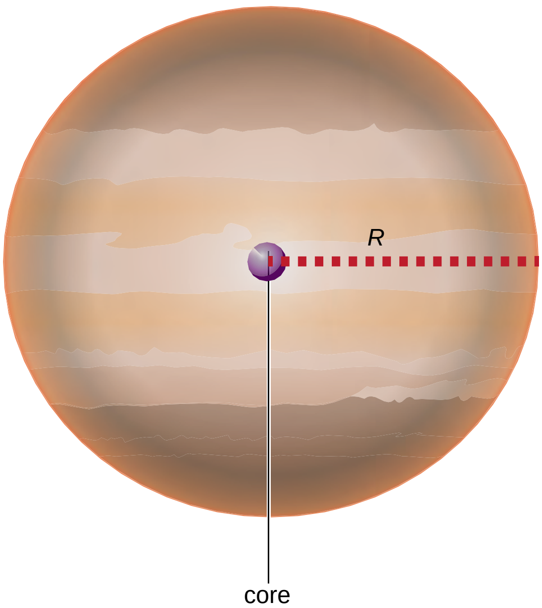


Figure 6 The radius, *R*, of a planet is the distance from the centre to the surface

When astronomers discuss the sizes of planets, it is cumbersome to use kilometres. It is far more convenient to introduce the unit 1 Earth radius, written 1 R_E (or sometimes 1 $R_\oplus$), when discussing terrestrial planets (Figure 7). It is obvious that a planet with a radius of say 1.1 R_E is slightly bigger than Earth, 10 per cent bigger to be exact. On the other hand, if a planet had a radius of 7020 km, you probably wouldn't immediately know how much bigger or smaller than Earth it is.

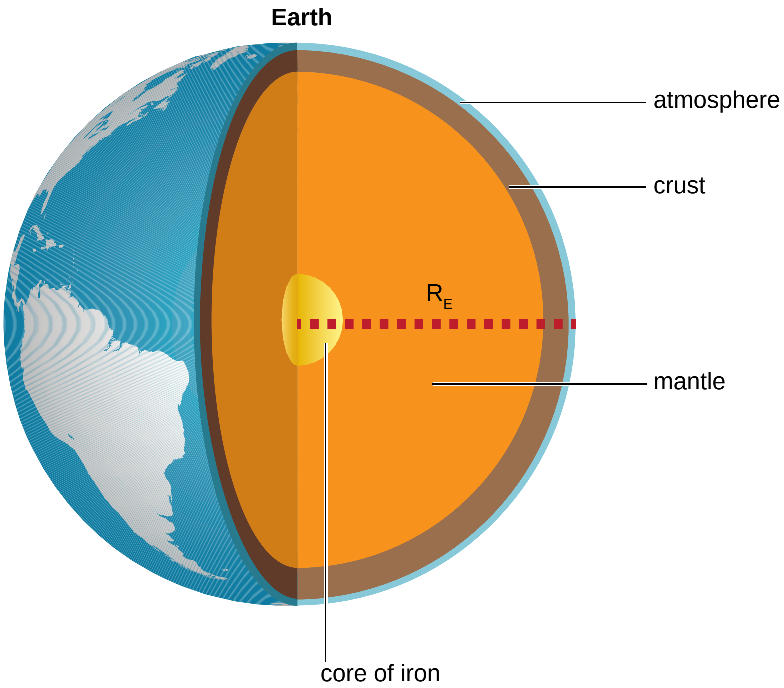


Figure 7 The radius of the Earth, 1 R_E, is used as a unit to measure the sizes of terrestrial planets

Similarly, when discussing giant planets, it is most convenient to use Jupiter's radius, so giant planet radii are generally given in units of R_J.

4.2 Planet volumes

We live in a world of three dimensions, and volume describes how big something is in three dimensions. The volume is the total amount of space inside an object, or its capacity. People often use the letter *V* to represent volume. As you learned in Week 1, to qualify as a planet an object must be nearly spherical in shape, so to work out the volume of a planet you need to know the volume of a sphere.

You will start by looking at how to work out the volume of a cube, which is a much more straightforward calculation. Figure 8 shows two cubes: the smaller cube has sides of length 1 cm, while the larger cube has sides of length 10 cm.

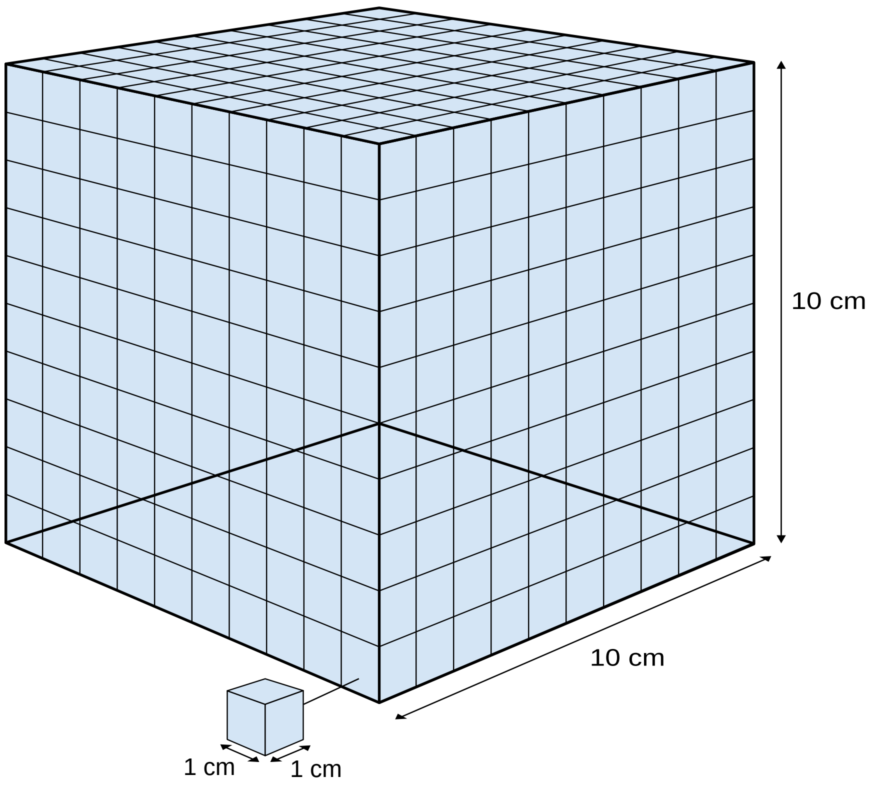


Figure 8 Two cubes: the smaller one with sides 1 cm × 1 cm × 1 cm, the larger one with sides 10 cm × 10 cm × 10 cm

The smaller cube has a volume of 1 cubic centimetre. 1 cubic centimetre is often written as 1 cm^3. You can work out the volume of the larger cube by calculating how many small cubes you can fit into the larger one.

Look at one face of the large cube in Figure 8 and count the number of small cubes on that face. There are 100 (10 × 10) small cubes in a layer of the large cube. Each layer of 100 small cubes is stacked together to form the large cube, and there are 10 layers. So, there are 10 × 10 × 10 small cubes in the large cube. Since 10 × 10 × 10 = 1000 the volume of the large cube is therefore 1000 cm^3.

If the length of the side of the cube is then the volume of the cube is . The volume of a cube is always the length of one of its edges cubed, that is, multiplied by itself three times.

The volume of a cube is easy to calculate, as you can see. You just need to multiply the length of one side by itself, then by itself again. This holds true, no matter how big the cube is. For a sphere, the volume is not just the size multiplied by itself three times. Because the shape is curved, the maths is more complicated, but there is a standard equation that uses the radius of a sphere to work out its volume. You may have encountered the exact equation before, but we can use a simplified version which is a good approximation:

$V = 4.19r^3$

Here, just as with , r^3 means $r \times r \times r$.

So, if you have a sphere with a radius of 1 m, then its volume will be 4.19 × 1 × 1 × 1 = 4.19 cubic metres, or 4.19 m^3. Generally, volume is measured in m^3 or cm^3.

4.3 Scaling radii and volumes

You learned that Jupiter is a factor of about 10 bigger than the Earth in size, meaning that the average radius of Jupiter is about 10 times the size of the radius of the Earth. In fact, it is 10.97 times as great to be more exact. This means that nearly 11 Earths could fit across Jupiter (Figure 9).

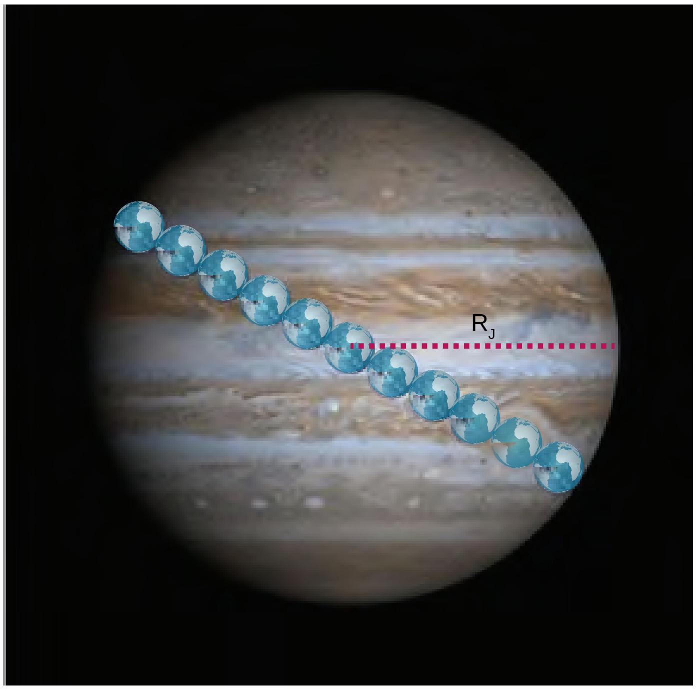


Figure 9 The diameter of Jupiter is 11 times the diameter of Earth, hence the radius of Jupiter is 11 times the radius of Earth

For any shape, if the length is scaled up by a factor of 10, the volume will scale up by a factor of 1000. You compared cubes with sides differing by a factor of 10, and saw the volume differs by a factor of 1000. Similarly, the volume of a sphere with a radius of 10 m will be 1000 times as large as the volume of a sphere with radius 1 m. So, the volume of a sphere with a radius of 10 m will be 4.19 × 1000 = 4190 m^3. It is easy to understand where this comes from: the radius is multiplied together three times during the calculation to get the volume. A factor of 10 multiplied by a factor of 10 multiplied by a factor of 10 will give a result 1000.

So, while Jupiter is a factor of over 10 larger than Earth in radius, it is over 1000 times larger in volume. This shows it is absolutely vital that you know exactly what you mean when you talk about how ‘big’ something is!

4.4 Mass and density

What is mass? Mass is simply how much matter something contains. So now, think about the masses of the planets in the Solar System.

You have seen that Jupiter’s volume is more than 1000 times Earth’s volume. If, instead of being planets, Jupiter and Earth were both enormous containers, then Jupiter could hold more than 1000 times as much water as Earth. This might make you think that Jupiter is more than 1000 times as massive as Earth – but, as it happens, that isn’t the case.

Jupiter has a mass of about 1900×10^{24} kg. By 10^{24} we mean 1 followed by 24 zeros, so the mass of Jupiter is 1900 000 000 000 000 000 000 000 000 kg. That's a lot of stuff! To avoid this unwieldy number, when discussing the masses of giant planets, astronomers use the mass of Jupiter, M_J, as the unit. Similarly, for terrestrial planets, the usual unit of mass is the mass of the Earth, which is given the symbol M_E (or $M_\oplus$).

Earth has a mass of about 6×10^{24} kg. So, while Jupiter is much more massive than Earth, it's not by as much as you might have expected – a factor of around 300 rather than over 1000.

This is because the material that Jupiter is made of is less tightly packed than the material Earth is made of – Jupiter is less dense. Density is a measure of how much 'stuff' there is within a space of a given size. Remember that Jupiter is mostly made of hydrogen gas, whereas Earth is mostly made of rock. That means that there is less matter per unit volume in Jupiter than there is in the same volume on Earth (Figure 10).

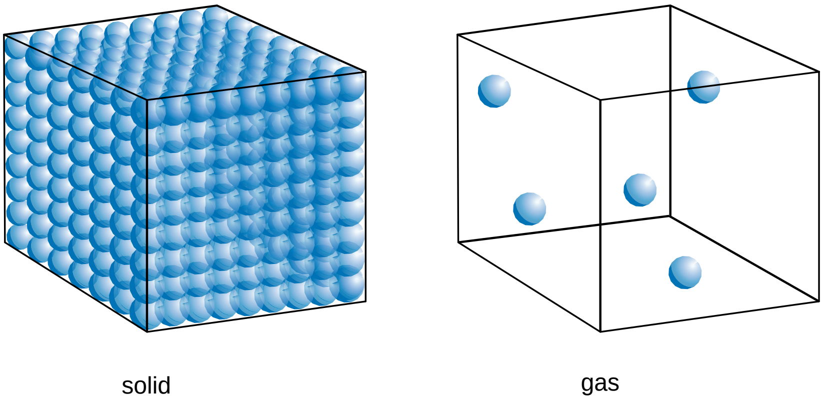


Figure 10 Relative densities of gases and solids. Particles in a solid are much closer together than particles in a gas. It's possible to fit more matter into the same space if it is in solid form.

4.5 Floating, sinking and planetary structure

One everyday effect related to density is whether something floats or sinks. Polystyrene packing beads float on water because they are less dense than water. Pebbles sink in water because they are more dense than water. Another effect can be observed if you make a traditional salad dressing from vinegar and oil: the denser liquid, vinegar, will sink and the less dense liquid, oil, will float on top of it. In the interiors of Earth and Jupiter, the denser material in each case sinks to the centre (Figure 11).

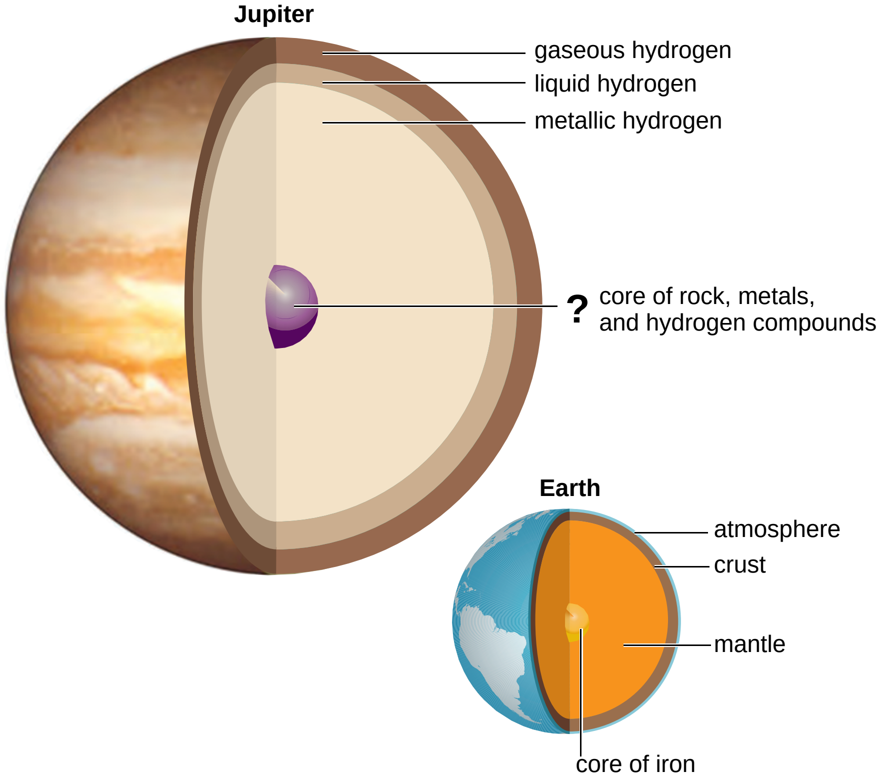


Figure 11 Cutaways showing the interiors of Jupiter and Earth. The core of the Earth is much denser than the rocks at the Earth's surface. Astronomers aren't yet certain what is at the core of Jupiter or other giant planets, and it is possible that they have rocky cores.

Generally, both planets and stars behave a bit like salad dressing: the denser material sinks and the less dense material floats. So if a planet is composed of several different materials, they will generally be arranged with the densest material at the centre and the least dense at the surface. Clearly it is not straightforward to make a direct measurement of the composition of the material at the centre of any planet. Scientists are fairly sure from indirect measurements that the Earth has an iron core. This sinking and floating would have taken place when the interior was molten early in Earth's formation.

4.6 Average densities

If a planet is composed of different layers each having different densities, then the density of the planet as a whole will be averaged over the various layers. To give the average density of a planet, the total mass is divided by the total volume:

In this way you can measure the average densities of some planets orbiting around other stars even though you can't see them, as you will learn in future weeks. If a planet has the density of rock, it is probably composed of rock. If it has the density of hydrogen gas, that is probably what it is composed of. Iron is the densest material you might expect to find in a planet, while a mixture of hydrogen gas with a small amount of helium is the least dense material you might expect to find.

However, you must be careful about conclusions such as those above. The average density of a planet might not tell you what the planet is made of. It is possible to imagine a planet with an iron core surrounded by hydrogen/helium gas, which averages out to exactly the density of rock. In this case, the conclusion that the planet is composed of rock would be completely wrong. From the average density, it is impossible to be sure exactly how much of each layer is present.

As you go down to deeper layers of the planet Jupiter, you can see how much the density increases (Figure 12). Density is often expressed in units of grams per cubic centimetre (g/cm^3), so the numbers in Figure 12 say how many grams of material are contained in each cubic centimetre. Near the core the density is expected to be around 25 g/cm^3, which means that each centimetre cube contains material that has a mass of 25 grams. As a comparison, the density of liquid water on Earth is 1 g/cm^3.

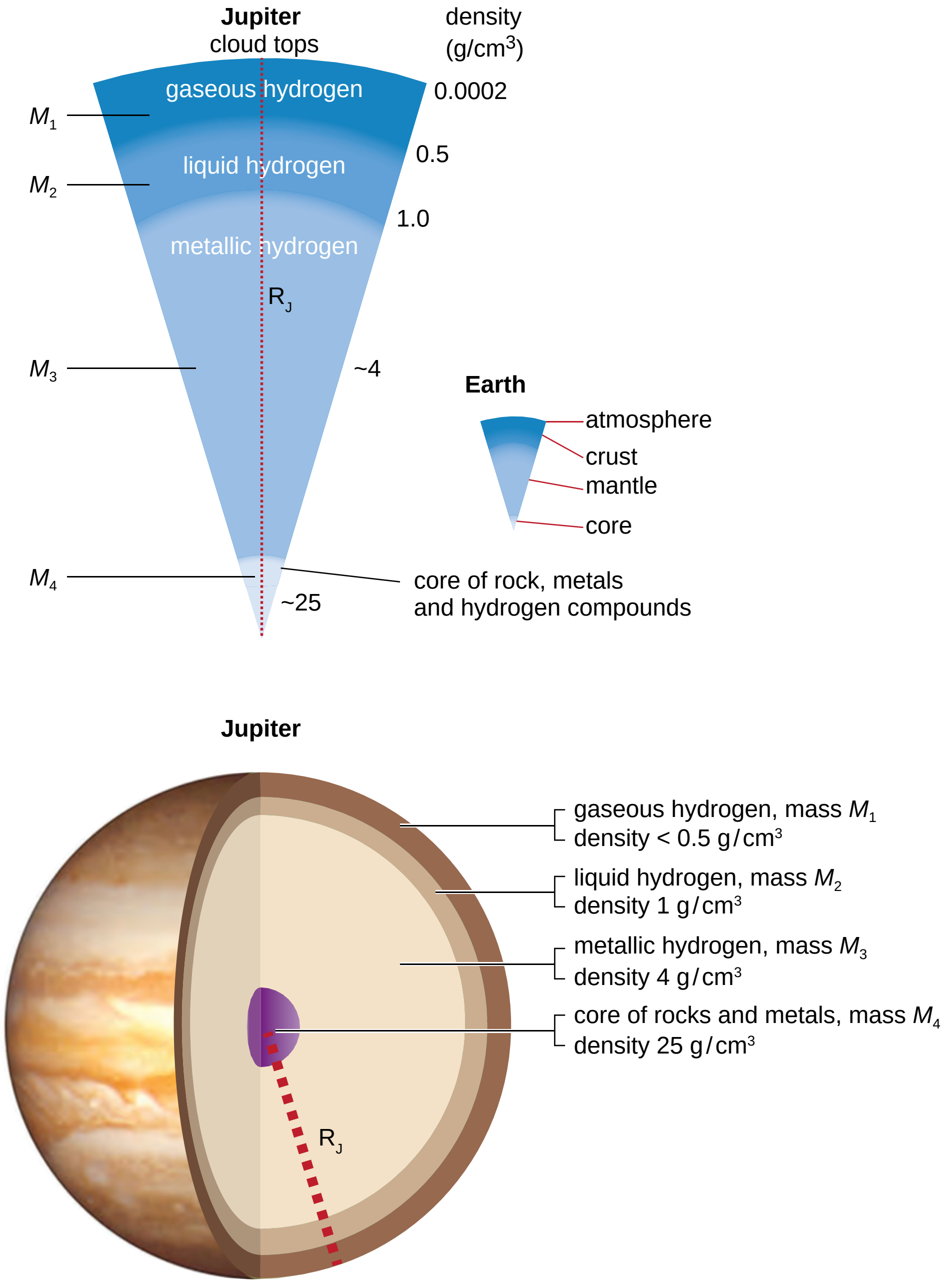


Figure 12 Density of Jupiter's layers

Activity 3 The density of a layered planet

Allow about 15 minutes

In this activity you will calculate the density of a layered planet, in this case, Jupiter, which is shown in Figure 12.

1. On a piece of paper, write down a sum giving the total mass M of Jupiter in terms of the masses of its four layers, M_1, M_2, M_3 and M_4.

Answer

---

2. Write down an expression for the volume of Jupiter in terms of its radius, R_J.

Answer

Look back at Section 4.2 if you are unsure where this comes from.

---

3. Referring to your answers to Part 1 and Part 2, write down an expression for the density of Jupiter in terms of M and R_J.

Answer

---

4. Use your answer to Part 3 and the data listed below to calculate the average density of Jupiter.

   Total mass of Jupiter: 1.898×10^{30} g

   Average radius of Jupiter: 6.991×10^{9} cm

Answer

We use the expression for density found in Part 3 and substitute the numbers for the mass and average radius into it. This gives

Jupiter's average density is 1.3 g/cm^3, which means that each centimetre cube of material has a mass of 1.3 grams on average – a little more than the density of water on Earth.

Note that the answer to a calculation like this should be rounded to convey how precisely the measurements used in the calculation are known. There are rules for this, but in this course it is generally suitable to round to two or three digits.

Maths help

The following OpenLearn resources may help with the maths in this section. Open the link in a new tab or window by holding down Ctrl (or Cmd on a Mac) when you click on the link. Remember to return here when you have finished.

- using formulas (Sections 3.1, 3.1.1, 3.2, 3.3 and 3.3.1)

- scientific notation on your calculator (Sections 5 and 5.1)
- rounding (nearest 10, 100, 1000) (Section 2)
- rounding (decimal places and significant figures) (Sections 1.4, 1.4.1, 1.5 and 1.5.1)
- how precise are the measurements? (Section 1.4)

4.7 Densities of Solar System planets

The planets in the Solar System all have different compositions, and this affects their densities.

In general, terrestrial (rocky) planets are denser than the gas and ice giants. Earth has a density of around 5.5 g/cm^3 compared with Jupiter's density of 1.3 g/cm^3.

Activity 4 Densities of Solar System planets

Allow about 5 minutes

You'll be shown a density value and you need to decide which of two planets it belongs to, based on the information provided above.

Density: 1.6 g/cm^3

- ○ Neptune
- ○ Mars

Density: 0.69 g/cm^3

- ○ Mercury
- ○ Saturn

Density: 5.2 g/cm^3

- ○ Venus
- ○ Uranus

Mercury and Earth are the densest planets in the Solar System (Figure 13) with densities similar to the iron-rich mineral haematite. Saturn, the least dense planet in the Solar System on the other hand, has a density lower than that of water. It may sound strange, but this means that Saturn would actually be able to float in a container of water if you could find one large enough.

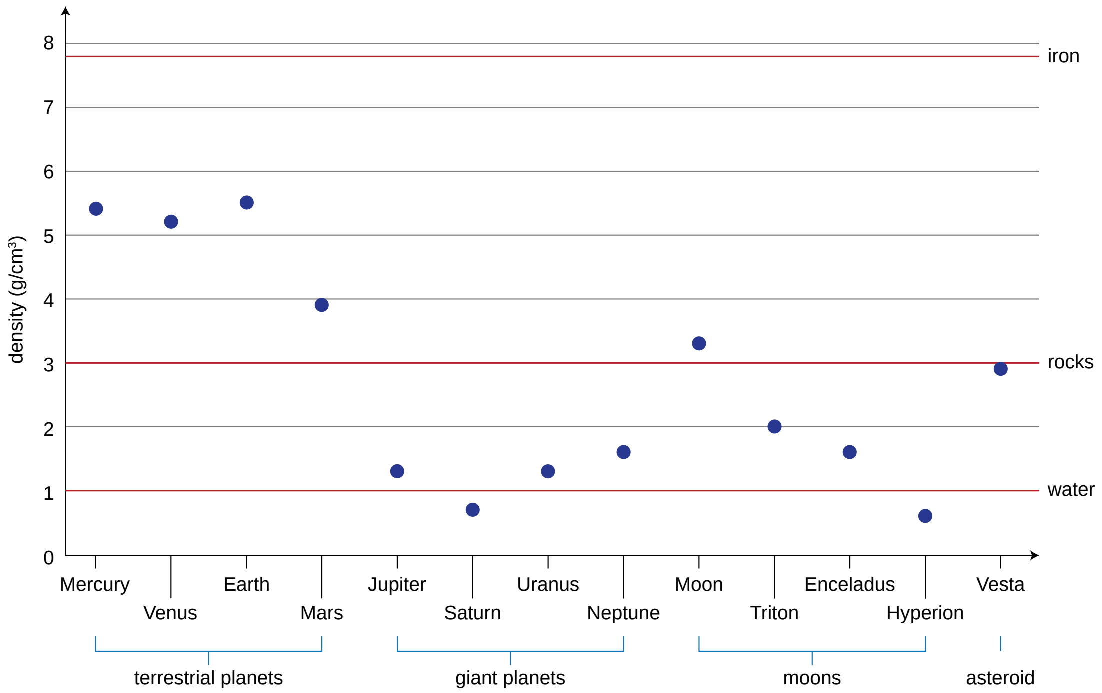


Figure 13 Solar System planet densities compared with the density of iron, rock and water. Densities of some moons and one asteroid are also shown.

5 Simplifying the numbers

You've seen in the last few sections that studying planets involves dealing with some very big numbers. To simplify calculations, astronomers have introduced their own units, and you've already seen most of the important units for this course.

- The sizes of planetary systems are measured in terms of astronomical units, written AU.
- Giant planets are measured in terms of the mass and radius of Jupiter, written M_J and R_J.
- Terrestrial planets are measured in terms of the mass and radius of the Earth, written M_E and R_E. Sometimes the alternative forms $M_\oplus$ and $R_\oplus$ are used, but you will use M_E and R_E in this course.
- Stars are measured in terms of the mass and radius of the Sun: the solar mass and solar radius, written M_{Sun} and R_{Sun}. Sometimes the alternative forms $M_\odot$ and $R_\odot$ are used, but you will use M_{Sun} and R_{Sun} in this course.

Table 2 Units used in exoplanet science

Quantity	Symbol	Value
Earth mass	M_E	5.97×10^{24} kg
Earth radius	R_E	6.38×10^{6} m
Jupiter mass	M_J	1.90×10^{27} kg
Jupiter radius	R_J	7.15×10^{7} m
Solar mass	M_{Sun}	1.99×10^{30} kg
Solar radius	R_{Sun}	6.96×10^{8} m
Distance between Earth and Sun	AU	1.50×10^{11} m

Now, instead of saying, for example, that the mass of Saturn is 5.68×10^{26} kg, you can express the mass of Saturn in terms of the mass of Jupiter, M_J. To do this you need to work out how many Jupiter masses there are in Saturn. Mathematically, divide the mass of Saturn by the mass of Jupiter and the answer is the number of Jupiter masses in Saturn.

So:

Or instead you could express Saturn's mass in terms of the mass of the Earth.

In this case:

So, you can say that Saturn's mass is 0.3 M_J, or 95 M_E. Both of these alternatives give you an immediate feeling for where Saturn fits compared with other planets.

Activity 5 Sizes and masses of planets in terms of Earth and Jupiter

Allow about 10 minutes

You are given the masses and radii for some of the Solar System planets. You need to calculate the masses in terms of M_J and M_E, and the radii in terms of R_J and R_E. For each planet, which is the most sensible comparison to use?

Useful values are provided in Table 3. Note that all radii are given in km here.

Table 3 Units used in exoplanet science

Quantity	Symbol	Value
Earth mass	M_E	5.97×10^{24} kg
Earth radius	R_E	6.38×10^{3} km
Jupiter mass	M_J	1.90×10^{27} kg
Jupiter radius	R_J	7.15×10^{4} km

1. Calculate the mass of Uranus in terms of Earth and Jupiter. Which comparison is more useful?

   Uranus mass: 8.68×10^{25} kg

Answer

0.046 M_J or 14.5 M_E; either comparison is useful.

2. Calculate the radius of Neptune in terms of Earth and Jupiter. Which comparison is more useful?

   Neptune radius: 2.48×10^{4} km

Answer

0.35 R_J or 3.9 R_E; either comparison is useful.

3. Calculate the radius of Mercury in terms of Earth and Jupiter. Which comparison is more useful?

   Mercury radius: 2.44×10^{3} km

Answer

0.034 R_J or 0.38 R_E; comparison with Earth is more useful.

6 Gallery of planet portraits

In the previous sections you examined a lot of the foundations needed for a sensible scientific discussion of planets. Now that you have those mathematical foundations in place, let us remind ourselves of the beautiful planets described by the numbers.

6.1 Terrestrial planets

Below is a selection of images of the terrestrial planets in our own Solar System.

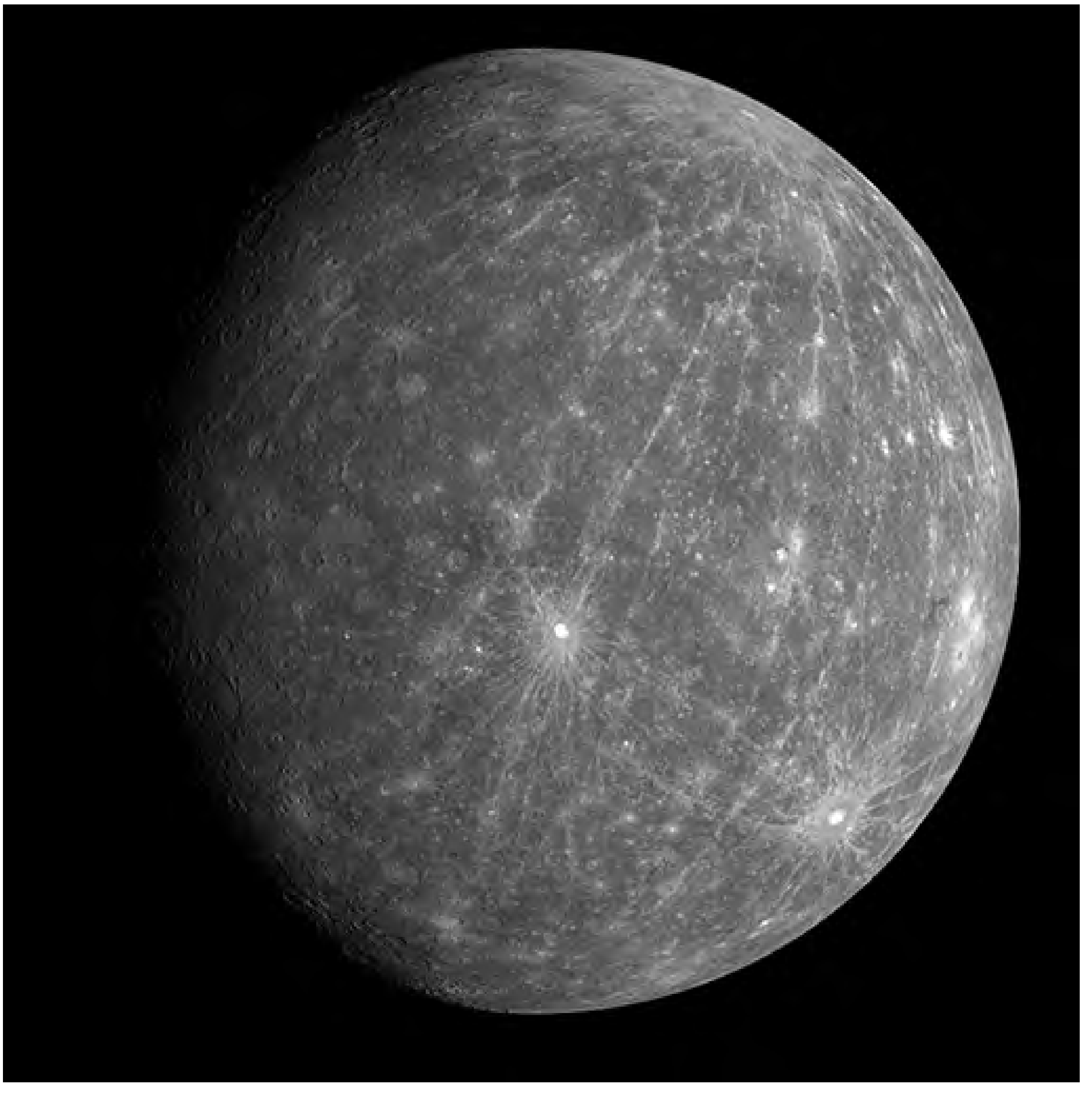


Figure 14 This image of Mercury was taken by the Messenger spacecraft in 2008 in a fly-by before it entered orbit around the planet. The long rays emanating from craters were a newly imaged feature.

Figure 15 This image of Venus was taken by the Mariner 10 spacecraft in 1974. Venus is very bright because it has a thick layer of highly reflective sulfuric acid clouds obscuring the surface.

Figure 16 'Earthrise' from lunar orbits. The first image is a composite made using NASA's Lunar Reconnaissance Orbiter in 2015. The second image was taken by the Apollo 8 astronauts on Christmas Eve in 1968.

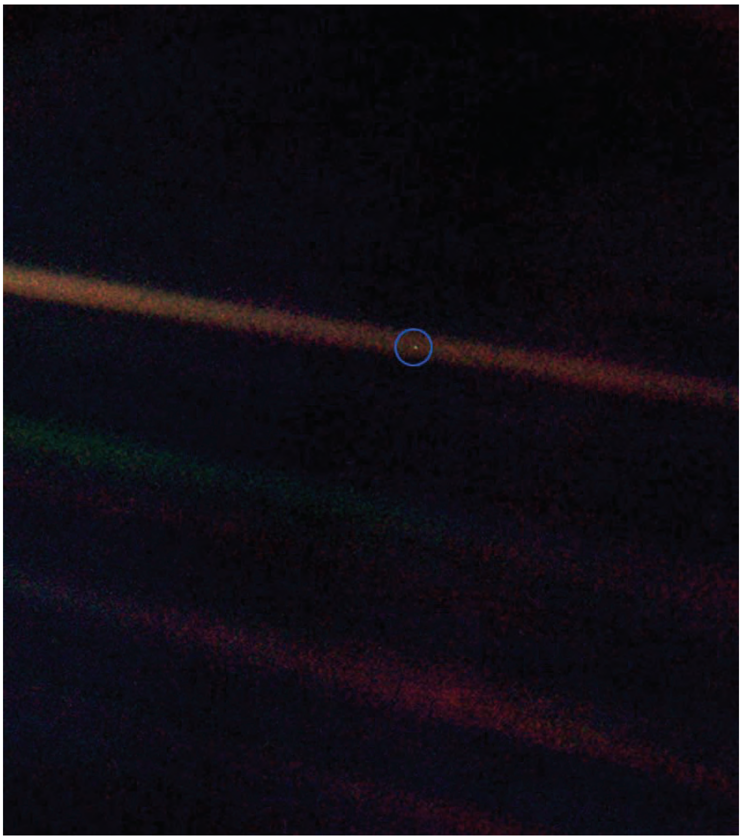


Figure 17 The ‘pale blue dot’ image of the Earth was taken from the Voyager spacecraft in 1990 as it was leaving the Solar System. Earth is circled in this image to help you see it.

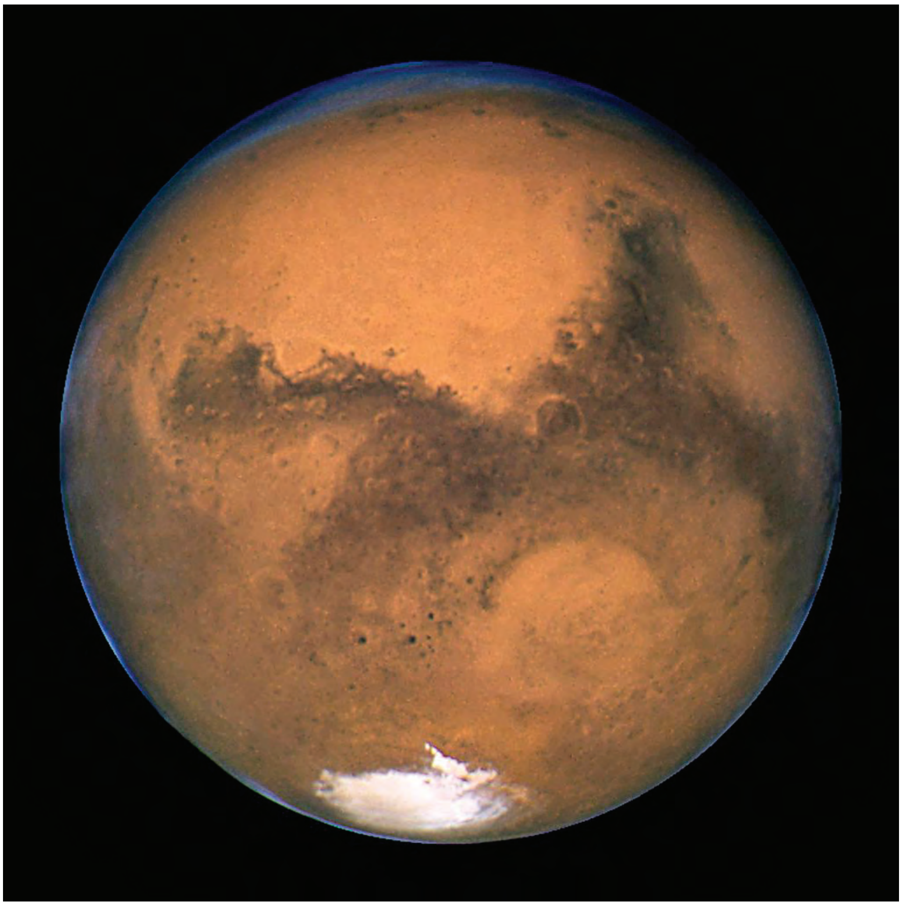


Figure 18 Image of Mars taken by the Hubble Space Telescope, clearly showing the southern polar ice cap of water ice and frozen carbon dioxide

6.2 Giant planets

Now take a look at these images of the giant planets.

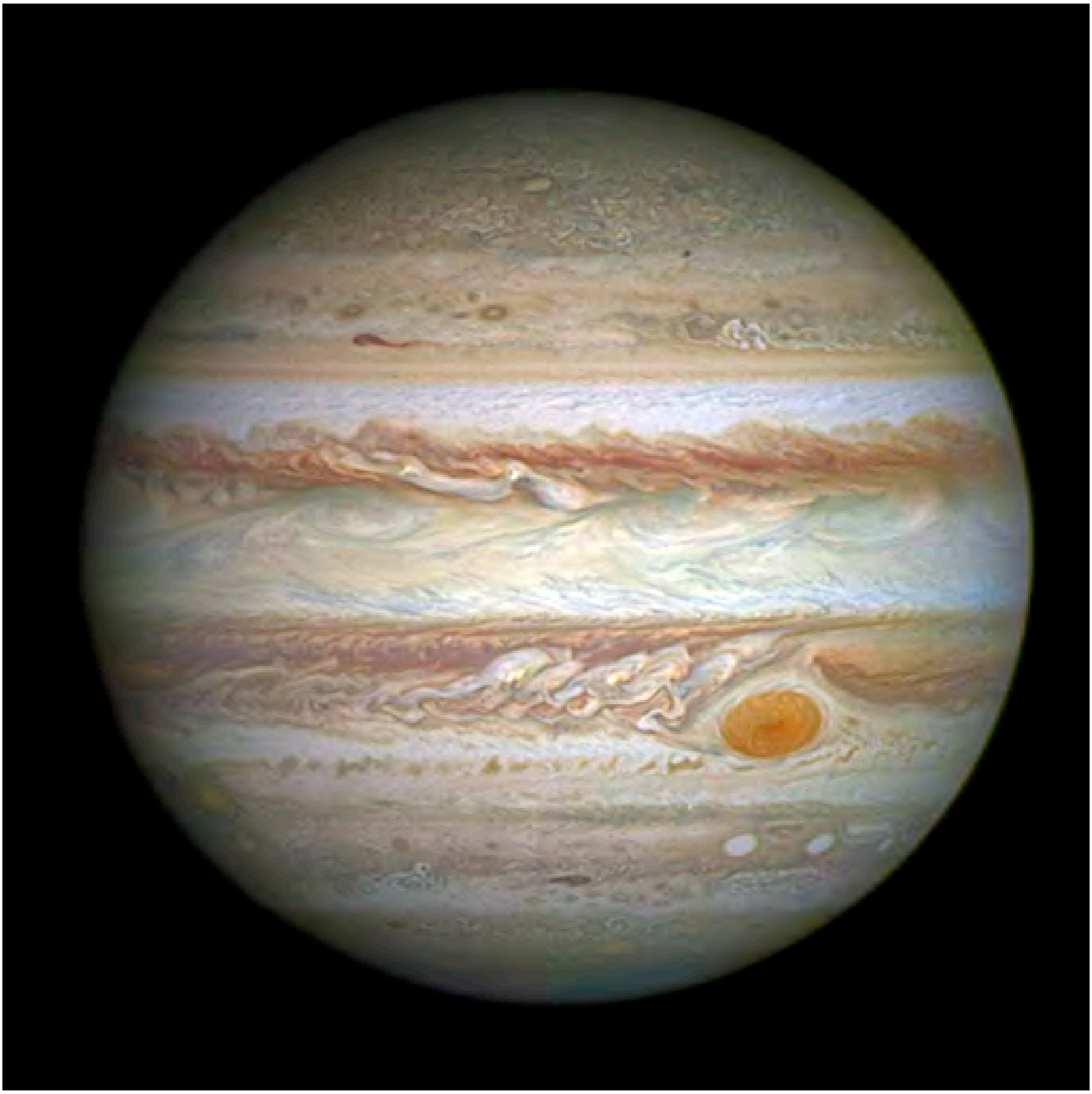


Figure 19 Image of Jupiter taken by the Hubble Space Telescope showing the motion of its bands of clouds around the Great Red Spot

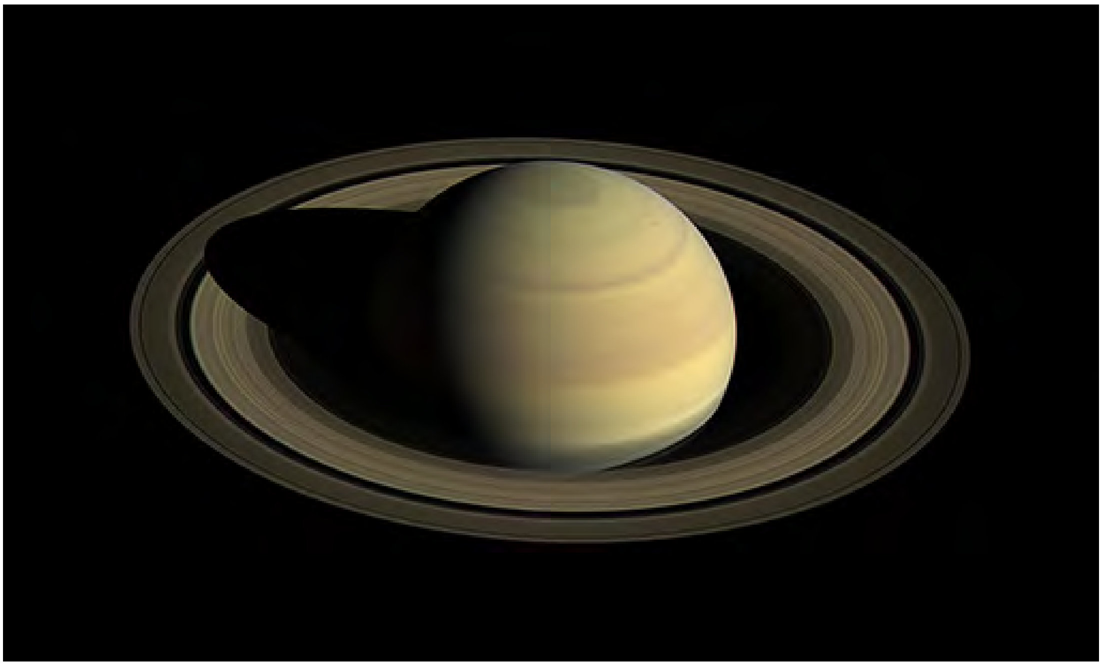


Figure 20 A spectacular image of Saturn and its rings, taken by the Cassini spacecraft in early 2016

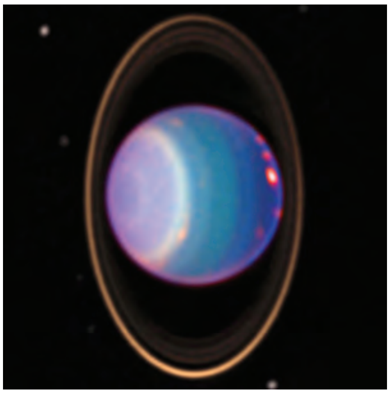


Figure 21 False-colour image of Uranus taken with the Hubble Space Telescope

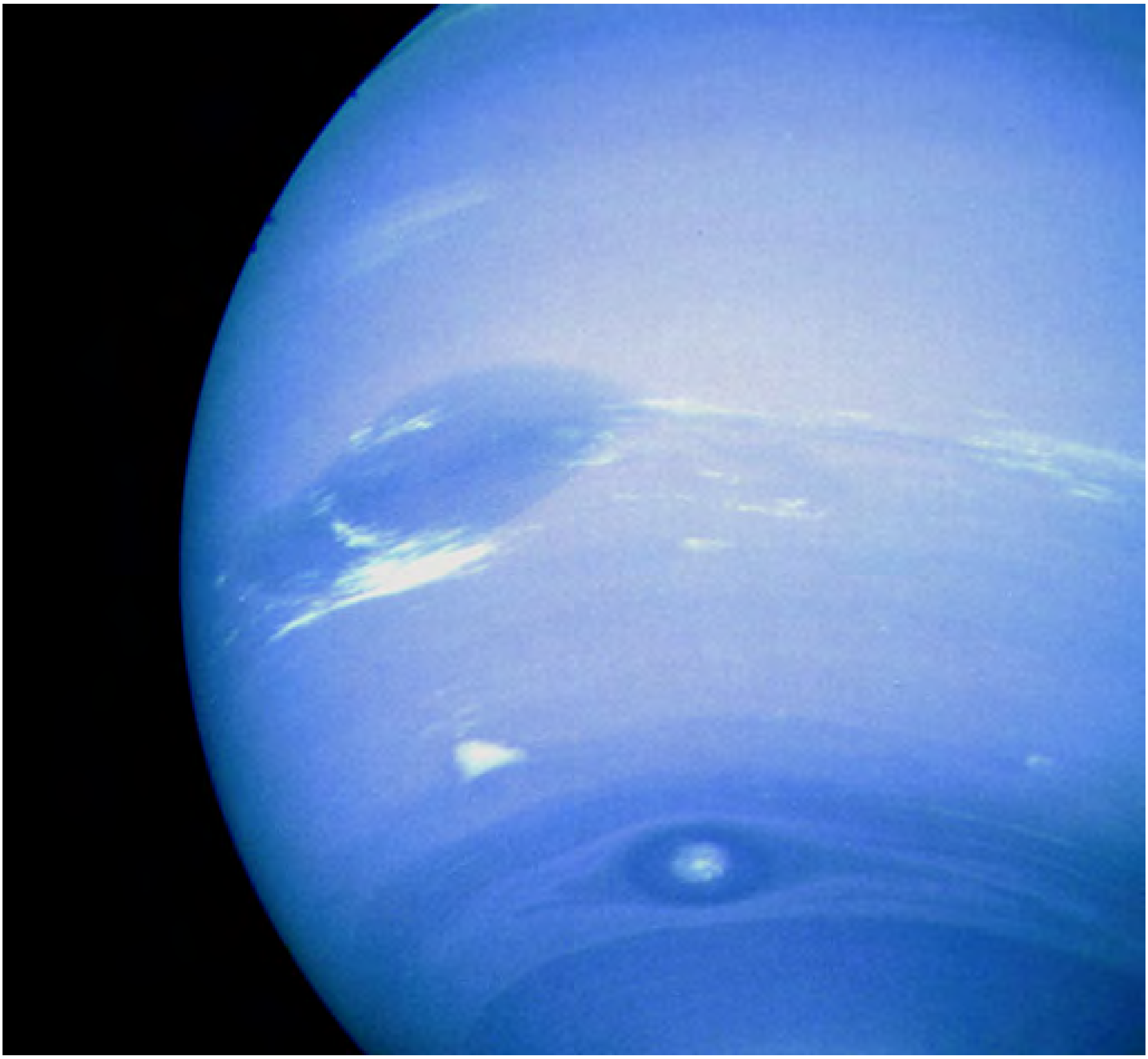


Figure 22 Neptune, snapped by Voyager 2 in 1989. The (enhanced) beautiful blue colour is due to the presence of methane in outer regions of the planet.

Here is a wonderful video of Jupiter in which images taken by amateur astronomers have been animated.

7 This week's quiz

Well done – you have reached the end of Week 2 and can now take the weekly quiz to test your understanding.

Week 2 practice quiz

Open the quiz in a new tab or window (by holding down Ctrl [or Cmd on a Mac] when you click the link).

8 Summary of Week 2

This week you have learned about the terrestrial planets Mercury, Venus, Earth and Mars, the gas giant planets Jupiter and Saturn, and the ice giants Uranus and Neptune. You've gained an appreciation for how vast everything is within the Solar System, and discovered ways of simplifying things by expressing mass and radius in terms of the sizes of Earth and Jupiter. You've also learned about the concepts of mass, volume and density, and how to calculate values of these using appropriate units.

You should now be able to:

- describe what is meant by a terrestrial planet and a giant planet, and the differences between these two planet types
- understand the scale of the Solar System and use the astronomical unit to measure it
- classify the planets Jupiter, Saturn, Uranus and Neptune as gas giants or ice giants
- describe what is meant by mass, radius, volume and density, and how these terms are used within astronomy
- understand the meaning of the symbols AU, M_J, R_J, M_E, R_E, $M_{\oplus,}$ $R_{\oplus}$,, $M_{Sun,}$, $R_{Sun,}$ $M_{\odot}$, $R_{\odot}$.

Next week you will start looking at planets outside the Solar System.

You can now go to Week 3.

Week 3: Dawn of the exoplanet era

Introduction

This week you are going to look at your first exoplanet – the first planet ever discovered orbiting another star. That planet is called 51 Pegasi b. You will learn about how the planet was discovered by measuring tiny changes in the properties of the light coming from the star 51 Pegasi, and you will also find out what kind of planet it is.

Watch the following video in which Carole Haswell talks about how the exoplanet era came about.

Video content is not available in this format.

By the end of this week, you will be able to:

- interpret the name of an exoplanet
- describe the characteristics of 51 Pegasi b
- explain the radial velocity method for detecting planets using the analogy of a see-saw
- understand that both light and sound are waves
- understand how the Doppler shift affects wave properties
- use the website Exoplanet.eu to find a list of planets discovered by the radial velocity method.

1 Exoplanet names

All planets outside our own Solar System are given a name that tells you which star they belong to. The planet's name is the star's name with a lower-case letter added, so for instance 51 Pegasi b is the first planet found orbiting the star 51 Pegasi. If a second planet is found orbiting this star, it will be called 51 Pegasi c.

In some systems several planets are known; for example, Kepler-444 b, Kepler-444 c, Kepler-444 d, Kepler-444 e, and Kepler-444 f are the five planets orbiting the star Kepler-444. Astronomers use only lower-case letters to designate planets.

Activity 1 What's in a name?

Allow about 5 minutes

What can you say immediately about these planets?

1. Aldebaran b

Answer

Aldebaran b is the first planet discovered orbiting the star called Aldebaran.

---

2. HD 96700 c

Answer

HD 96700 c is the second planet discovered orbiting the star called HD 96700. This name is just a catalogue number.

---

3. K2-19 d

Answer

K2-19 d is the third planet discovered orbiting the star called K2-19.

---

2 The first exoplanet: 51 Pegasi b

51 Pegasi b (or 51 Peg b for short) was first discovered in 1995 by astronomers from the Geneva Observatory. For a long time astronomers had expected there to be planets in orbit around other stars, but it was difficult to detect them because planets are very small and faint compared with the stars they orbit around. In our Solar System you can see the planets easily only at night when the Sun is out of sight. The same problem occurs when trying to spot planets around other stars. Separating out the tiny amount of light reflected by the planet is very difficult indeed.

The astronomers at Geneva designed an instrument capable of detecting planets without actually being able to see them at all. By the end of this week you will know exactly how they did that.

It was immediately very clear that 51 Peg b was not going to be like any planet in our own Solar System. 51 Peg b is roughly Jupiter-sized but is *much* closer to its star than even Mercury is to the Sun, which was completely unexpected. This was the first clue that planetary systems around other stars might be very different from our own.

Because of its size, it is expected that 51 Peg b is a gas giant but, because it is so close to a star, 51 Peg b must be very different from Jupiter. Estimated temperatures for 51 Peg b are around 1000 °C, which is *very hot indeed*! 51 Peg b was the first example of a new type of planet, named 'hot Jupiters'. Hot Jupiters are gas giant planets found in orbits very close to their host star. You will learn more about hot Jupiters over the next few weeks.

Figure 1 is an artist's impression of what 51 Pegasi b might look like. It's worth noting that really the only thing we can be sure of about this planet is its minimum mass and orbital properties. There is often a lot of artistic imagination in images like these!

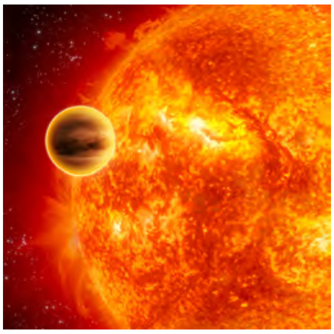


Figure 1 Artist's impression of 51 Pegasi b, which has a similar mass to Jupiter, so is likely to be a gas giant. It is much hotter than any planet in our Solar System.

3 Wobbling stars

Because stars are so much bigger and brighter than planets, they are much easier to study. Astronomers work with light, and the most successful methods used to find planets rely on astronomers doing clever analysis of starlight. 51 Peg b was found by clues in the light astronomers collected from its host star, 51 Peg. The light revealed that the star 'wobbles' because it has a planet orbiting around it. The wobbles are far too small to see directly but they can be inferred. Let's see how this works.

3.1 Gravity, orbits and see-saws

The clever technique used to find 51 Peg b relies on gravity. Gravity is the attraction of anything that has mass to everything else that has mass. For objects in everyday life this effect is too small to be noticeable. For objects as big as planets and stars, however, gravity makes a big difference.

Gravity holds us to the surface of the Earth, and gravity keeps the Earth in orbit around the Sun. In the same way, gravity keeps 51 Peg b in orbit around 51 Peg. But the important thing about gravity is that the force between any two objects is equal and opposite.

That means that 51 Peg b is pulling its star towards it with exactly the same force as the star is pulling on 51 Peg b. So why does 51 Peg b orbit the star, and not the other way around?

Actually, 51 Peg b doesn't orbit the star. The star and its planet are *both* in orbit. They both orbit a point in space called the common centre of mass. The word 'common' indicates that it is shared, in common, between the star and the planet. This is true for our own Solar System too, where there is more than one planet to consider: all of the masses in the Solar System, including the Sun, orbit their mutual centre of mass. Because the Sun has most of the mass in the Solar System, people often say that everything else in the Solar System orbits the Sun. This is almost, but not exactly, correct.

Scientists can work out the exact position of each large mass in the Solar System, as was demonstrated by the thrilling landing of the Rosetta space probe's Philae lander on the surface of a comet. To do this requires more calculations than you have time for in this course, but you will cover the underlying principles. For the purposes of this course you might be relieved to know that you will stick to the simpler case of a single planet and its star in orbit.

Figure 2 shows how a planet and star orbit their common centre of mass. As you'd expect, the common centre of mass is always closer to the more massive object, the star. In fact, there is a more mathematical relationship between the masses of the orbiting bodies and their distance to the centre of mass. Dividing the mass of the star by the mass of the planet gives the same answer as dividing the distance of the planet from the common centre of mass by the distance of the star from the common centre of mass. This fact is shown in the diagram: the ratio of the masses ($M_{\text{star}} / M_{\text{planet}}$) is equal to the ratio of the distances from the common centre of mass ($a_{\text{planet}} / a_{\text{star}}$). So, the larger M_{star} is, the smaller a_{star} is, as expected.

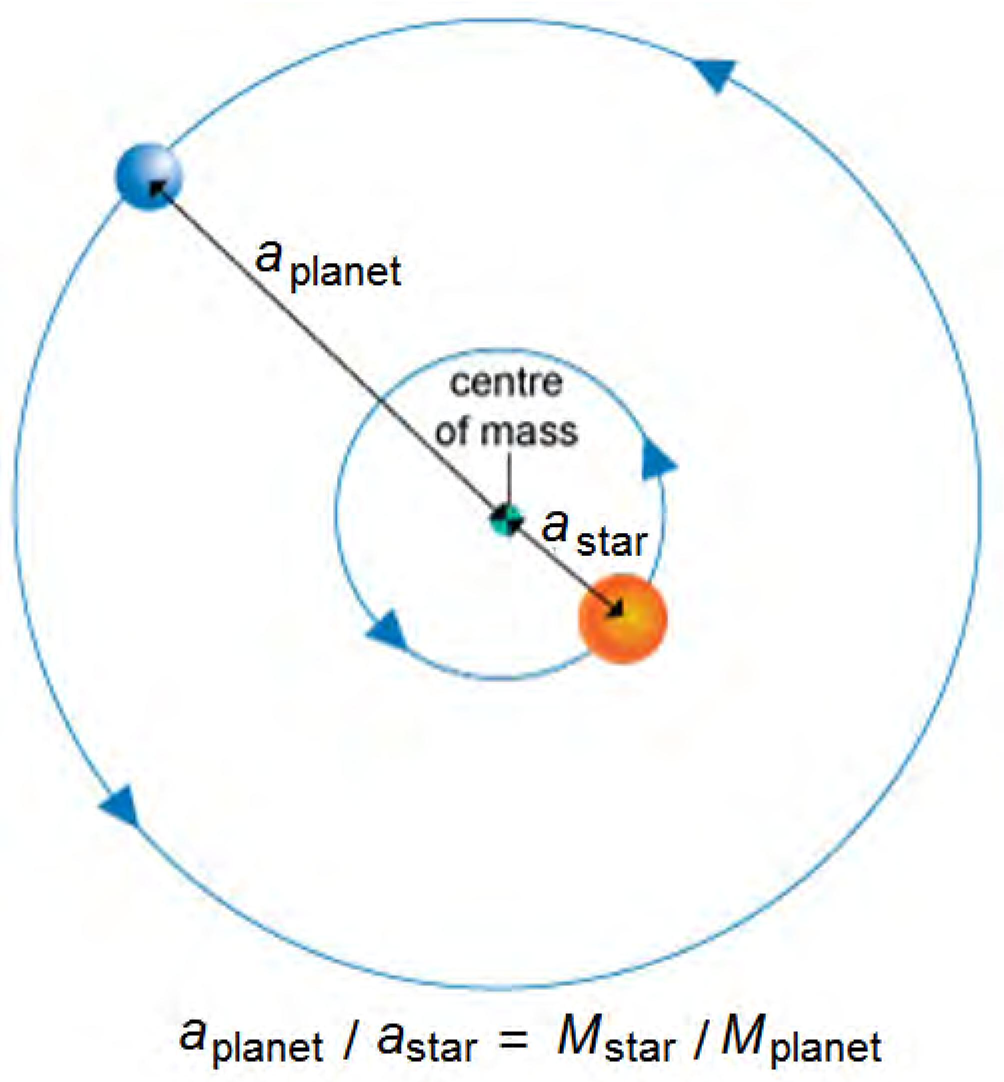


Figure 2 Orbit of a star and planet around their common centre of mass. *M* represents the mass and *a* represents the distance from the centre of mass (the symbol *a* is conventionally used by astronomers rather than the *d* that you might expect).

Because the mass of the star, M_{star}, is so much larger than the mass of the planet, M_{planet}, the common centre of mass is often inside the star (Figure 3). But, crucially, the common centre of mass is not at the *centre* of the star. This means that the star wobbles a bit as the planet goes around it.

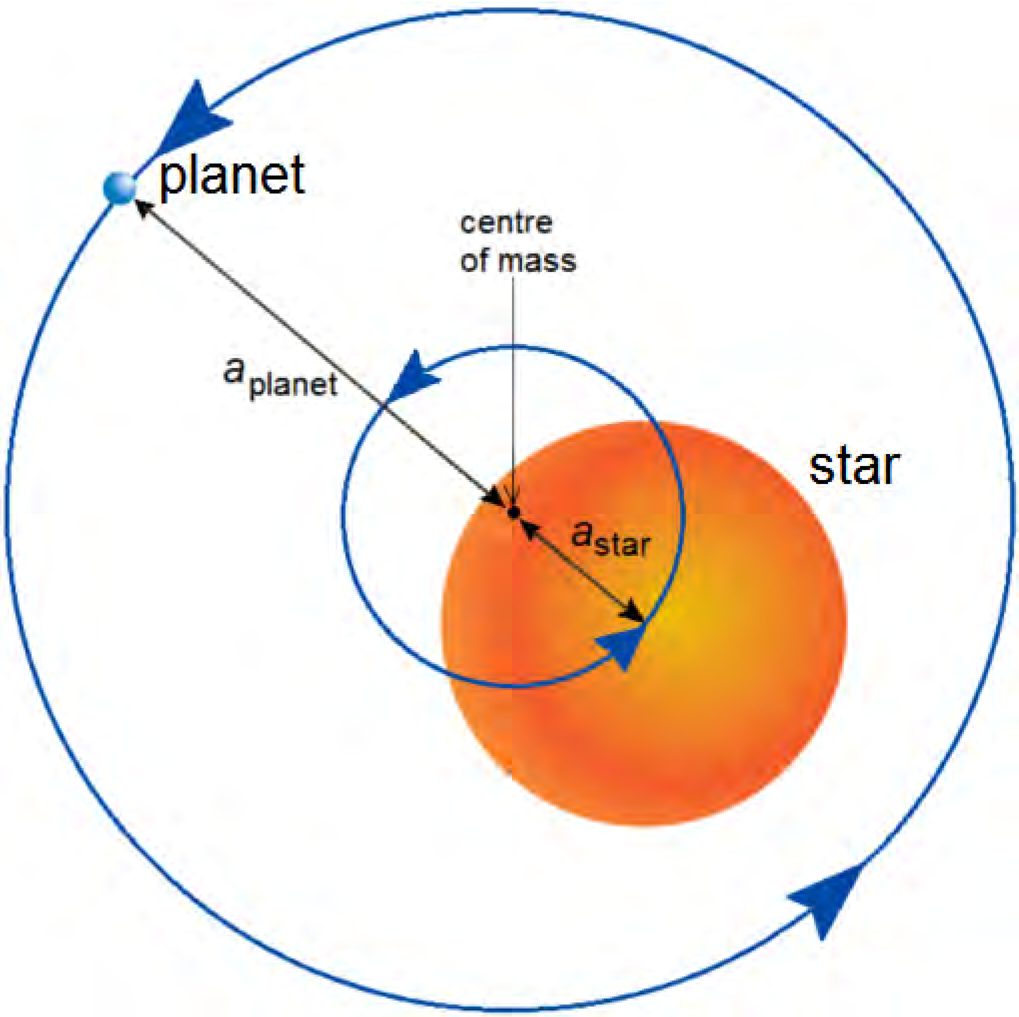


Figure 3 Orbit of a star and planet around their common centre of mass where the mass of the star is much greater than the mass of the planet

This video animates the orbits of a star and planet where the common centre of mass lies inside the star (marked with a small cross) similar to the situation illustrated in Figure 3.

You can think of this like two people on a see-saw – say a small child and her father. To make sure that the see-saw is perfectly balanced, the heavier father will have to sit close to the pivot, while the little girl sits right at the end of the seat. As the see-saw bounces, the father barely moves at all but the little girl moves a lot.

This same thing happens with the planet and its star. The planet moves in a wide circle around the common centre of mass, while the star moves in a much tighter one. Because stars are so much bigger than planets, the situation in fact resembles a sumo wrestler and a hamster on a see-saw! Sumo wrestlers are about 3000 times the mass of a dwarf hamster, just as the Sun is about 3000 times the mass of Saturn. If you can imagine this, the sumo wrestler would have to literally sit *on top of* the see-saw's pivot. In a similar way, the common centre of mass is *inside* the star.

3.2 Getting a feel for the common centre of mass

You can get a feel for the centre of mass idea on a see-saw, though please don't experiment with hamsters! In the next two sections, you will use an interactive application to get a sense of the maths involved.

Centre of mass interactive activity part 1

This interactive application lets you see how the position of the centre of mass depends on the masses of the star and planet. Using the sliders, you can set the value of the mass of a star and the mass of its planet. You can adjust the mass of the star between 0.02 solar masses and 5 solar masses (0.02 M_{Sun} and 5 M_{Sun}). In reality, 'stars' which are less massive than about 0.08 solar masses aren't stars at all but are cooler objects called 'brown dwarfs'. Independently, you can adjust the mass of the planet between 0.05 Jupiter masses and 13 Jupiter masses (0.05 M_J and 13 M_J).

Click on the [ ] button if you would like to work with the application in a separate page. This gives the option of zooming in and out using the + and – buttons below the application screen.

Interactive content is not available in this format.

Play with the common centre of mass application and watch how the centre of mass responds to your choice of mass values. For very fine adjustments, you can use the arrow keys on your keyboard rather than your mouse.

As you alter the mass values, the application will respond by showing the calculated position of the centre of mass (labelled CoM). The 'mass ratio', that is, the mass of the star divided by the mass of the planet, is always shown in numbers. This mass ratio is simply:

1. You will get a different (and incorrect) number for the mass ratio if you simply divide the two numbers given on the sliders.

- Question: Why is this?
- The mass of the star and the mass of the planet on the sliders are expressed in different units, M_{Sun} and M_J, respectively. To work out the mass ratio you need to take this into account, for example by converting both into kg.

2. Set the value of the star's mass to 0.14 M_{Sun} and the value of the planet's mass to 13 M_J.

- Question: What is the value of the star–planet mass ratio for these choices?
- 11.3

3. Using a ruler, measure the onscreen distance of the centre of mass (labelled CoM) from both the centre of the star and the centre of the planet. Write down the values you measure (remember to include units). Divide the distance you measured from the planet to the centre of mass by the distance you measured from the star to the centre of mass.

- Question: What value did you get?
- You should have a value that is somewhere between 11 and 11.5. If you had been able to measure very precisely, you would have got 11.3, but it is difficult to measure distances on a screen this precisely.

- Question: Referring back to Figure 2, comment on the result you get for the distance ratio.
- The mass ratio (M_{star}/M_{planet}) is the same as the ratio of the planet and star distances from the common centre of mass (a_{planet}/a_{star}). The results from the interactive application agree with this.

4. Set the values of the star's mass and the planet's mass to those appropriate for the Sun and Jupiter.

- Question: What value do you get for the mass ratio?
- By setting the masses to 1 solar mass and 1 Jupiter mass, respectively, you should get a mass ratio of 1.05 x 10^3, which is 1050 written in scientific notation.

- Question: Where does the centre of mass appear to be?
- It appears to be at the centre of the star. The size of the star and the planet are drawn at a much larger scale relative to the distance between them. The mass ratio is so big that it is impossible to visually perceive the small distance between the centre of the star and the centre of mass, unless you zoom in a great deal.

5. In reality, the distance of Jupiter is about 8×10^{11} m from the centre of mass.

- Using the mass ratio you found above, calculate the distance of the Sun from the centre of mass.
- About 8×10^8 m.

  You know that:

  $$a_{planet} / a_{star} = 1050$$

  so

  $$a_{star} = a_{planet} / 1050$$
  $$a_{star} = 8 \times 10^{11} \text{ m} / 1050$$
  $$a_{star} = 8 \times 10^8 \text{ m}.$$

  Note: if you did this with a calculator it probably told you the answer is 7.619 047… × 10^8 m. Because you started with 'about 8 × 10^{11} m' it makes sense to give your answer to 'about' a number, i.e. with only one digit multiplied by the appropriate number of zeros. Because 7.6 is closer to 8 than it is to 7, the best answer to give in this case is 8 × 10^8 m.

6. Using the internet, look up the radius of the Sun, giving your answer to a precision of just a single digit. If necessary, convert it into metres.

- Question: What value did you get?
- About 7×10^8 m.

  The value that comes up on Google is 695 508 km.

  1 km = 10^3 m

  So the radius of the Sun is:

  $R_{Sun} = 6.95508 \times 10^5 \times 10^3$ m $= 6.95508 \times 10^8$ m

  Or, using only one digit, about 7×10^8 m

- Question: Is the centre of mass of the Sun and Jupiter inside or outside the Sun itself?
- Just outside. The distance of the centre of the Sun from the centre of mass is 8×10^8 m while the radius of the Sun is slightly smaller at about 7×10^8 m. This means that the Sun orbits a point just outside its surface in response to Jupiter's gravitational pull.

Maths help

?

The following OpenLearn resources may help with the maths in this section. Open the link in a new tab or window by holding down Ctrl (or Cmd on a Mac) when you click on the link. Remember to return here when you have finished.

- multiplying powers (Section 2.3)

Centre of mass interactive activity part 2

In this slightly modified interactive application, the arithmetic is spelled out for you for any available combination of mass choices. The laws of physics mean that the centre of mass is always positioned so the value of two ratios, the ratio of the masses and the ratio of the distances from the centre of mass, multiplied together is exactly 1. This comes from the fact that was illustrated in Figure 2. (The figure 1047 that appears in the calculation is the mass ratio of the Sun and Jupiter, M_{Sun}/M_J. This is a slightly more accurate figure than 1050 that was displayed on screen in the previous part.)

Interactive content is not available in this format.

Play with choices of masses, and watch how the position of the centre of mass and the values of the ratios change. One of the most beautiful mysteries of the Universe is the fact that it can be described by mathematics that can be written down and understood.

3.3 The common centre of mass of our Solar System

Recall that all the objects in the Solar System orbit their mutual centre of mass, and this includes the Sun. The Sun's orbital motion is shown in the following video, which was generated by computer calculation using freely available software. Because the Sun responds to the gravitational pull of all the other masses in the Solar System, its motion is not a simple circular orbit. Jupiter accounts for most of the Solar System mass aside from the Sun though, so the largest effect on the Sun's movement is caused by Jupiter. If alien astronomers were watching the Sun, they would see it wobble once every 12 years in response to Jupiter's orbit.

The Sun's motion around the Solar System Barycenter The viewpoint in the video is different from Section 3.1 – it's looking from the side rather than down on the orbits. The Sun's orbital 'dance' is clearer if you speed up the application by dragging the scrollbar along.

3.4 Down to Earth: a practical exploration of planet and star orbits

In the following activity you will explore the implications of the centre of mass in a tactile way.

Activity 2 Orbits

Allow about 20 minutes

You will need a short garden cane, a piece of string, a tennis ball and a ping pong ball. (Note that the balls will not be usable again afterwards.)

Stick one end of the garden cane into the centre of the tennis ball and the other end into the centre of the ping pong ball. You might need to start things off with some scissors. If you are going to use scissors, do so with care!

Secure with sticky tape if needed.

Attach the string to the cane with a loop so it can move freely up and down the cane. Slide the string until you find the point along the cane where it is balanced, then attach it to the cane with tape.

You don't quite have a star and planet here because the sizes and masses of the balls are more similar than those of most stars and planets, but what you do have is an example of how a binary star system might work. Binary stars are two stars orbiting around each other, following exactly the same principles as a star and planet system.

Hold the string, use a hook or tie it to a washing line to suspend the balanced stick. Push the tennis ball so that it moves in a circle, twisting and untwisting the string. Notice how much further the ping pong ball moves compared to the tennis ball.

3.5 Interactive orbits

We couldn't explore the way star and planet orbits work with our tactile example in the previous activity because the planet's orbit is so much bigger than the star's. But using interactive applications we can do this. Generally, mathematical treatments like that underlying the interactive application allow us to understand and predict the behaviour of things which are too big, too small, too hot, too dense or too complex to allow us to build physical models. The ball and stick model is a physical model, while the interactive application is a mathematical model, built with the equations which describe the motions of masses. Mathematical models are so useful and powerful that generally when scientists use the word model, they mean a mathematical model.

This interactive application lets you see the motion of a star and planet around a centre of mass. As before, you can set the value of the mass of a star and the mass of its planet. The orbital paths of the star and planet are indicated by black circles. This application has two additional sliders, the first of which allows you to choose the distance of the planet from the centre of mass.

Interactive content is not available in this format.

Play with the top three sliders for the masses and distance of the planet from the centre of mass and watch how the orbital paths respond. As before, you can also use the arrow keys on the keyboard to amend the values. You may need to click anywhere on the application screen to ensure that it calculates and displays the correct orbits for your choice of values. Again you can work with the application in a separate page by clicking on the [ ] button. You may need to adjust the magnification in your browser to view the full application panel.

Set the mass of the star to 0.3 M_{Sun}, the mass of the planet to about 10 M_J and the distance of the planet from the centre of mass to about 4.5 AU.

1. Take the fourth slider, which controls simulated time, to the value 0, and then move it slowly to the value 1. Watch the planet.

- Question: Describe the motion of the planet.
- The planet starts off at the right-hand side of the application, at 3 o'clock and moves anticlockwise all the way around the circle representing its orbital path, returning to 3 o'clock when t = 1.

- Time on the slider is given in units of the orbital period. Based on what you observe when you vary the time from 0 to 1, explain what is meant by the orbital period.
- The orbital period is the time taken for the planet to complete one loop around its orbit. The orbital period is the same as the planet's year. So, the Earth takes one Earth year to complete its orbit. Astronomers talk about the orbital period of the planet, rather than the planet's year because there is a danger of becoming confused between the planet's year and our own Earth year.

2. Take the fourth slider back to the value 0, and then move it slowly to the value 1 again. Watch the star this time.

- Question: Describe the motion of the star.
- The star starts off at the left hand side of its small orbit near the centre of the application, at 9 o'clock, and moves anticlockwise all the way around the small circle, returning to 9 o'clock when t = 1. Because the orbit is so small, the star's motion looks like a small circular wobble.

3. Move the fourth slider slowly from 0 to 1 again. Watch the relative positions of the planet and the star. You may find it helpful to adjust the zoom using the + and − buttons.

- Question: Describe the how the positions of the planet and the star change relative to each other and the centre of mass.
- The star and the planet are always on exactly opposite sides of the centre of mass. You could always connect the centre of the star and the centre of the planet with a straight line that would pass exactly through the centre of mass. The orbital periods of the planet and the star about the centre of mass are exactly the same.

4 Measuring the movement of stars

Stars that wobble, such as the Sun in the video in Section 3.3, are revealing that they have another mass in orbit with them. In some cases, the other mass in the orbit is a second star, in which case the light from two stars may be visible. If a star has a small wobble and there is no light from a second star, then there is an invisible planet in orbit with the star. Therefore, it is possible to discover a planet belonging to the star even if there is no light at all from the planet itself.

Unfortunately, it's not as simple as watching stars to see if they move. The motion of the stars is so tiny that you generally can't actually see any movement from them. So, you have a moving star that you can't see moving, and a planet that you can't see at all!

Fortunately, there are two facts that you can use to design a way of inferring that a star is wobbling. The first is a fact about light, and the second is a fact about stars. You will look at what those are in a minute, but first you need to understand what velocity means.

4.1 Velocity and speed

Speed is a measure of how fast something is moving. Velocity is also a measure of how fast something is moving, but when talking about velocity the direction is important as well.

Imagine standing in the middle of a bridge above a UK motorway watching the cars. Assume everyone is obeying the speed limit and driving at exactly 70 miles per hour. Everyone is therefore travelling at the same speed, but the cars on opposite sides of the road are travelling in opposite directions. Everyone on the left, travelling away from you, has a velocity of 70 mph, but everyone on the right and travelling towards you has a velocity of *minus* 70 mph, so they are travelling at the same speed as the drivers going away from you, but in the opposite (negative) direction (Figure 4).

Figure 4 Motorway velocity diagram. Velocity includes information about direction of motion as well as speed, so the cars on the left have a velocity of 70 mph but the cars on the right have a velocity of −70 mph

Direction of motion is very important when measuring wobbling stars, as you will see in the next section.

4.2 Light as a wave and the Doppler effect

You can measure a star's wobble by looking at the light from the star. Light and sound are both waves, and have some things in common with the waves you can see on lakes and oceans. You can't directly see the crests and troughs of the waves of light and sound, but your eyes and ears are sensitive to them. The properties of light waves and sound waves are rendered into the colour of light and the pitch of sound by your eyes and ears.

The colour of light is determined by its wavelength, which is the distance between the crests of the waves. In the same way, the pitch of a sound is also determined by its wavelength. Longer wavelengths of light and sound correspond to redder colours and lower pitches, and shorter wavelengths to bluer colours and higher pitches.

Figure 5 shows how wavelength is measured: it is the space between two consecutive peaks or two consecutive troughs in a wave. For this wave, the wavelength is 10 metres.

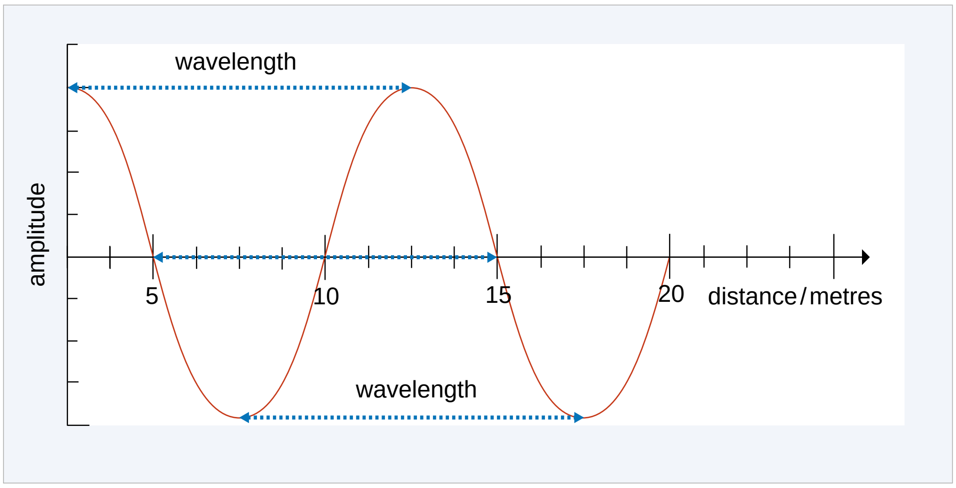


Figure 5 Measuring wavelength

If the object emitting light or sound is moving relative to the person seeing the light or hearing the sound, then the light or sound waves can seem to be stretched or compressed.

This is why the pitch of a police car siren sounds higher when the police car is coming towards you, and then drops when the police car goes past and moves away from you (Figure 6). This stretching and compression of waves emitted by a moving object is called the Doppler effect.

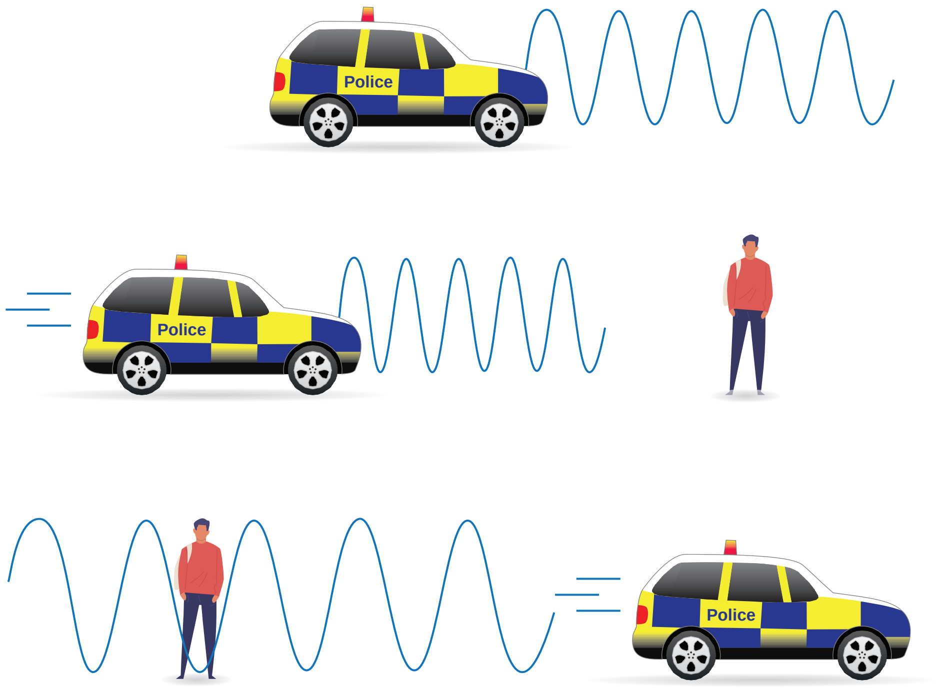


Figure 6 Police car siren pitch

As the police car travels towards the listener the sound waves are compressed, the wavelength shortens, and the pitch sounds higher (the second picture in Figure 6). Once the car has passed and begins to travel away, the sound waves are stretched out, the wavelength lengthens and the pitch becomes lower (the third picture in Figure 6).

The effect is more extreme the faster the car is moving: the sound waves become even more compressed or stretched out. This means that a faster car will have a siren sounding even higher or lower pitched.

So, the speed at which the police car is moving changes how marked the effect is, while the direction in which the police car is moving determines whether you hear a higher or lower pitch. To understand what has happened to the sound from the siren, you need to know the velocity of the car, not just the speed.

Something very similar happens when stars wobble, but rather than hearing the effect in sound waves you can see it in light waves. As a star moves around the centre of mass of the star–planet system, its light is repeatedly stretched and compressed. A stretch as the star moves away makes the wavelength slightly longer, and compression as the star comes towards you makes the wavelength slightly shorter. Of course, planets take longer to complete an orbit than the time a police car would take to pass you in the street. This means that some patience is required to measure the wavelength changes: it can take days, months, years or even decades, depending on the time taken for a planet to complete an orbit.

If you can detect the tiny wavelength changes caused by this stretching and compression, then you know the star is moving. If you see the movement repeat itself, you can work out that the star is in an orbit. For this to happen, the star must have a companion star or planet with which it is in orbit.

Even more remarkably we can work out the mass of the star's companion. The motion of a star is caused by the gravity of a moving companion that pulls on the star. How much a star moves depends on how strong the gravity of its companion is. The strength of the gravitational pull depends on the mass of the companion. This means that, by measuring the wavelength changes caused by the Doppler effect, you can work out the companion's mass. More massive companions will make a star move faster, and therefore make the wavelength of the light change more.

4.3 Chemical fingerprints in starlight

You have learned that wavelength determines the colour of light. You have also learned that light from a moving object has its wavelength stretched or compressed by the Doppler effect. So, you might think you could know that a star is moving because its colour changes. In fact, it isn't quite so easy. The changes in the colour of the starlight, caused by the star's wobble, are extremely slight and they are not something that your eyes would be able to detect. Detection requires the use of a technique called spectroscopy, which spreads the light out into a stretched-out rainbow of very gradually changing colours called a spectrum. Using this technique, a specific property of starlight can be used to enable the measurement of the tiny colour changes.

In Week 1, you learned that stars are big balls of hydrogen and helium gas. But stars also contain very small amounts of other chemicals in gaseous form. These include other gases such as oxygen, as well as substances that you are used to seeing as solids on Earth – for example metals such as iron and calcium. All of these other gases are present throughout the star, including in its outer layers. The outer layers of a star are where the starlight you see originates – the gases here leave their signatures in the starlight. This is extremely useful to astronomers, who can gather lots of information from it.

What are these signatures? Every chemical has a special fingerprint of its own that is visible when light shines through it. Each chemical absorbs very specific colours of light. Their signatures are all different, which is something you will learn more about in later weeks of this course. For now, it's enough to know that astronomers have very precise knowledge of the colours or wavelengths of light that each gas absorbs.

Astronomers spread out the light they collect into its different wavelengths, and measure exactly how much light a particular star emits at each precise wavelength. A graph showing the amount of light at each wavelength is also called a spectrum (plural: spectra). If a particular gas is present in the outer layers of the star, it will produce a distinctive pattern in the spectrum. The pattern is the same whether the gas is in a laboratory on Earth, in the outer layers of the Sun, or in a distant galaxy. This simple and beautiful fact is the foundation of most of what we know about the Universe.

Figure 7a shows some of the precise wavelengths or colours of light absorbed by different gases in the Sun's outer layers. For example, the dark line in the red part of the spectrum is there because hydrogen gas absorbs that colour of light. The yellowy-orange that is absorbed by sodium is the same colour you see in sodium street lights. We call these dark lines in the spectrum absorption lines. Figure 7b shows how incredibly detailed the real spectrum of the Sun is.

Figure 7a Simplified solar spectrum showing prominent absorption lines

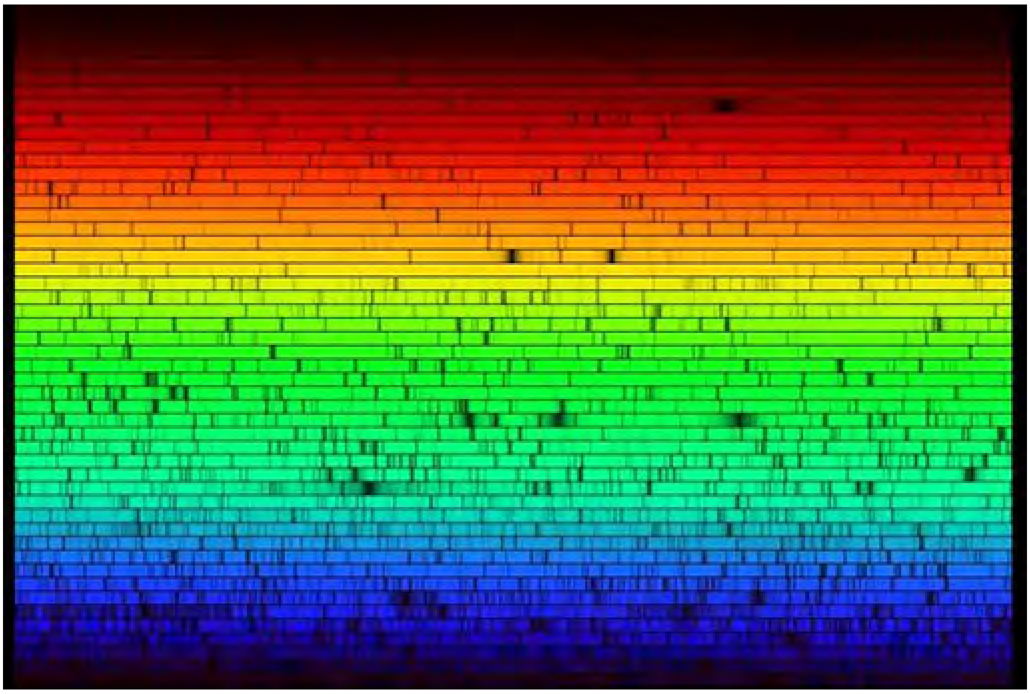


Figure 7b The solar spectrum

Helium is named after the Sun ('Helios' is Greek for 'Sun'). The reason for this is that helium was detected by astronomers using the spectrum of the Sun before anyone had discovered it on Earth. The chemical fingerprints in starlight can be extremely informative.

4.4 Spectra, the Doppler effect and radial velocities

When stars wobble and their light is Doppler stretched or compressed, the colour and therefore the wavelength of the light you see changes slightly. This means that the wavelengths of those tell-tale fingerprints – the absorption lines – in the star's spectrum will also vary. Because you know precisely which wavelengths those fingerprints should occur at, you can measure how much they have changed to work out how fast, and in what direction, the star is moving.

Video 1 shows how a star wobbles as a planet orbits it, and how absorption lines in the star's spectrum shift with the tiny wavelength changes. This method of detecting exoplanets is called the 'radial velocity' method – you'll learn why we use this term in a moment.

View at: youtube:B-oZYm3L1JE

Video 1 Radial velocity method and spectral shift (please note this video has no audio)

Activity 3 How is the star moving?

Allow about 10 minutes

You will be shown four spectra of a star taken at different times during a planet's orbit, as well as the unshifted version of the spectrum measured using gases in a laboratory. You need to decide whether the star was moving towards or away from you, and if so, whether it was moving slowly or quickly.

(Hint: check back to 4.2 Light as a wave and the Doppler effect. When wavelengths get smaller, does light get bluer or redder?)

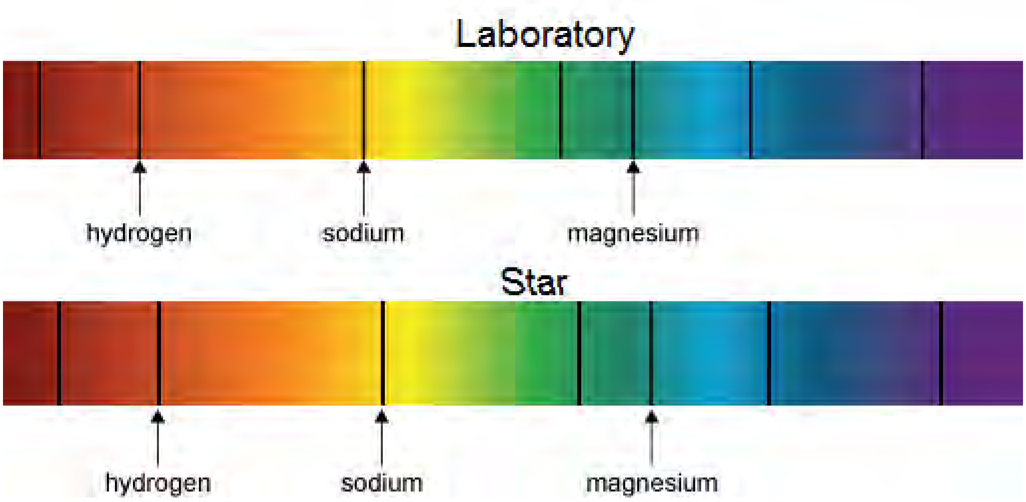


Figure 8

- ○ towards you, slowly
- ○ away from you, fast
- ○ not moving away from you or towards you
- ○ away from you, slowly

Answer

The light from the star has got bluer – we can see this because the absorption lines have shifted towards the blue end of the star spectrum. Blue light has a shorter wavelength so this means that the light waves have been compressed. So, we can tell that the star was moving towards us.

The absorption lines have only shifted by a very small amount so the star must be moving relatively slowly towards us.

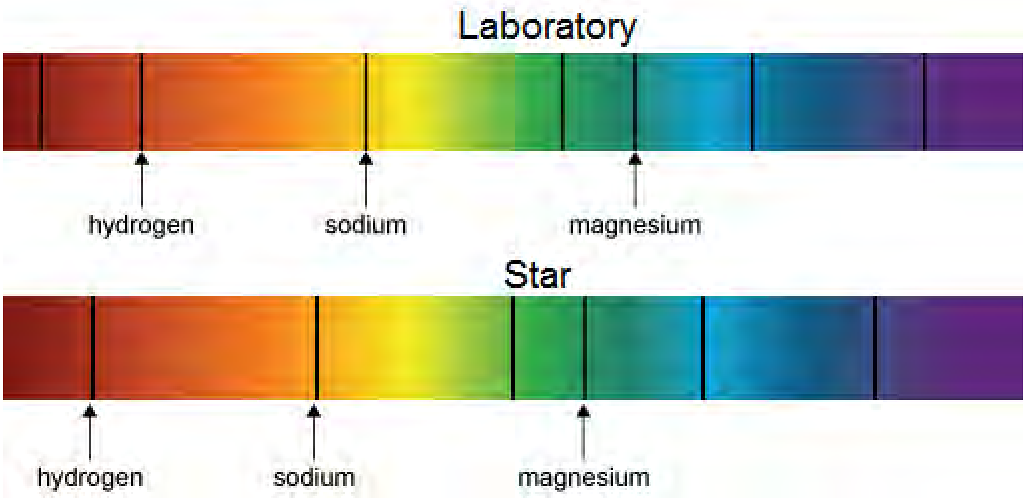


Figure 9

- ○ towards you, slowly
- ○ away from you, fast
- ○ not moving away from you or towards you
- ○ away from you, slowly

Answer

The light from the star has got redder – we can see this because the absorption lines have shifted towards the red end of the star spectrum. Red light has a longer wavelength so this means that the light waves have been stretched out. So, we can tell that the star was moving away from us.

The absorption lines have shifted by a greater amount than in Figure 8 so the star must be moving relatively fast away from us.

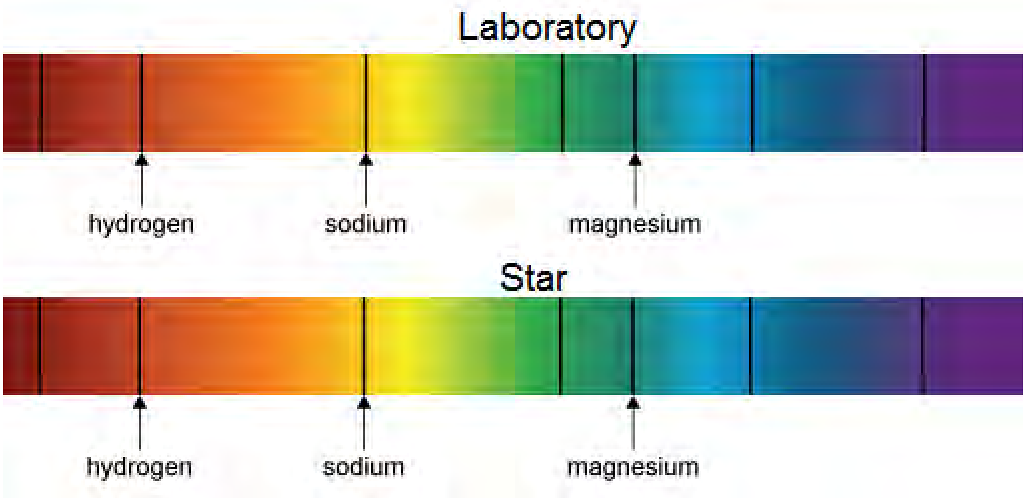


Figure 10

- ○ towards you, slowly
- ○ away from you, fast
- ○ not moving away from you or towards you

○ away from you, slowly

Answer

The light from the star hasn't changed colour – we can see this because the absorption lines are in the same place as the laboratory spectrum. So, we can tell that the star wasn't moving towards or away from us. (It could still be moving across our line of sight however.)

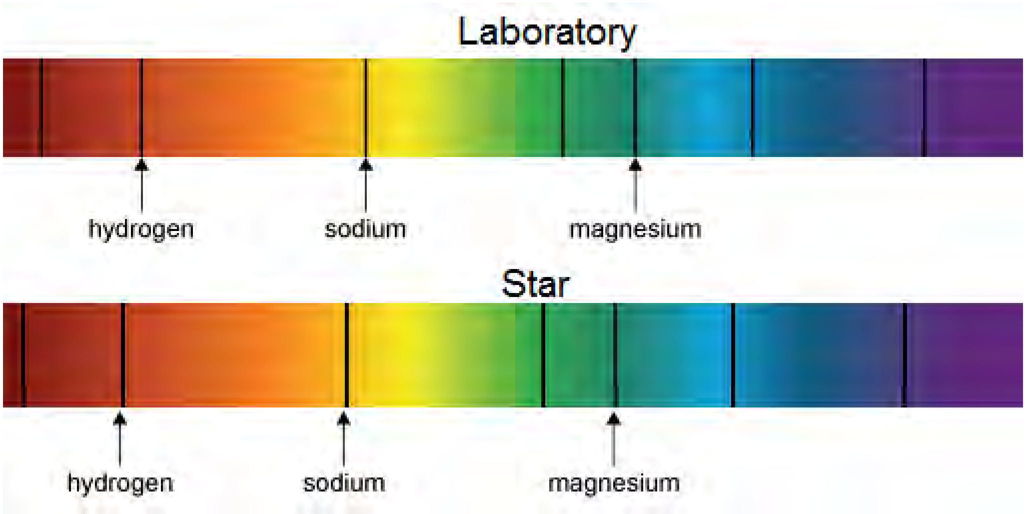


Figure 11

○ towards you, slowly

○ away from you, fast

○ not moving away from you or towards you

○ away from you, slowly

Answer

The light from the star has got redder – we can see this because the absorption lines have shifted towards the red end of the star spectrum. Red light has a longer wavelength so this means that the light waves have been stretched out. So, we can tell that the star was moving away from us.

The absorption lines have only shifted by a very small amount so the star must be moving relatively slowly away from us.

The compression, or stretching, of waves tells you about motion towards or away from you. Imagine yourself at the centre of an enormous sphere. If something moves outwards from you at the centre, in whatever direction, its light will be stretched. If it moves inwards towards you, its light will be compressed. The Doppler shift therefore tells you about motion in a particular direction along the radius of the imaginary sphere. For this reason, the velocity you can work out from the wavelength shift is called the radial velocity.

During a planet's orbit, its star's speed is constant. But, because the direction of the star's motion changes continually, the velocity also changes continually. As the velocity changes, the star's motion towards and away from you also changes. Or in other words the star's radial velocity changes. Sometimes the star is not moving towards or away from you at all, sometimes it is moving towards you, and sometimes it is moving away from you. These changes in radial velocity cause changes in the measured wavelengths of the chemical fingerprints – the patterns of absorption lines. You can translate the wavelength changes into the speed of motion towards or away from you, and these changes can be shown on a graph. This graph is called a radial velocity curve. Here's the curve for the star 51 Pegasi (Figure 12).

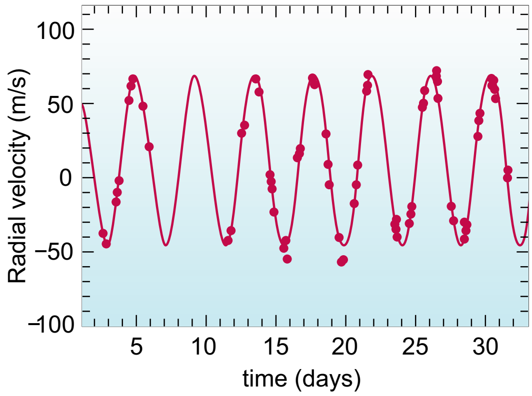


Figure 12 Radial velocity curve for 51 Pegasi

Here you can see the measurements of 51 Pegasi's radial velocity that enabled the planet 51 Pegasi b to be detected. You can see the (horizontal) space between peaks is around four days, which is how long it takes 51 Pegasi b to orbit its star. The star moves relative to us at a maximum speed of about 50 metres per second (m/s).

- Planetary systems can be oriented in any random way relative to our line of sight. In Section 3.5, as shown in Figure 13, your viewpoint on the orbiting star and planet was looking down from above. Describe the radial velocity graph for a planetary system oriented like this.

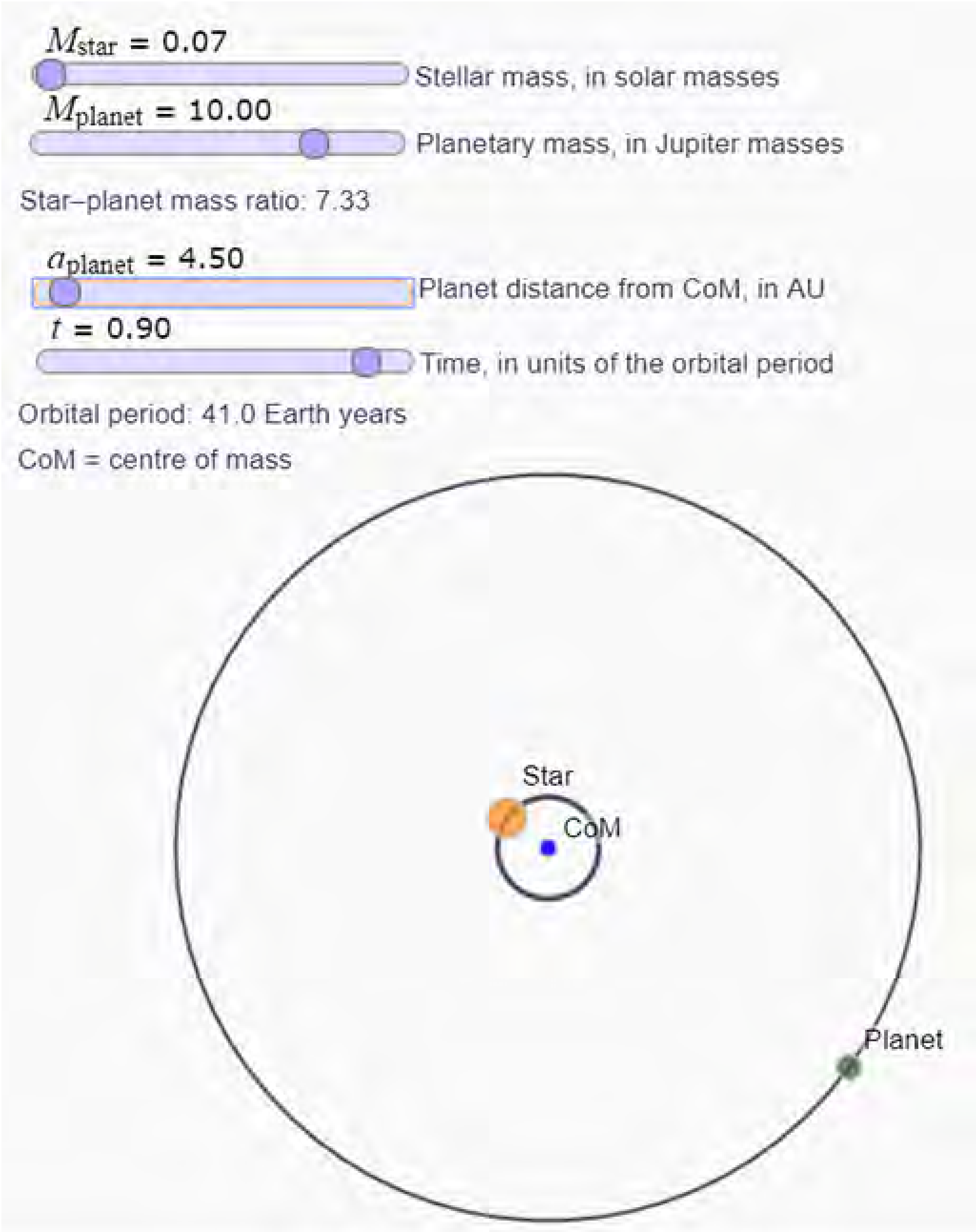


Figure 13 A screenshot from the interactive application you worked with in Section 3.5

- From this viewpoint, neither the star nor the planet move towards or away from you. As radial velocity *is* the motion towards or away from you, it is exactly zero at all points around the orbit. The graph would therefore be a straight line with radial velocity equal to zero throughout the orbit.

4.5 Interpreting the radial velocity curve

From the radial velocity curve you can work out the orbital period of a planet – the time it takes to complete an orbit. As you have already learned, the time taken for the Earth to complete an orbit is one year. The maximum radial velocity tells you how fast a star is moving in its orbit around the centre of mass. You can read that off the radial velocity curve – it's the value at the top of the peak. If you know the mass of the star, combining this with the measured orbital speed allows you to work out the mass of the planet.

Interactive orbits

You are going to return to the interactive application you have already used, which shows the mathematical model of the motion of a star and planet orbiting around their centre of mass. You are now going to look at it from a different perspective.

Activity 4 Interactive orbits

Allow about 15 minutes

Interactive content is not available in this format.

You have already seen a different view of this interactive application. When it appeared in Section 3.5 you saw a two-dimensional (2D) view looking down on the orbits from above. Now you are seeing a three-dimensional (3D) view, as if you were looking down on the orbit from an inclined view. Consequently the orbital path of the planet appears foreshortened, just as any circle does when you view it like this.

You can change your viewpoint of the orbital plane – the pale red grid in which the orbits lie – by clicking anywhere on it, holding down the mouse button and moving your mouse around (by 'clicking and dragging').

Set the mass of the star to 0.3 M_{Sun}, the mass of the planet to about 10 M_J and the distance of the planet from the centre of mass to about 4.5 AU.

1. Take the fourth slider, which controls simulated time, to the value 0, and then move it slowly to the value 1. As before, you can also use the arrow keys on the keyboard to amend the values. Watch the planet.

Describe the motion of the planet.

Answer

The planet starts off on the axis that is initially pointing towards the right-hand side of the application, and moves anticlockwise all the way around the foreshortened circle, returning to its original position on the axis when t = 1.

2. Take the fourth slider back to the value 0, and then move it slowly to the value 1 again. Watch the star this time.

Describe the motion of the star.

Answer

The star starts off slightly to the left of this same axis and moves anticlockwise all the way around the small foreshortened circle, returning to its original position when t = 1. Because the orbit is so small, the star's motion looks like a small wobble.

From this viewpoint, does the star move towards and away from you during its orbital motion? You may find it helpful to adjust the zoom to focus on the star's orbital path.

Answer

Yes. The star gets closer to you as it travels from the furthest point on the foreshortened circle, and travels away from you as it moves from the closest point back towards the furthest point.

The velocity of a star as it follows its orbit is independent of the angle you happen to view it from. The star doesn't care whether or not it is being watched. However, all astronomers can measure is the *radial* velocity – that is to say the star's motion towards or away from you. The unknown viewing angle limits what we know about almost all of the planets discovered by the radial velocity method.

The orbital inclination

Once again we are going to return to the interactive application. This time you will see how the apparent motion is affected by our viewing angle. Astronomers call this viewing angle the orbital inclination. This is measured in the opposite way to what you might expect – an orbital inclination of 0° means that we on Earth are viewing the orbit face-on, like we did in Section 3.5, whereas an orbital inclination of 90° means that we are viewing the orbit edge-on.

Activity 5 Orbits from above

Allow about 20 minutes

Interactive content is not available in this format.

This interactive application now shows both a 2D view, looking down on the orbits from above, and a foreshortened 3D view. Remember that if you work with the application in a separate page (by clicking on the [ ] button) you may need to adjust the magnification in your browser to view both panels.

This application has a new slider, labelled orbital inclination (*i*). The mass ratio and the size of the orbit are fixed to allow you to concentrate on the effect of changing the orbital inclination.

The purple line in the 3D view is the direction to the observer, using a telescope to make measurements. You are looking from a different perspective as if you were in a spaceship near the star. At i = 0° the observer is looking down on the system, as in the viewpoint of Figure 13. At i = 90° the observer is looking from a direction that aligns exactly with the orbits. Use the slider to vary the value of the orbital inclination, *i*. You may find it helpful to move the orbital plane around to more clearly see the orbital inclination - the angle between the *perpendicular to the* orbital plane and the purple line to the distant observer. To do this, click on the orbital plane and drag it around until you are viewing it nearly edge-on.

Click the play button to set the planet and star in motion.

From which orbital inclination will the radial velocity be the largest? In other words, where would you position the observer so that the star's motion towards and away from them during its orbital motion is as pronounced as possible?

Answer

For orbital inclination $i = 90°$, the star will move exactly towards and exactly away from the observation point once per orbit. An observer positioned here will see a value of radial velocity that gives the full extent of the orbital motion.

The star's motion

For this activity we will use the interactive application to show the movement of the star.

Activity 6 The star's motion

Allow about 15 minutes

Interactive content is not available in this format.

This application is zoomed in on the centre of mass, so the star's orbit appears larger on the screen and the planet is too far away from the star to be visible within the views shown. The direction to the planet is indicated with a green line. The direction to the hypothetical observer (not you) is indicated with a purple line.

Click on the play button and the application will start. Notice that the line from the star to the (unseen) planet always passes through the centre of mass of the system.

Set the orbital inclination to the value $i = 90°$ exactly, using the arrow keys on the keyboard to amend the values if necessary. Using the play/pause button, halt the application when the star is moving exactly towards the observer. What is the value of t (see the slider position) when this is the case?

Answer

The value is $t = 0.25$ give or take however much uncertainty your clicking led to. There should be a right-angle (exactly 90°) between the green and purple lines, with the star at the bottom of the circle shown in the 2D graphics window. At this instant, the star is moving horizontally to the right in the 2D window, exactly towards the observer.

At this instant, what direction is the planet moving in?

Answer

The planet is moving exactly away from the observer, to the left in the 2D window.

Using the slider, change the value of the orbital inclination to $i = 70°$. Set the application to play.

What is the definition of radial velocity?

Answer

Radial velocity is the motion towards or away from the observer.

Using the play/pause button, halt the application when the star has maximum radial velocity away from the observer. What is the value of t (see the slider position) when this is the case?

Answer

The value is $t = 0.75$ give or take however much uncertainty your clicking led to. There should be a right-angle (exactly 90°) between the green and purple lines, with the star at the top of the circle shown in the 2D graphics window. At this instant, the star is moving horizontally to the left in the 2D window. This is as close at it will get to moving exactly away from the observer, who is positioned off to the right and above the 2D graphics.

Orbital motion and radial velocity

We are now going to explore how the motions around the centre of mass and the radial velocity are related. In reality all astronomers 'see' is a point of light on the sky: the star. The laws of physics, which underly the changes in the light that astronomers collect from the star, allow the real motion of the star and its planet(s) to be determined. Astronomy proceeds by unlocking the information carried by light from objects we are unlikely to ever be able to view up close.

Activity 7 Orbital motion and radial velocity

Allow about 20 minutes

This application shows orbital motions in a system where a star is 1500 times more massive than its planet. The separations are scaled so the planet's orbit just fits on the screen - the planet and star are shown much larger relative to their separation than they would really be. With the initial settings the observer is looking at the system from above and to the right of the orbital plane.

The application shows two animated arrow vectors – light green represents the true velocity of the star. The star's speed stays the same as it moves around its circular orbit, but its velocity continuously changes direction as shown. Remember, the star and the planet move in *opposite* directions at each instant. The star moves much more slowly than the planet: in the time that it takes for the planet to move around the big circle, the star moves around a circle that is too small to even be seen in this application. The star's motion is just a wobble around the centre of mass that is too small to easily discern.

The second animated arrow vector, in orange-brown, shows the radial velocity of the star relative to the distant observer. When the star is moving to the right, the radial velocity arrow points towards the observer, along the purple line. When the star moves to the left, the radial velocity arrow points away from the observer, along the extension of the purple line below the orbital plane. To help you to see this, remember that you can drag the orbital plane around to change your viewpoint.

The application gives the values of the stellar orbital speed (which never changes) and the stellar radial velocity, which changes continuously as the direction of the star's motion changes continuously as it moves around its orbit.

Interactive content is not available in this format.

When the radial velocity is towards the observer (orange-brown arrow aligned along the purple line), is the value of the stellar radial velocity positive or negative?

Answer

Negative.

When the radial velocity is away from the observer (orange-brown arrow aligned away from the purple line), is the value of the radial velocity positive or negative? (You can pause the application if you need to.)

Answer

Positive.

What is the biggest value the stellar radial velocity ever has with the initial settings? (If necessary, you can refresh the page to reset all of the sliders to the initial settings, i = 77° and a_{planet} = 14.55.)

Answer

10.8 m/s (give or take however much uncertainty your clicking led to).

In what direction is the true velocity of the star pointing when the radial velocity has its maximum value?

Answer

To the left, away from the observer, who is to the right and above the orbital plane.

Keeping the application paused at its maximum value of radial velocity, adjust the orbital inclination, i, using the slider. You can also use the arrow keys on the keyboard to amend the values.

For orbital inclination i = 90° exactly, what value does the stellar radial velocity now show? What do you notice about this value?

Answer

11.1 m/s. This value is the same as the orbital speed. When the orbit is exactly aligned with the direction to the observer like this, the maximum radial velocity will be the same as the speed because the motion is exactly along the line to the observer.

For orbital inclination i = 30° exactly, or as close as you can get it, what value does the stellar radial velocity now show? What do you notice about this value?

Answer

5.56 m/s. This is about half the value obtained at i = 90°.

Even when the observer is looking quite steeply down on the orbit, the radial velocity reaches half the orbital speed.

Radial velocity

In this activity you will be able to see the radial velocity curve that we'd measure from spectra of the star when an unseen planet is in orbit.

Activity 8 The impact of radial velocity

Allow about 20 minutes

Interactive content is not available in this format.

This application shows you the radial velocity curve for the star, like the example of 51 Pegasi in Figure 12. The green wavy line plots the radial velocity that the orange-brown arrow was measuring in the previous activity. The time on the horizontal axis is measured in Earth years.

Change the orbital inclination to exactly i = 90°. What change do you see in the green radial velocity curve? If you need to start again, refresh the page.

Answer

The radial velocity curve becomes taller. It reaches values of about 40 m/s and –40 m/s. In fact, these values are exactly 36.7 m/s and –36.7 m/s, because the orbital speed of the star is 36.7 m/s.

Now set i = 30°, or close to this. What values do the green radial velocity curve extend to now? What do you notice about these?

Answer

It reaches values of 20 m/s and −20 m/s. This is half the value found when i = 90°.

If you double the star mass, what happens to the orbital speed of the star?

Answer

It goes down, to nearly 26 m/s.

A bigger star will pull the centre of mass towards its own centre so the size of the star's orbit decreases. Because the star moves around a smaller orbit in one orbital period, its speed decreases. So it would be reasonable to expect that doubling the star's mass would halve the maximum velocity for that star. But actually it doesn't.

Move the star's mass back and forth between about 2 solar masses and 4 solar masses. Watch the screen carefully while you do this.

Apart from the maximum radial velocity of the star, what else changes?

Answer

The orbital period changes.

As recorded below the sliders, it is 4.63 Earth years for M_{star} = 2 M_{Sun}, and 3.27 Earth years for M_{star} = 4 M_{Sun}. This is the time for the green radial velocity curve to complete one down and up wave before it repeats itself, which corresponds to one orbit.

In conclusion then, a more massive star moves around a smaller orbit, but it takes less time to complete the circuit. The relationship between star and planet masses, their separation and the time taken to complete an orbit is described by one of the more important laws of astronomy. It's called Kepler's Third Law. You don't need to worry about the equation for it here, but you should know that astronomers use it a lot. It is the fundamental method used to determine the mass of everything in astronomy, from our familiar Sun and Moon to the black hole at the centre of our Galaxy, and it can even be modified to be used on entire galaxies. If you study more astronomy you will definitely come across it again.

Set the mass of the star to exactly 1 M_{Sun}.

Set the mass of the planet to exactly 1 M_J.

Set the planet distance from the star to be a_{planet} = 5.2 AU.

What is the orbital period of the star–planet system that has been chosen?

Answer

11.9 Earth years.

Can you name a planet–star pair that has properties very like the one that has been chosen?

Answer

The application has been set up to simulate the orbit of Jupiter and the Sun, ignoring the effects of all the other Solar System planets.

Using the sliders, adjust the application to find out what the orbital period of a planet like Jupiter would be if it were at a distance of 1 AU from the centre of mass.

What value do you get for the orbital period? Comment on your answer.

Answer

The orbital period is 1.00 Earth years. If Jupiter were put in Earth's place in the Solar System, then it would follow the Earth's orbit, taking one Earth year to complete it, just like Earth does.

Because the Sun is more than 1000 times more massive than even Jupiter, the most massive planet in the Solar System, it is the mass of the Sun that dominates. It is the value of the Sun's mass that determines how long it takes for any planet in the Solar System to complete its orbit.

Using the sliders in the application, find out what the orbital period would be for a Jupiter-like planet orbiting at 1 AU from a star with a mass of 5 M_{Sun}.

Answer

0.447 Earth years.

Reading from the graph, what is the maximum radial velocity for this system? (Remember that you may need to adjust the orbital inclination to see the maximum value.)

Answer

Just over 12 m/s.

This is the maximum value, obtained with orbital inclination i = 90° exactly.

4.6 DIY chemical fingerprints

This is an optional section for those of you who would like to experience the power of spectroscopy yourself. The video will tell you more about the spectra of stars even if you don't have time to make a spectrometer.

Activity 9 Make your own spectrometer

Allow about 1 hour, plus time for experimentation

If you want to really see what a spectrum is like, you can very easily make your own spectrometer – a device that allows you to split up the light coming from a source to see what colours are present. Watch the following video for instructions and ideas about what to look at.

Make your own CD spectrometer

You will need:

- an old CD you don't want anymore
- a cereal box
- scissors
- tin foil
- sticky tape.

5 The exoplanet collection

Since that first exoplanet, 51 Pegasi b (51 Peg b), was discovered, lots more have been found. We now know of more than 4000 planets orbiting other stars, with many more candidates in the pipeline. The candidates are objects that astronomers think are exoplanets, but which need further study for them to be sure.

Many of these planets were discovered in exactly the same way as 51 Pegasi b. For these so-called 'radial velocity planets', astronomers patiently looked at the spectrum of the host star night after night. This allowed them to see whether there were tiny wavelength shifts indicating a planet's gravitational pull. However, most of the known exoplanets were first discovered using a different, more efficient, method known as the transit method. You will learn more about the transit method in the weeks to come. For now, you can explore the catalogue of exoplanets on the Extrasolar Planets Encyclopaedia at the Exoplanet.eu website.

At the time of writing, the Exoplanets.eu catalogue lists over 4000 confirmed planets. That's rather a lot! To make this huge catalogue easier to explore, you can perform searches for planets in particular categories. You could just look at the planets discovered using the radial velocity method, for example.

If you go onto the Exoplanet.eu website and click on the link labelled 'All Catalogs', you will come to the screen shown in Figure 14. If you click on the drop-down menu towards the top left labelled 'Detection' you can select 'Radial Velocity'. To get the whole list you need to change the third drop-down menu from 'Show 100 entries' to 'Show All entries'.

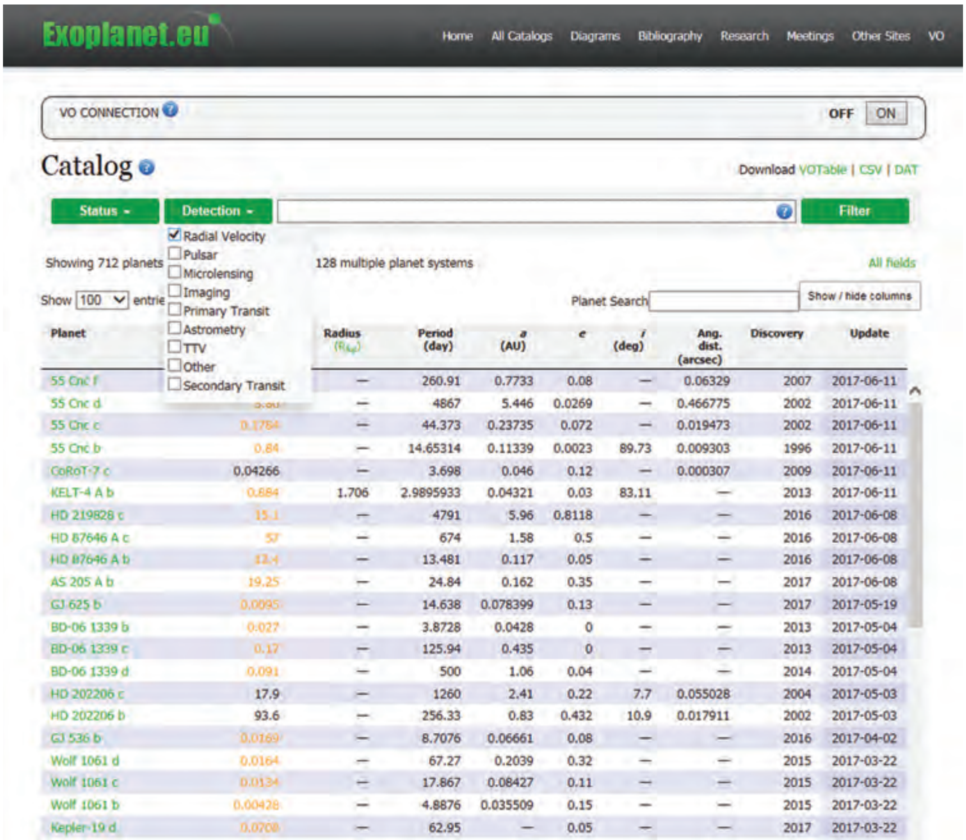


Figure 14 Screenshot of Exoplanet.eu

Activity 10 Exoplanet.eu database

Allow as long as you like

Explore the Exoplanet.eu database. You will notice at the top of the table that there are headings such as ‘Planet’, ‘Mass’ and ‘Radius’ (Figure 15). If you want to reorder the table by any of these, just click on the heading and the table will reorder itself. To order in the opposite direction, click the same heading again.

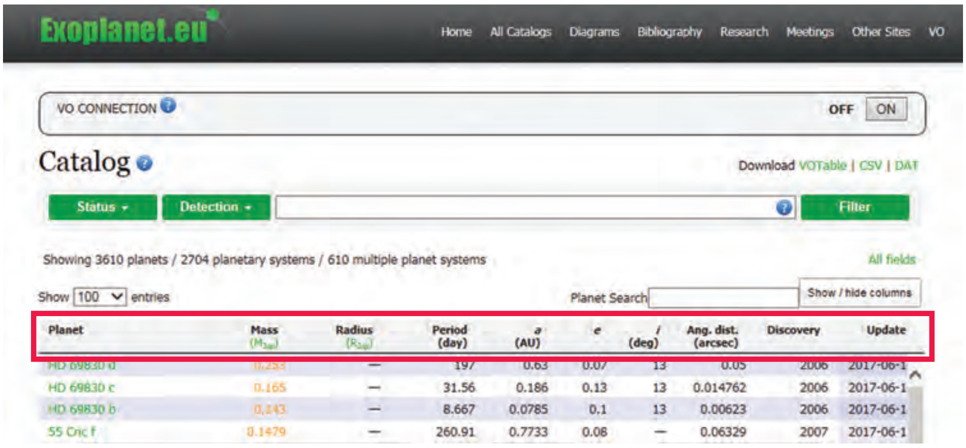


Figure 15 Screenshot of table headings on Exoplanet.eu

You can search for particular planets by name by typing in the ‘Planet Search’ box.

Type 51 Peg b in the box and write down the mass and period that comes up. Notice that the mass is measured in M_J, as you saw in Week 2.

Answer

Mass = 0.47 M_J,

Period = 4.2308 days.

Did you notice anything surprising about the period of 51 Peg b?

Answer

The period is only 4.23 days: 51 Peg b’s year is only a few Earth days!

6 This week's quiz

Well done – you have reached the end of Week 3 and can now take the weekly quiz to test your understanding.

Week 3 practice quiz

Open the quiz in a new tab or window (by holding down Ctrl [or Cmd on a Mac] when you click the link).

7 Summary of Week 3

This week you've learned about the first exoplanet discovered orbiting a Sun-like star. This planet is 51 Pegasi b, a 'hot Jupiter'. You have seen how planets can be detected by measuring the movements of wobbling stars – the radial velocity method. This has introduced you to spectroscopy: the science of spreading out the light from an object to separate the colours from one another. There is a lot of information that can be extracted using spectroscopy – what you have learned here is only the beginning. You have also had the chance to explore the Exoplanet.eu website and make your own spectrometer. Finally, in the interactive application activities you have explored the consequences of one of the most important laws in astronomy: Kepler's Third Law.

You should now be able to:

- interpret the name of an exoplanet
- describe the characteristics of 51 Pegasi b
- explain the radial velocity method for detecting planets using the analogy of a see-saw
- understand that both light and sound are waves
- understand how the Doppler shift affects wave properties
- use the website Exoplanet.eu to find a list of planets discovered by the radial velocity method.

Next week you will be looking at another very successful way of detecting exoplanets – the transit method.

You can now go to Week 4.

Week 4: You're in my light – transits

Introduction

Last week you learned how astronomers detect exoplanets by measuring the wobble of their stars. This week you will learn about a different technique for spotting them – waiting for them to pass in front of, or transit, their parent stars. You'll start off by looking at planets that transit in our own Solar System, and then move on to exoplanet detection.

Watch this video in which Carole Haswell talks about what you will be doing this week.

Video content is not available in this format.

By the end of this week, you will be able to:

- state which planets in the Solar System are observed to transit the Sun, and explain why
- outline how transits can be used to identify exoplanets and measure the size of stars and planets
- state the relationship between radius and cross-sectional area for a sphere
- show you understand the size ratio between the Sun, Jupiter and Earth

- describe the relationship between transit depth and the ratio of radii of the planet and star $(R_p / R_{star})^2$.

1 Transits in the Solar System

What is a transit? As you learned in Week 1, a transit is what happens when a planet passes in front of the Sun and blocks some of the light from the Sun. Exoplanets – planets outside of the Solar System – can also transit their host star. For a transit to occur, the planet's orbit must cross an imaginary straight line running from the observer to the star.

In our Solar System, the transits of only two of our fellow planets are visible from the Earth. Mercury and Venus transit the Sun because they are closer to the Sun than Earth is. Planets that orbit further from the Sun than the Earth does can never pass directly between the Earth and the Sun – we could only see their transits from a spaceship outside of the Solar System.

In Figure 1, you can see how only Mercury and Venus could possibly pass between the Sun and an observer on Earth.

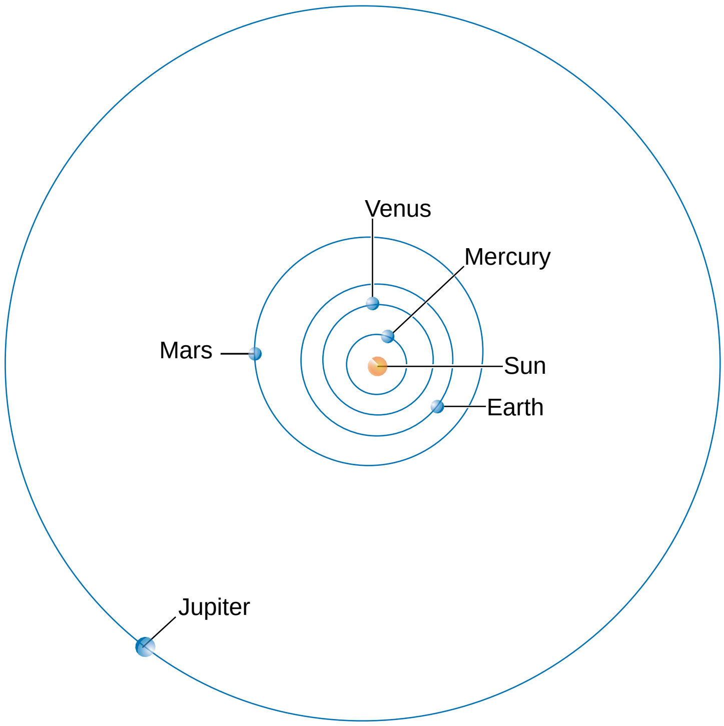


Figure 1 The Sun, the inner Solar System planets and Jupiter. Please note the Sun and planets is not to scale.

Planets close to their star complete an orbit in less time than planets that are farther out. Last week you learned that 51 Peg b, which is very close to its star, completes an orbit in just a few Earth days. Mercury's orbital period is 88 Earth days, while Venus' orbital period is 225 Earth days. Earth's orbital period is of course (just over) 365 Earth days – an Earth year.

Mercury overtakes Earth on the inside a few times in each Earth year, and Venus does the same thing roughly every one and a half Earth years. From this information, you might expect to see Mercury transit the Sun a few times each year, and Venus to transit the Sun approximately once every year and a half. But this isn’t what happens. The orbits of all the planets in the Solar System are slightly tilted, as shown in Figure 2a.

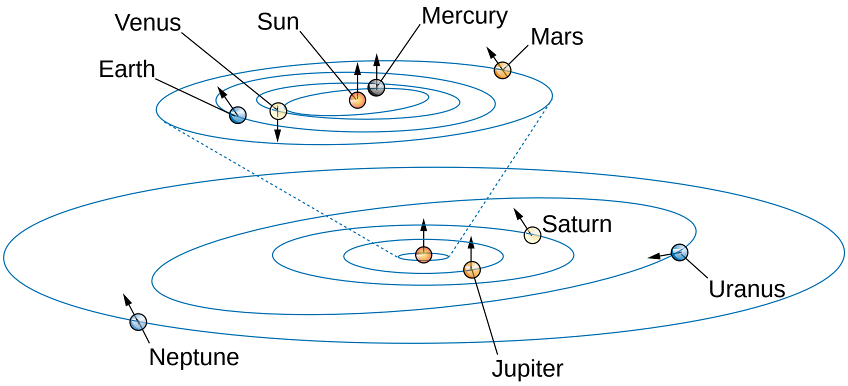


Figure 2a The orbits of the Solar System planets are slightly tilted when compared with the orbit of the Earth. The small arrows show the direction of the rotation axis of each planet.

The tilted orbits mean that when the planets Mercury and Venus overtake Earth on the inside, they usually appear above or below the Sun. For a transit to occur, the planet has to line up exactly in two dimensions, so transits are quite rare. Figure 2b shows where Venus can line up exactly with the Sun. A transit happens only if Venus overtakes the Earth when it is at one of two particular places in its orbit.

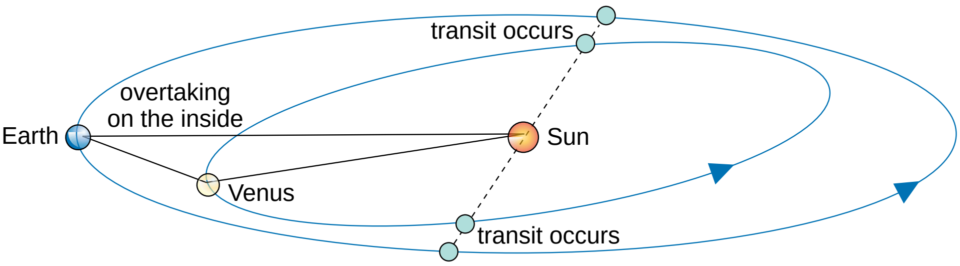


Figure 2b Transits occur only when the overtaking happens at one of the two points where Venus lines up with the Sun

In fact, there are only 13 transits of Mercury every century. Venus transits are even less frequent. The last transit of Venus was in 2012, and the next will be in December 2117.

2 Size matters

Even though planets are dim, we can learn about them by studying the decrease in sunlight or starlight reaching us when a transit happens. The most obvious thing we can learn is the size of the planet, and you'll see how in the next section.

2.1 Transits of Mercury and Venus

Figure 3 shows a close-up of the Sun during the 2004 transit of Venus. Venus is in front of the Sun from the Earth's point of view, and has blocked some of the Sun's light, appearing in silhouette.

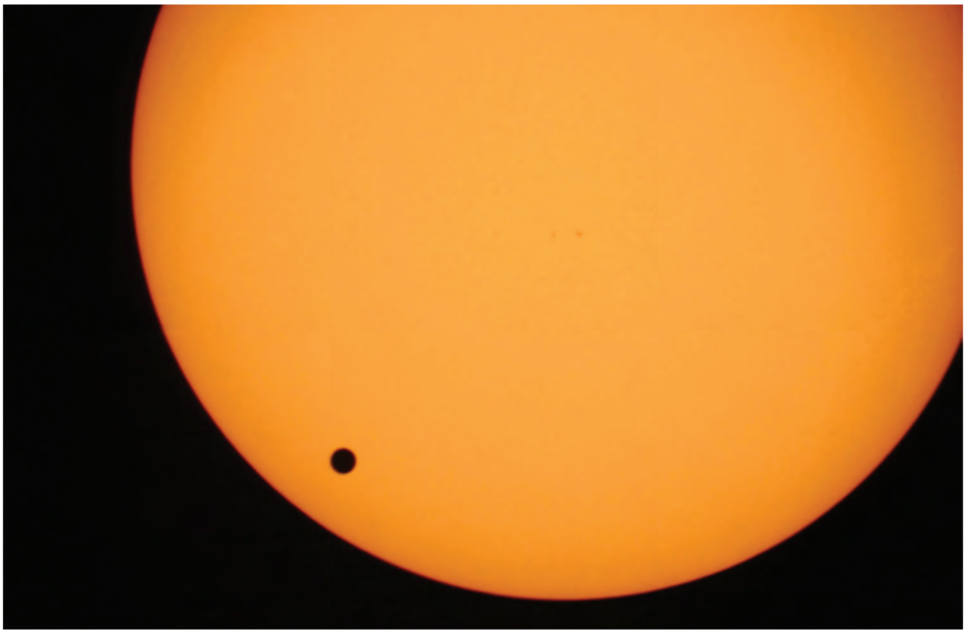


Figure 3 The 2004 transit of Venus, taken with a telescope in Belgium. Venus is passing in front of the Sun, and forms a dark circular silhouette.

The video at the link below is a speeded-up time-lapse sequence of the 2006 transit of Mercury. In reality it took five hours for Mercury to complete its transit.

Transit of Mercury: watch as planet passes in front of the Sun for first time in a decade

In some images of the Sun, you will also see dark patches that are actually on the surface of the Sun. These are caused by sunspots. Figure 4 shows an example.

Figure 4 The transit of Mercury on 9 May 2016, with sunspots also visible. Mercury is the left-most dark circle.

It is also possible for other, much closer, objects to get in the way and block some of the light from the Sun, as Figure 5 shows.

Figure 5 Transit of an aeroplane during the transit of Venus on 5 June 2012, taken from San Francisco, California, USA by MacNeil Fernandes

Figures 3 and 4 are photographs taken during transits of Venus and Mercury. The obvious difference between them is the size of the silhouette, with that of Mercury being much smaller. That makes perfect sense, because Mercury is less than half the size of Venus.

Astronomers know how big Mercury and Venus are. But if they didn’t, Figure 6 shows that they could work out the sizes of the planets by measuring their transits, given knowledge of three more things:

- how far away Mercury/Venus is from Earth
- how far away the Sun is from Earth
- how big the Sun is.

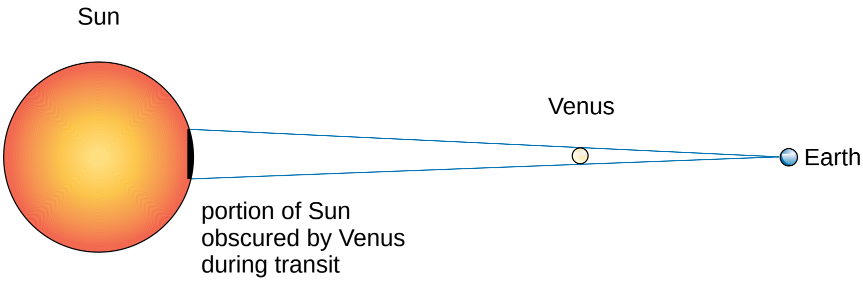


Figure 6 Side-on transit diagram for Venus showing how the amount of sunlight that gets blocked depends on both the relative sizes of Venus and the Sun, and on the distances of Venus and the Sun from Earth. Note that the diagram is not to scale – the Sun would be very much bigger than the planets and the distances between them greater if drawn to

scale.

2.2 Transits of exoplanets

It is also possible to see transits of exoplanets. If our view of a star happens to cross the orbital path of one of the star’s planets, a transit will occur. Just as Mercury and Venus block some of the Sun’s light, in the same way an exoplanet can block some of the light from its host star.

You have already seen that a small planet, such as Mercury, blocks less light than a larger planet, such as Venus. This is true for exoplanets too. So, it is possible to learn how big an exoplanet is from measuring how much starlight is blocked during its transit.

Figure 6 (in the previous section) showed the information we would need to work out the size of Venus from its transit. However, even our next nearest star is very far away compared with distances between planets in the Solar System. This means that for exoplanets, the distance between Earth and the exoplanet is almost identical to the distance between Earth and its star. This actually makes it easier to work out the size of an exoplanet from its transit than it is to work out the size of Venus! In fact, all you need to know to work out the size of a transiting exoplanet is the size of its star.

2.3 Stars, colour and size

Once the transit of an exoplanet has been spotted, how is the size of the star measured? Most of the time stars are too distant for us to measure their sizes directly – they just appear as points of light in the sky in even the most powerful telescopes. Fortunately though, stars are pretty well-behaved and astronomers have a good understanding of how they work. They can use the measurements of the few stars that are close enough to the Earth to work out what other more distant stars are like.

Stars such as our Sun are part of what astronomers call the ‘main sequence’, a phase in which they spend most of their luminous lifetime. As you saw in Week 1, the properties of main sequence stars follow some simple rules – the largest are very hot stars and blueish in colour, while the smallest are cooler and are reddish in colour. Figure 7 shows the relative sizes and colours of the different types of main sequence star, ranging from the largest, bluest and hottest (‘O stars’) to the smallest, reddest and coolest (‘M stars’). In fact, there’s a whole continuous sequence of star sizes.

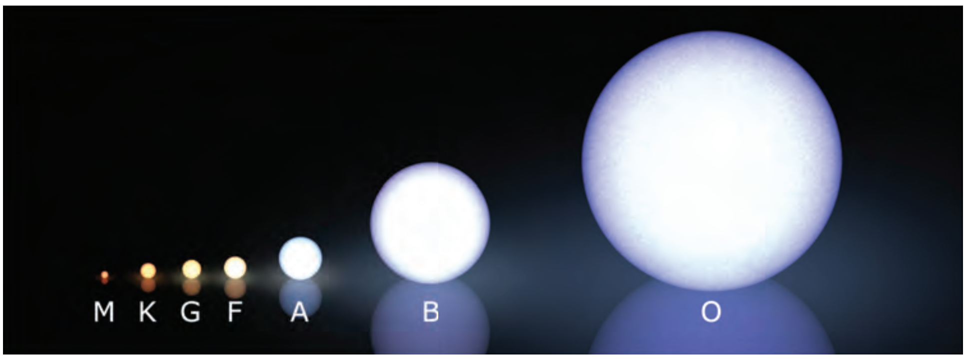


Figure 7 Stellar type diagram for main sequence stars

Last week you learned that the spectra of stars contain fingerprints of the gases they are made of – the patterns of absorption lines. Stars with similar temperatures tend to have similar patterns in their spectra. So, we can determine which category a star is in from its spectrum. Because of this, it is possible to gauge the size of a star, even if it can’t be measured directly.

2.4 Circles and spheres

Once the size of a star is known, it is possible to work out the size of any planet that transits in front of it. This is done simply by measuring how much light from the star is blocked by the planet.

But how much light is that? To work it out, you need to think about the cross-sectional area of a sphere.

Activity 1 Cross-sectional shapes

Allow about 5 minutes

The cross-section of an object is the shape you would see if you took a slice through that object. Can you work out the cross-sectional shapes of these solids?

1. What shape is the cross-section of this cube?

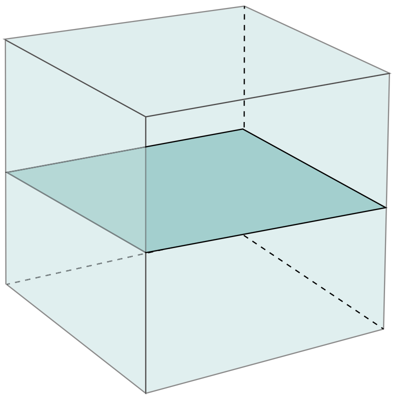


Figure 8 Cube with cross-section cut marked

- ○ Square
- ○ Diamond
- ○ Rectangle

2. What shape is the cross-section of this cone?

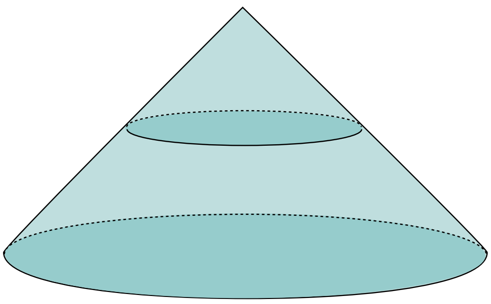


Figure 9 Cone with cross-section cut marked

○ Triangle
○ Circle
○ Square

3. What shape is the cross-section of this solid?

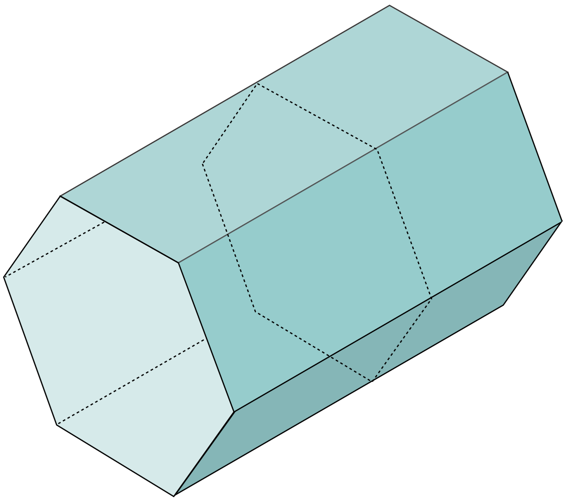


Figure 10 Prism with cross-section cut marked

○ Square
○ Diamond
○ Hexagon

In terms of transits, it is important to know what a sphere looks like if it’s projected onto a flat surface. When we view spherical objects such as footballs and planets we see their cross-section, which is a circle.

The term ‘cross-sectional area’ refers to the area of the shape that is the cross-section. So, the cross-sectional area of a sphere is the area of the circle we see. The radius of this circle, the distance from the centre to the edge, is just the same as the radius of the sphere (Figure 11).

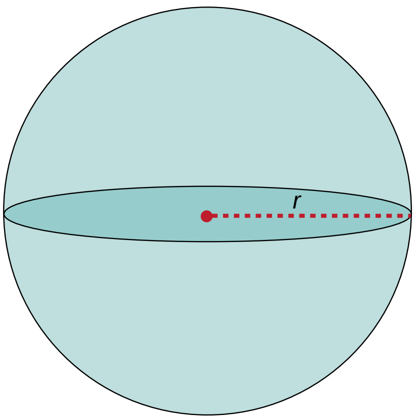


Figure 11 A circle as a cross-section of a sphere of radius *r*

As with the pictures of the transits of Mercury and Venus in Figures 3 and 4, if you were close to the host star of a transiting exoplanet, you would see a bright circle of star with a smaller dark circle of planet on top of it. To work out how much of the bright star is 'missing', you need to know the areas of these two circles.

The host stars are incredibly far away though, so we can't *see* these circles – all we can measure is the amount of light coming from the point of light that is the star. Figure 12 shows how the light coming from a star is reduced when a planet transits in front of it. This graph measuring the amount of light, with its particular shape, is called a light curve. The dip in the light curve tells us how much of the star's light is blocked by the planet, from which we can calculate the relative areas of the two circles and hence the size of the planet.

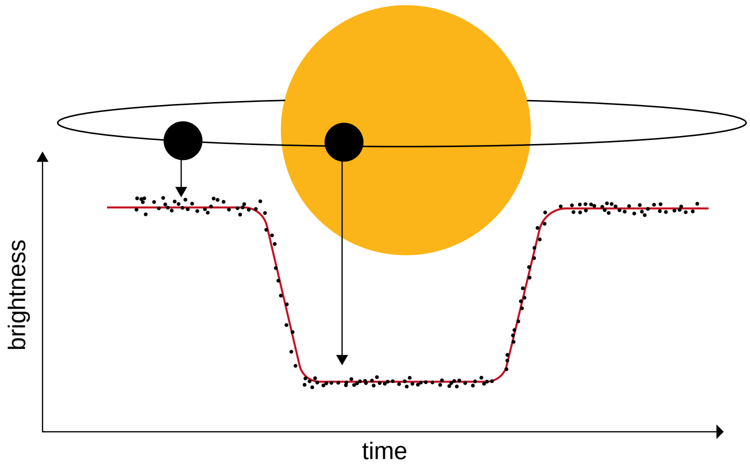


Figure 12 Schematic of a transit and the measured light curve

2.5 Circles, radii and area

Astronomers use maths to interpret the light they collect. One very useful bit of maths for astronomy is the area of a circle. Astronomy features spherical objects like stars and planets and you have already seen that when we view them we see their cross-section as a circle. In the next section you'll see how the area of a circle is calculated.

The equation for the area of a circle

The area of a circle is related to the radius of the circle, just as the volume of a sphere is related to the radius of the sphere as you saw in Week 2. Remember that the radius of the two-dimensional circle we see as a star is actually the same as the radius of the three-dimensional, spherical star itself.

It has been known since at least the time of the ancient Babylonians that the area of a circle is a little more than three times its radius squared. To find the exact area of a circle the radius squared is multiplied by a numerical constant called 'pi', which has the symbol π and is pronounced 'pie'. Pi is close to the value 3.14, but if you have a calculator with a 'π' button it's best to use that when working out areas and volumes.

So, the area of a circle is given by:

(Equation 1)

which can also be written as:

(Equation 2)

This is shown in Figure 13.

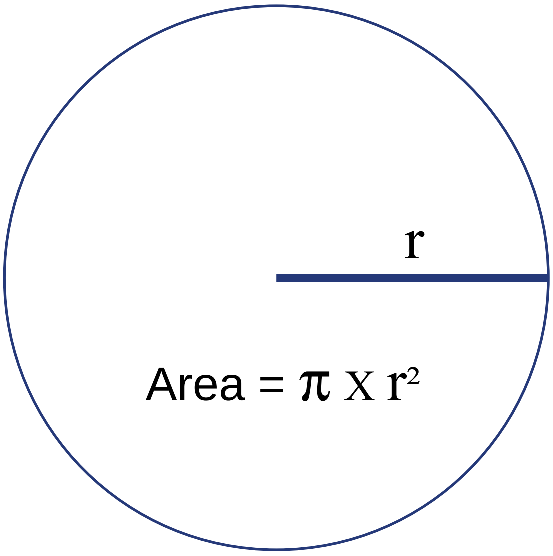


Figure 13 Area of a circle with radius *r*

For example, the area of a circle with a radius of 10 m would be

Generally, you measure area in m^2 or cm^2.

The cross-sectional area of a sphere with radius 10 m would also be 314 m^2.

Comparing areas for circles of differing size

In Week 2 you learned that the volume of a sphere depends on the radius cubed (radius × radius × radius, that is, r^3). There you saw that increasing the radius by a factor of 10 increases the volume by a factor of 10 × 10 × 10 = 1000.

The area of a circle depends on the radius squared (radius × radius, that is, r^2). In a similar way, if the radius is increased by a factor of 10 then the area is increased by a factor of 10 × 10 = 100.

Similarly, if the radius is doubled, the area is increased by a factor of four. The factor of four comes about because the radius is multiplied by itself, and 2 × 2 = 4.

The Earth's radius is close to three times that of Mercury's. Figure 14 shows how much larger the Earth's cross-sectional area is than Mercury's: it's a bit less than 3 × 3 = 9 times the area. Count the squares overlying each planet to verify this.

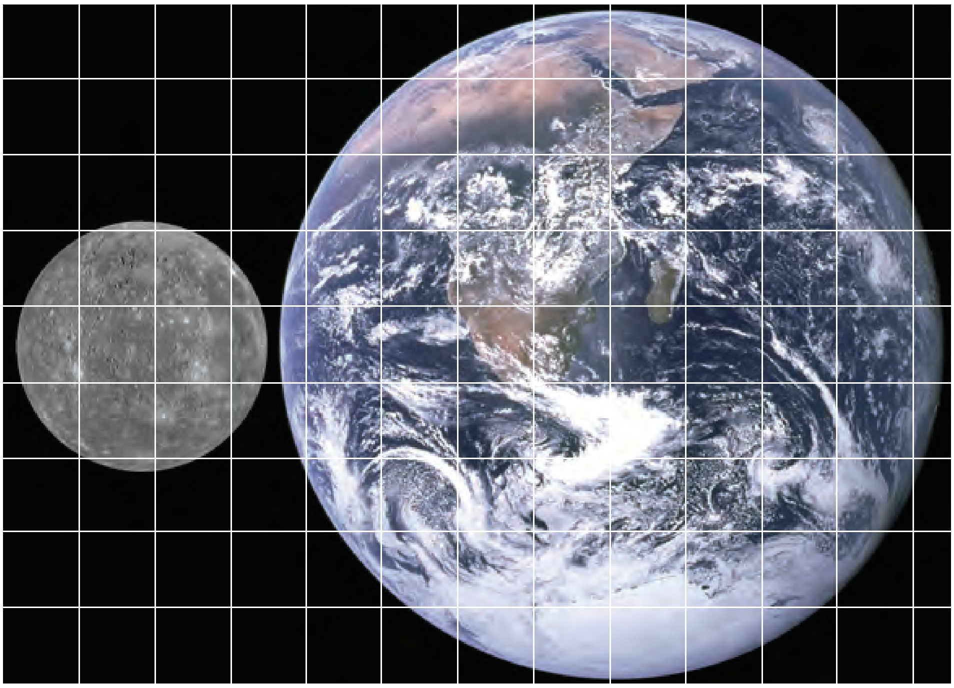


Figure 14 Cross-sectional areas of Mercury and Earth

Activity 2 Cross-sectional areas

Allow about 10 minutes

You have been given the approximate radii of the Sun and some of the Solar System planets. You need to select the correct ratio of the cross-sectional areas between two objects from a list of possible answers. Use a calculator if you need to. (Remember that R_E represents the radius of Earth.)

Sun: approximately 100 R_E

Jupiter: approximately 10 R_E

Mercury: approximately 0.5 R_E

Venus: approximately 1 R_E

In the rest of this activity ‘area’ refers to the cross-sectional area.

1. Is the area of the Sun:

- 10 times the area of Jupiter?
- 100 times the area of Jupiter?
- 20 times the area of Jupiter?

Answer

The radius of the Sun is 10 times the radius of Jupiter so the area of the Sun is 10 × 10 = 100 times the area of Jupiter.

2. Is the area of Venus:

- 1/100th the area of the Sun?
- 1/1000th the area of the Sun?
- 1/10 000th the area of the Sun?

Answer

The radius of Venus is th the radius of the Sun so the area of the Venus is th the area of the Sun.

(Alternatively, the radius of the Sun is 100 times the radius of Venus so the area of the Sun is 100 × 100 = 10 000 times the area of Venus, and hence the area of the Venus is th the area of the Sun.)

3. Is the area of Jupiter:

- ○ 400 times the area of Mercury?
- ○ 20 times the area of Mercury?
- ○ 40 times the area of Mercury?

Answer

The radius of Jupiter is 10 times the radius of Earth, and the radius of Earth is two times the radius of Mercury. This means that the radius of Jupiter is 20 times the radius of Mercury. Therefore, the area of Jupiter is 20 × 20 = 400 times the area of Mercury.

2.6 Remember, stars are big!

In Activity 2 you saw that the Sun has a radius around 10 times bigger than that of Jupiter, so it has a cross-sectional area of about 100 times that of Jupiter. In Week 2 you compared their volumes and saw that the Sun has a volume more than 1000 times greater than Jupiter’s. And, the average densities of the Sun and Jupiter are similar, so their masses differ by this same factor. In fact, the Sun’s mass is a whopping 2×10^{30} kg, which is remember, 2 with 30 zeros after it!

And the Sun is quite a modest star!

The largest O-type main sequence stars can have radii twenty times greater than the Sun, while the very smallest M-type stars are sometimes not much larger than Jupiter, around 1/10th the size of the Sun. There are even far more gigantic stars out there that are at a later stage in their lives than the main sequence – the largest currently known stars have radii of more than 1500 times that of the Sun!

3 Putting the ingredients together

You've seen that the cross-section of a sphere is a circle, and you've seen how to work out the area of a circle. You've seen that a transit allows us to work out the relative sizes of a star and an orbiting planet, based on the fraction of the star's light that is blocked by the planet's silhouette. Finally, you've learned that the size of a star can be gauged using spectroscopy, i.e. studying the finely spread rainbow of light from the star. This last point is something that can't really be proven here, but if you study more astronomy you will learn how it's done.

In the remainder of this week's work you will be putting these ingredients together to develop a recipe that allows direct measurement of the size of some exoplanets, even though the planets themselves can't be seen.

Next you will see how astronomers detect and interpret transits. You will begin by considering some of the practical aspects, and then you will look at the underlying maths.

3.1 Measuring a transit

In Figure 12 (repeated below) you saw how a transiting planet changes the measured brightness of its star as it blocks some of the star's light. But what exactly do astronomers need to do to detect a transiting planet?

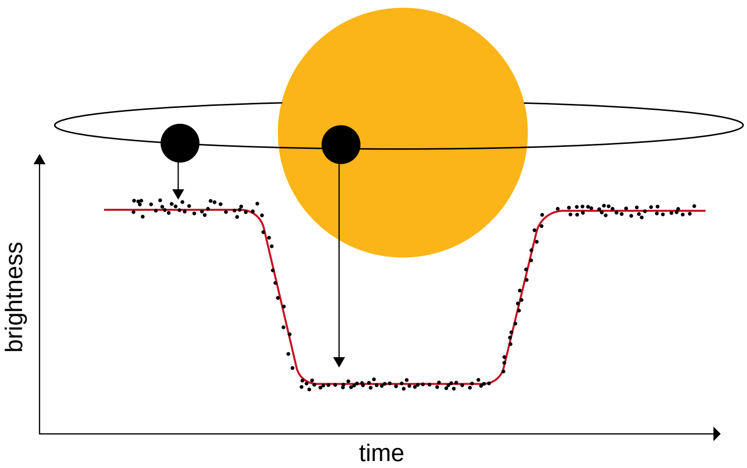


Figure 12 (repeated) Schematic of a transit and the measured light curve

The basic technique for detecting a transiting planet is to observe a star over a period of time and measure how bright it is. If a dip in brightness, such as that shown in Figure 12, is observed, then a planet may have been detected. Planets orbit regularly, so if the dip is caused by a transiting planet, it should also recur regularly. And the time between dips should be of equal length: it's the time taken by the planet to complete each orbit.

The dip in brightness needs to have the specific U-shape shown in Figure 12 to be caused by a transiting planet. V-shaped dips are more likely to be caused by a pair of stars orbiting each other, just eclipsing each other's edges. Dips with other shapes could be caused by spotty regions on the surface of a star coming into view, like the sunspots you saw in Figure 4. Unfortunately, there are lots of things that can make a star appear slightly less bright.

You’ve learned that planets are much smaller than stars, so when a planet transits it doesn’t block out much starlight at all. Jupiter would only block out about 1 per cent of the light of the Sun if it were possible to observe its transit from afar. Fortunately, it is not particularly difficult to measure the brightness of a star to within 1 per cent. In fact, there are quite a few amateur astronomers who are now doing this as a hobby.

3.2 An introduction to professional transit searches

The next video focuses on SuperWASP, one of the first and most successful projects that searches for exoplanet transits. SuperWASP is able to measure the brightness of many stars simultaneously. This allows it to find the small fraction of stars that show regular dips in their brightness, revealing that they each host a planet whose orbit happens to be aligned so that a transit can be seen. The Open University is a part of the SuperWASP consortium. These planets are all given names like WASP-12 b, where 12 indicates that it was the twelfth planet found by SuperWASP.

SuperWASP

3.3 From dips to planet size measurement

The size of the planet relative to the star is worked out by measuring the difference between the normal brightness of the star and the brightness of the star during the deepest part of the dip. This difference, expressed as a fraction or percentage, is called the *transit depth* and it is the key measurement taken for transiting exoplanets. If it is possible to detect the dip and measure how deep it is, then it is possible to work out the size of the planet causing it.

The amount of light blocked by a planet passing in front of its star depends on the area of the star blocked from view. The fraction of light missing, the transit depth, is calculated simply by working out the cross-sectional area of the planet, and dividing that by the cross-sectional area of the star.

Now, you know that the cross-sectional area of a sphere is a circle of the same radius, so the cross-sectional area of a planet can be written as:

$A_p = \pi R_p^2$,

and the cross-sectional area of a star as:

$A_{star} = \pi R_{star}^2$

where R_p is the radius of a planet and R_{star} is the radius of the star.

Dividing these expressions gives the transit depth, so the transit depth is equal to:

or

Because the constant π appears in both the top and bottom parts of this fraction, it cancels out and disappears.

So, the transit depth is simply:

(Equation 3)

This can also be written as:

(Equation 4)

Often this fraction is converted into a percentage by multiplying it by 100.

Now, this is what we need to work out the size of the planet. We can measure the transit depth from the light curve and we can estimate the radius of the star from its spectrum. This means that R_p can be calculated, and you will see how this works next week.

3.4 Do it yourself: planet size measurement

You've now learned everything you need to know to interpret some transits.

Activity 3 When are exoplanet transits seen?

Allow about 30 minutes

The interactive application below allows you to simulate a transit light curve. The sliders at the top allow you to choose the radii of the star and planet, the orbital period and the orbital inclination. You can also use the arrow keys on the keyboard to amend the values.

What does the term 'orbital period' mean?

Answer

It is the time taken for a planet (and its star) to complete one orbit around the centre of mass.

What does the term 'orbital inclination' mean?

Answer

It is the angle from which the system is viewed. An orbital inclination of exactly 90˚ would mean the orbits were seen exactly edge-on, and the planet would transit across the centre of the star from the observer's point of view.

Below the sliders is a graph that shows the brightness of the star – a light curve. The vertical axis is brightness, with a value of 1 indicating the normal brightness of the star if looked at through a telescope with nothing obscuring the view. The horizontal axis is time in hours. The moment at which the planet passes closest to us is chosen to be time zero on this graph.

Interactive content is not available in this format.

Reading from the graph, what is the measured brightness of the star at t = 0? You may find that a transparent ruler is helpful here. '(Make sure the sliders are set to R_{star} = 1.27 R_{Sun}; R_{planet} = 1.75 R_J; P_{orb} = 10 days; i = 90°.)

Answer

0.98; you may have got a slightly different answer depending on how accurately you measured from the screen.

What is the value for the transit depth (displayed in the text on the right-hand side above the graph)?

Answer

2.00%

How does this value of 2% for the transit depth relate to the measured brightness of the star at mid-transit?

Answer

The measured brightness of the star is 0.98, which is 2% less than the value of exactly 1 that is the normal brightness of the star. The transit depth tells us how much light is blocked by the planet, and is expressed as a percentage of light blocked from the star.

Interactive content is not available in this format.

The interactive application has been repeated so the sliders can be adjusted as you work through the next questions.

Adjust the value of the orbital inclination, slowly reducing it from i = 90° to i = 85.5°. Watch carefully how the graph changes.

Describe the graph for i = 85.5°.

Answer

The graph is almost entirely a straight line of brightness equal to exactly 1. There is just a tiny dip centred on t = 0.

What is the transit depth for these settings? (R_{star} = 1.27 $\mathrm{R_{Sun}}$; R_{planet} = 1.75 $\mathrm{R_J}$; P_{orb} = 10 days; i = 85.5°.)

Answer

0.15% according to the text shown in the application. It would be impossible to measure the graph with this precision.

Can you explain the changes in the graph as you varied the orbital inclination?

Hint: it might help to look back at Figure 12, and imagine what would happen to your three-dimensional view if your viewpoint got higher. A higher viewpoint is what a decrease in the angle i means.

Answer

For i = 90° exactly, the planet crosses the middle of the star's circular cross-section, passing through the centre of the circle. As i is decreased, your viewpoint gets higher, and the planet appears to cross the star below the middle. The planet is in front of your view of the star for a shorter time for i < 90°; as shown in Figure 12, the planet's path across the star is slightly shorter when it appears below the centre. As the planet's path across the star gets lower as a result of our viewpoint getting higher, it also gets shorter. Finally, the planet will just graze the edge of the star. Now, the area covering the star is less than a full circle so the transit depth decreases. The light curve also changes shape: the dip is no longer flat-bottomed because the amount of light being blocked is continuously changing. It is this grazing transit that is shown by the graph for orbital inclinations between about i = 86.4° and i = 85.5°.

Can you predict what the graph will show when the orbital inclination decreases from i = 85° down to i = 0°? Explain your reasoning.

Answer

For smaller values of *i* our viewpoint will be so high that the planet will never appear to pass in front of the star. The full brightness of the star should be visible at all times. The graph will be a straight line with measured brightness of exactly 1 throughout.

3.5 Planet size and transit depth

In the last activity you explored changing the orbital inclination. This time you will explore changing the planet size.

Activity 4 Planet size and transit depth

Allow about 15 minutes

With the initial parameters as set (R_{star} = 1.27 R_{Sun}; R_{planet} = 1.75 R_J; P_{orb} = 10 days; i = 90°), you should see a 2% transit depth. Adjust the size of the planet using the slider. Observe how the graph changes as you choose larger and smaller values for R_{planet}.

The slider for this application only allows planet sizes up to 2.5 R_J, which is larger than more than 99% of the exoplanets currently known.

Interactive content is not available in this format.

Adjust the planetary radius to R_{planet} = 2.40 R_J. What is the value of the transit depth now?

Answer

3.77%

Adjust the planetary radius to R_{planet} = 1.20 R_J. What is the new value of the transit depth?

Answer

0.94%

Discussion

You reduced the size of the planet by a factor of two while keeping everything else the same. Let’s consider whether the transit depths you obtained agree with Equation 3 in Section 3.3.

The equation told us that the transit depth depends on the size of the planet, that is to say the square of its radius R_p, i.e. R_p^2. So if the size of the planet is reduced by a factor of 2, the equation tells us that the transit depth should decrease by a factor of 2^2 (= 2 × 2 = 4). If you divide the transit depth of 3.77% by 4 you get 0.9425%, which is 0.94% rounded to 2 decimal places, exactly as the interactive application showed.

Play with the values of R_{planet}, and check that the transit depths you obtain always behave as predicted by Equation 3.

3.6 Star size and transit depth

In the last activity you explored changing the planet size. This time you will explore changing the star size.

Activity 5 Star size and transit depth

Allow about 10 minutes

Interactive content is not available in this format.

If the radius of the star is doubled, what would you expect to happen to the transit depth? Explain your reasoning.

Answer

The transit depth depends on the relative areas of the star and the planet. Areas depend on the square of the radius, so doubling the star's radius will lead to a factor of four change in the transit depth. Because the change is making the star bigger, but not altering the size of the planet, it will reduce the fraction of the starlight blocked out. So, the transit depth should be reduced by a factor of four.

Note that the *amount* of starlight being blocked hasn't changed – the planet is still the same size so has the same cross-sectional area. The transit depth though measures the *fraction* of starlight being blocked.

Adjust the stellar radius to R_{star} = 1.24 R_{Sun} (check that the other sliders are set to the values R_{planet} = 1.75 R_{J}; P_{orb} = 10 days; i = 90°).

What value of transit depth do these choices lead to?

Answer

The transit depth is 2.10%.

If you double the radius of the star to 2.48 R_{Sun}, what value would you expect for the transit depth? Explain your reasoning.

Answer

The transit depth should be reduced by a factor of four, so you would expect a value of 2.10% ÷ 4 = 0.525%, which can be rounded to 0.53%. You can confirm this with the application.

Adjust the stellar radius to R_{star} = 0.60 R_{Sun} (check that the other sliders are set to the values R_{planet} = 1.75 R_{J}; P_{orb} = 10 days; i = 90°). Note that the star's radius is just over half its initial value.

What is the value of the transit depth now?

Answer

A transit depth of 8.97%.

If the star's radius was reduced, you would expect the transit depth to be bigger than it was originally.

Does this value agree with the predictions of Equation 3? Explain your reasoning.

Answer

If the star’s radius is reduced, you would expect the transit depth to be greater than it was originally. Compared with the original value, R_{star} = 1.24 R_{Sun}, the size of the star has been roughly halved. Equation 3 says you should expect the transit depth to be about four times deeper, i.e. it should be about 2.1% × 4 = 8.4%. Because the star is slightly less than half its original size, the transit depth is slightly deeper than 8.4%.

Discussion

If you are keen on calculations, you can work out the exact value of $(1.24/0.6)^2$ and check the answer given.

Adjust the values of R_{star}, and check that the transit depths you obtain always behave as predicted by Equation 3.

Now, suppose that an astronomer has been observing a distant star over a number of weeks, monitoring its brightness. The light curve for the star shows regularly repeating dips that occur every 5.2 days. These dips have the same flat-bottomed shape as Figure 12. Averaging them together, the dips in brightness are measured to be 1.4%.

What is likely to be causing these regular dips in the brightness of the star?

Answer

A transiting planet with an orbital period of 5.2 days.

The star undergoes further study using a telescope with a spectrograph. The patterns of absorption lines in the star’s spectrum show that it is an F-type main sequence star, which have radii of 1.3 R_{Sun}.

Use the interactive simulation to find out what the radius of the planet could be.

Answer

1.5 R_J.

Note that the shape of the dips shows that it is not a grazing transit, so the orbital inclination must be greater than about 85°.

4 This week’s quiz

Well done – you have reached the end of Week 4. It’s now time to complete the Week 4 badge quiz. It is similar to previous quizzes but instead of 5 questions there are 15.

Week 4 compulsory badge quiz

Remember, this quiz counts towards your badge. If you’re not successful in passing it you can have another go in 24 hours.

Open the quiz in a new tab or window (by holding down Ctrl [or Cmd on a Mac] when you click the link).

5 Summary of Week 4

This week you've learned about transiting planets both inside and outside the Solar System. You have seen how transits can be used to find and measure the size of exoplanets. You've learned how the transit depth is measured, and how that depends on the relative sizes of the star and the planet in question.

You should now be able to:

- state which planets in the Solar System are observed to transit the Sun, and explain why
- outline how transits can be used to identify exoplanets and measure the size of stars and planets
- state the relationship between radius and cross-sectional area for a sphere
- show you understand the size ratio between the Sun, Jupiter and Earth
- describe the relationship between transit depth and the ratio of radii of the planet and star $(R_p / R_{star})^2$.

You are now halfway through the course. The Open University would really appreciate your feedback and suggestions for future improvement in our optional end-of-course survey, which you will also have an opportunity to complete at the end of Week 8. Participation will be completely confidential and we will not pass on your details to others.

Next week you will be learning more about how to measure the properties of individual planets using the transit technique and the radial velocity technique that you learned about in Week 3.

You can now go to Week 5.

Week 5: How to measure your exoplanet

Introduction

Over the last two weeks you've learned two methods for detecting exoplanets: radial velocity and transits. This week, you're going to look in more detail at the first transiting exoplanet to be discovered, HD 209458 b, and learn how astronomers have measured its properties.

Watch the following video with Carole Haswell.

Video content is not available in this format.

By the end of the week, you will be able to:

- know HD 209458 b was the first transiting exoplanet
- explain how astronomers measure an exoplanet's size and mass
- appreciate the importance of transiting exoplanets
- describe the numbers of exoplanets discovered by the transit and radial velocity methods
- know that close-in exoplanets are more likely to transit.

1 The first transiting planet – HD 209458 b

The idea that an exoplanet might be detectable when it transits its star was first suggested in the 1950s. This was proved in 1999 when HD 209458 b became the first transiting exoplanet to be detected, four years after 51 Pegasi b was discovered by the radial velocity method. HD 209458 b orbits the star HD 209458, which is just a catalogue number.

Like 51 Pegasi b, HD 209458 b is very unlike any planet in our Solar System. Its orbital period is just three and a half days so it orbits very close to its parent star. This means it's extremely hot – like 51 Pegasi b, HD 209458 b is one of the new class of planets called hot Jupiters. Figure 1 is an artist's impression of exoplanet HD 209458 b passing in front of its parent star.

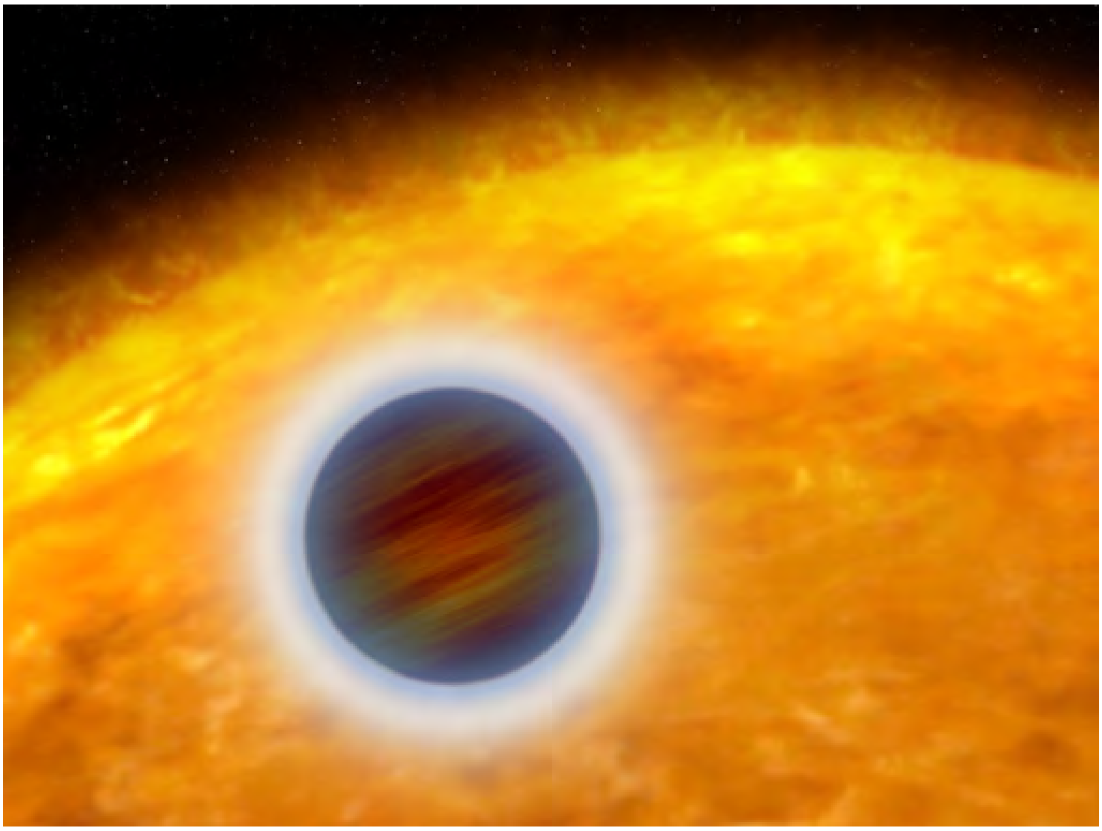


Figure 1 Artist's impression of HD 209458 b

2 Hot Jupiter transits are easy to measure

Astronomers in the 1950s realised that the transits of planets like Jupiter could be detected if a star was being continuously observed when the transit occurred. Of course, Jupiter transits only once every 12 years, and there is a less than one in 1000 chance of the orbit being lined up enough for transits of Jupiter-like planets to be seen at all (more on this later). With 1950s technology, observing thousands of stars continuously for years was utterly impossible, so no one tried. With twenty-first-century technology – digital cameras, cheap large-scale data storage and powerful computer processing capabilities – transits of hot Jupiters are easy to measure.

2.1 HD 209458 b transit: discovered in a car park

HD 209458 b was originally discovered using the same technique that found 51 Pegasi b, the radial velocity method. However, things became really interesting when a group of astronomers working on the STARE (Stellar Astrophysics and Research on Exoplanets) project used a small telescope, set up in a car park outside a laboratory in Boulder, Colorado, to literally 'stare' at the star HD 209458.

What did they see?

Suddenly, the star dropped in brightness by about 1 per cent. It stayed fainter for around three hours, then the brightness increased again to the original level. This was the first detection of a transiting exoplanet.

Figure 2a shows the light curves of the first two observed transits of HD 209458 b. They have been shown on top of each other to make the shape of the transit light curve clearer. Figure 2b is the telescope that discovered the transit of HD 209458 b.

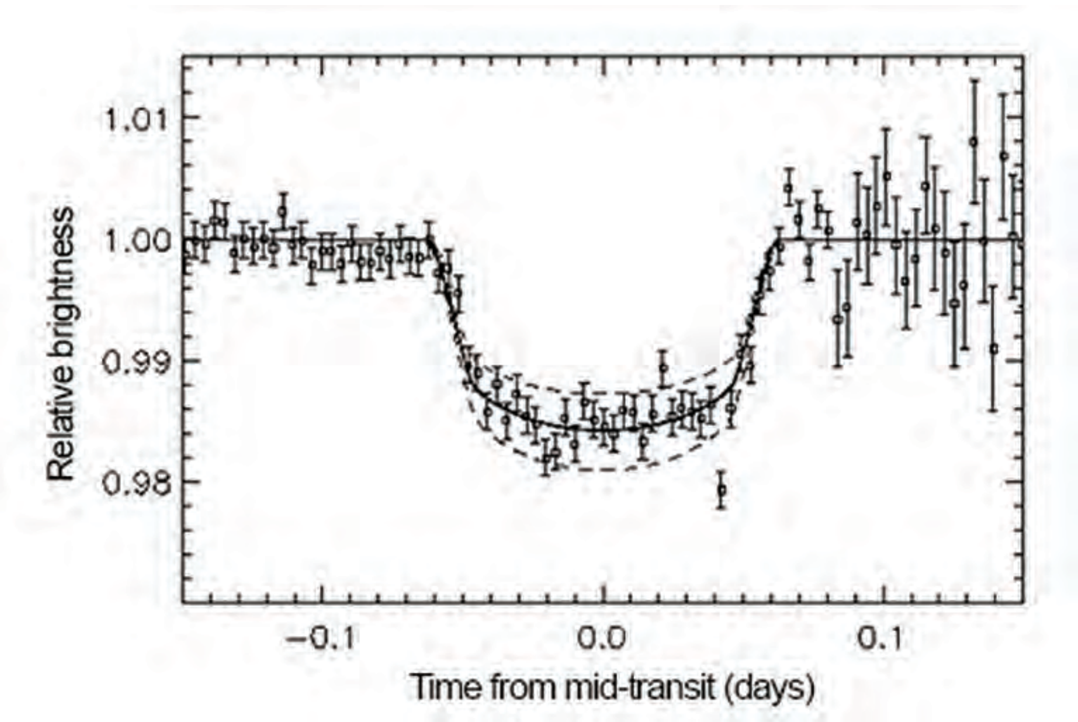


Figure 2a HD 209458 b transit light curve

Figure 2b STARE telescope

2.2 WASP: Wide area search for planets

After HD 209458 b was discovered, the search was on for further transiting exoplanets. Over the next few years there were more discoveries, including OGLE-TR-56 b, the first exoplanet to be discovered via its transits in 2002. Astronomers quickly realised that dedicated telescopes could find many more of these fascinating planets, and so the SuperWASP survey was born.

In Week 4 you watched a video about the WASP survey and how it works. You will recall that the WASP cameras capture a wide area of sky in a single exposure, enabling the brightness of many stars to be monitored simultaneously. In 2006, the first two WASP discoveries, WASP-1 b and WASP-2 b, were announced. Both of these are Jupiter-sized planets orbiting close to their parent stars. Since then, WASP telescopes in the northern and southern hemispheres have discovered around 200 planets, all of them giant planets orbiting fairly close to their stars.

3 The names of transiting planets

The first planet discovered by the WASP project was called WASP-1 b, the second was called WASP-2 b, and so on. In general, transiting exoplanets are named after the project that discovered them, and their host stars are renamed accordingly. So, the hyphen and number forms part of the new name for the star which hosts the exoplanet. Before its exoplanet was discovered, the star WASP-1 was known only by its catalogue number: GSC 02265-00107. WASP-1 b is a more memorable name for a planet than GSC 02265-00107 b!

As you've already seen with HD 209458 b, sometimes transiting planets are known simply by their star's catalogue number. This is most likely to happen if the planet was discovered by radial velocity observations before the transits were detected. These examples follow the naming convention described in Week 3.

4 How to measure an exoplanet's size and mass

Why are transiting planets so special? What can you learn about them?

The key advantage held by studies of transiting exoplanets is that astronomers have a measurement of the exoplanets' size relative to their stars. For planets that don't transit, it isn't possible to measure their physical size, so transiting planets can give us much more information than other planets can.

4.1 Transit depth gives size

Last week you learned how to interpret transit light curves. By measuring the brightness of the star before and during the transit you can work out how much starlight is blocked by the planet, and therefore the relative sizes of the planet and the star. What you measure directly is the transit depth – the fractional amount of light missing (usually expressed as a percentage). Last week we worked out that the transit depth reveals the ratio of cross-sectional areas for the planet and the star, which is the same as the squared ratio of the planetary and stellar radii:

(Equation 1)

We'll briefly revisit the interactive application from last week that calculates transit depths for us and then you will be invited to have a go at using Equation 1 for yourself.

Activity 1 The transit depth of a familiar planet

Allow about 10 minutes

Interactive content is not available in this format.

Using this interactive application, set R_{star} = 1.00 R_{Sun} and R_{planet} = 1.00 R_J. You can also use the arrow keys on the keyboard to amend the values.

1. To which familiar planet do these sizes correspond?

Answer

These sizes are those of Jupiter and its star, the Sun.

2. What transit depth would an extraterrestrial astronomer see if they measured the brightness of the Sun while Jupiter passes exactly between them and the Sun?

(Remember that the transit depth is usually expressed as a percentage of starlight blocked.)

Answer

If Jupiter passes exactly between the Sun and the extraterrestrial astronomer then the orbital inclination is i = 90°. According to the interactive application this gives a transit depth of 1.05%. If you estimated it from the graph you probably said 1%.

Note that the orbital period of Jupiter is very different from the value indicated, but for working out the transit depth it is only the size ratio that matters. Equation 1 tells you the transit depth depends *only* on the two radii.

In Activity 1 you saw that Jupiter's transit depth is about 1%. You can generalise this to say any Jupiter-sized planet orbiting a Sun-sized star will produce a transit depth of about 1%.

4.2 Planet sizes with a pocket calculator

Once you begin comparing and contrasting different giant exoplanets, you need to be a bit more precise than 'about 1%'. The interactive application you worked with in Activity 1 performs precise calculations using Equation 1, and you can go back to it and use it for other examples. If you are confident with maths, you can also use Equation 1 yourself.

If you want to calculate the radius of a transiting planet then you need to rearrange the equation to give:

(Equation 2)

means take the square root of the quantity under the sign.

If you put in a transit depth of 1% (i.e. 0.01, expressing '1%' as an ordinary number) and a star of radius 1 R_{Sun} then this would become:

(Equation 3)

(Equation 4)

In the step between Equations 3 and 4 we have taken the square root of 0.01. This is correct because if you square 0.1 you get 0.1 × 0.1 = 0.01, as you can check using a calculator. Equivalently, your calculator will tell you that . Try it if you are unsure!

Equation 4 is simply telling you that the radius of Jupiter is about one-tenth that of the Sun or, equivalently, that the radius of the Sun is about ten times that of Jupiter, which is just what you found in Activity 2 in Week 4. If you use a calculator to put in precise numbers for the transit depth and the radius of the star, Equation 2 will give you a precise number for the radius of the transiting planet.

4.3 The radial velocity see-saw gives mass

If the star is bright enough and the planet is massive enough, which is indeed the case for many of the transiting planets discovered from the ground, then astronomers can use the radial velocity (RV) method to measure the mass of the planet. You learned about the RV method in Week 3. In a nutshell: as the planet orbits the star, the star wobbles, creating a Doppler shift in the light from the star. This produces tiny changes in the wavelengths of the fingerprints in the spectrum of the star. These tiny changes are measurable and can be used to work out the mass of the planet.

With both the radius and the mass of a planet we can work out a really useful quantity – its density. This gives us a good idea what the planet is actually made of, as you learned in Week 2. You'll look at this idea in more detail later this week.

Activity 2 How the radial velocity reveals the planet mass

Allow about 15 minutes

This interactive application is set up to simulate the radial velocity curve for one of the hottest of the known hot Jupiters, a planet called WASP-12 b. Its orbital period is just 26 hours! The star WASP-12 has a mass of 1.35 M_{Sun}, and this value for the star's mass doesn't change. The planet transits and so the inclination is close to 90°.

Interactive content is not available in this format.

WASP-12 b completes an orbit in just over a day – 1.09 days to be precise, measured from the time between the transit dips in the light curve.

1. What is the value of 1.09 days expressed in units of years?

Answer

You need to work out what fraction of a year is equal to 1.09 days. There are 365.25 days in a year – the 0.25 comes from the leap day inserted every four years. So the number required is 1.09 ÷ 365.25 = 0.003 rounded to 3 decimal places.

If you know the mass of the star and the orbital period, you can work out the distance between the star and the planet. This comes from Kepler's Third Law, which was mentioned in Week 3. It is probably the most important equation in astronomy, and the interactive application you are using is calculating its consequences.

Using the slider, adjust the value of a_{planet} until the orbital period is 0.003 Earth years. You can also use the arrow keys on the keyboard to amend the values.

2. What value of a_{planet} is needed to make the orbital period equal to 0.003 Earth years?

Answer

The application gives a small range of possible values centred on about 0.025 AU.

The green graph shows how the measured radial velocity for WASP-12 would behave if you made a continuous series of measurements. As you saw in Week 3, for an orbital inclination of exactly 90° you see the star move exactly towards you and exactly away from you once per orbit. By comparing the maximum and minimum observed values of the radial velocity, you can work out how fast the star is moving because of the pull of the orbiting planet.

The star moves faster if the planet has more mass, as you will see if you move the slider to adjust the planet mass. Precise measurements of the star's radial velocity give you precise measurements of the mass of the orbiting exoplanet. This is true even though you can't see the planet itself.

Observations of WASP-12 show it has an orbital speed of 226 m/s, measured from the radial velocity curve which is derived from the size of the wavelength changes in the spectra. Use the slider to adjust the value of M_{planet} until the stellar orbital speed is 226 m/s.

3. What value of M_{planet} is needed to make the stellar orbital speed 226 m/s?

Answer

M_{planet} = 1.46 M_J

(Your answer may be slightly different from this – you should get this value when a_{planet}= 0.025 AU.)

4.4 Applying this to HD 209458 b

Now you've reminded yourself of how to work out a planet's radius and mass, it's your turn to become a planet investigator. What is the first transiting exoplanet, HD 209458 b, like?

Activity 3 Become a planet investigator – what is HD 209458 b like?

Allow about 15 minutes

Part 1 The radius

HD 209458 b orbits a star only very slightly larger than the Sun, and has a transit depth of around 1.46%. Remember, in Activity 1 you learned that Jupiter orbiting the Sun would have a transit depth of 1.05%. Based on these numbers, and assuming that you use 1 R_{Sun} for the stellar radius, can you work out the approximate radius of HD 209458 b in terms of R_J?

Hints

Look back at Equation 2. This tells us that the radius of the planet, R_p, depends on the radius of the star and on the square root of the transit depth. To work out the radius of HD 209458 b in terms of Jupiter we can put in relative values that compare the HD 209458 system with the Jupiter–Sun system. We're assuming that HD 209458 is the same size as the Sun, so the relative value for R_{star} is just 1. What is the relative value for the transit depth?

If you are stuck you can go back to Activity 1 and use the interactive application there to do the calculation.

Answer

Answer: 1.2 R_J

Equation 2 is

The transit depth for HD 209458 b is 1.46% ÷ 1.05% = 1.39 times the transit depth for Jupiter. So, the radius of HD 209458 b in units of Jupiter radii is

Therefore, HD 209458 b has an approximate radius of 1.2 R_J based on this simple comparison with Jupiter. In fact, because the star HD 209458 is actually a bit bigger than the Sun, the real radius of HD 209458 b is about 1.3 R_J.

Part 2 The mass

The mass obtained for HD 209458 b from radial velocity measurements is 1.35 × 10^{27} kg. Remember, Jupiter's mass is 1.90 × 10^{27} kg. What is the mass of HD 209458 b in M_J?

Answer

To find the mass of HD 209458 b in Jupiter masses, divide its mass in kilograms by the mass of Jupiter in kilograms:

Part 3 The density

You'll have noticed that HD 209458 b has a larger radius, and therefore volume, than Jupiter, but a smaller mass. What does this mean for the density of HD 209458 b? Is it less dense or more dense than Jupiter?

Answer

Answer: Less dense

HD 209458 b has a smaller mass but larger volume than Jupiter. This means that it is less dense than Jupiter – there is less mass in each cubic centimetre.

5 Transits from space

Ground-based surveys like SuperWASP have been very successful in detecting transiting exoplanets, but they are working with two major disadvantages – both of which can be overcome by heading into space. Space missions are expensive though, so how are transit surveys in space justified?

5.1 Continuous observations

The first difficulty with a telescope on the ground is the impossibility of making truly continuous observations. As the Earth rotates, different parts of the sky go in and out of view from any particular telescope. The video clip below shows this, with some dramatic footage of the Milky Way moving across the sky as the Earth rotates. But with transits you can't just observe the star at any old time – it has to be when the planet is transiting. If you haven't detected a planet yet you don't know when it's going to transit! For this reason, it's really useful to be able to continuously measure the brightness of the star you are studying. This is possible from some telescopes in space (but not all – it depends on the orbit that the space telescope itself follows).

This video shows the motion of stars in the night sky as the Earth rotates underneath.

Time-lapse photography of the night sky

5.2 Prevent the stars from twinkling

As you've seen in Section 2, hot Jupiter transits *can* be measured from the Earth with inexpensive equipment. However, there is a problem: the air we breathe interferes. Earth's atmosphere tends to get in the way of light coming from space, especially if conditions are humid and there is a lot of water in the atmosphere. You can see this in action when you look at a bright star – the star often appears to twinkle. That twinkle is caused by atmospheric currents that cause the air you're looking through to move.

The animation in Figure 3 shows how the motion of air currents in Earth's atmosphere can cause stars to appear to twinkle – to apparently flicker or very slightly change their positions. As you might imagine, this effect makes it difficult to get a really precise measurement from the ground of how much light is coming from the star.

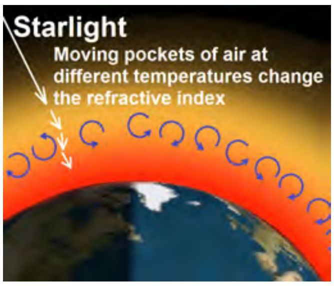


Figure 3 Why stars twinkle

Telescopes in space, however, don't have this problem. Compare the light curve of HD 209458 b from the ground with the one taken by the Hubble Space Telescope (Figure 4).

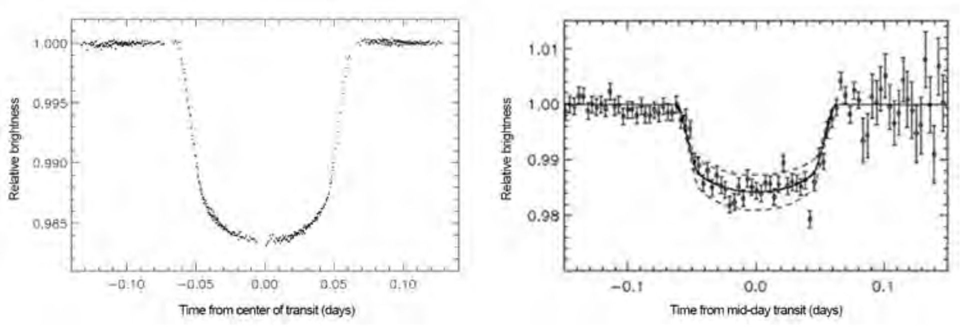


Figure 4 Light curves of HD 209458 b from space and from the ground

The right-hand panel shows the transit of HD 209458 b as observed from the ground, and the left-hand panel shows the transit observed using the Hubble Space Telescope. Observing from space allows much more precise measurements.

5.3 Small rocky planets

You've seen that the smaller the planet, the smaller the dip in brightness when a transit occurs. It is perfectly easy to detect the transit of a Jupiter-sized giant planet from the ground. But it turns out that from the ground it is nearly impossible to detect the transit of an Earth-sized planet across a Sun-sized star – you just can't measure precise enough light curves.

Activity 4 The transit depth

Allow about 10 minutes

For a star approximately the same size as the Sun and a planet approximately the same size as Jupiter, the transit depth is roughly 1%.

What would be the transit depth if the planet radius was:

1. Half the size of Jupiter's radius? (Hint: think about how the cross-sectional area of the planet would change – you may find Equation 1 useful.)

Provide your answer...

Answer

Answer: 0.25% or ¼%

The cross-sectional area of the planet depends on the square of its radius. If the radius is halved then the area will be quartered (1/2 × 1/2 = 1/4).

This means that the transit depth will also be quartered. The transit depth for Jupiter is roughly 1%, so the transit depth for this smaller planet will be about 1/4%.

If you prefer, from Equation 1, if R_p is halved and R_{star} stays the same then the ratio R_p/R_{star} will be halved, and so $(R_p/R_{star})^2$ will be quartered.

2. One-third the size of Jupiter's radius?

Provide your answer...

Answer

Answer: 0.111% or 1/9%

The cross-sectional area of the planet depends on the square of its radius. If the radius is multiplied by 1/3 then the area will be multiplied by 1/3 × 1/3 = 1/9.

This means that the transit depth will also be multiplied by 1/9. The transit depth for Jupiter is roughly 1%, so the transit depth for this smaller planet will be about 1/9%.

3. One-tenth the size of Jupiter's radius?

Provide your answer...

Answer

Answer: 0.01% or 1/100%

The cross-sectional area of the planet depends on the square of its radius. If the radius is multiplied by 1/10 then the area will be multiplied by 1/10 × 1/10 = 1/100.

This means that the transit depth will also be multiplied by 1/100. The transit depth for Jupiter is roughly 1%, so the transit depth for this smaller planet will be about 1/100% or 0.01%.

Remember, Earth is approximately one-tenth the radius of Jupiter, so its transit would be 100 times smaller – a transit depth of just 0.01% of the light from the star! This would be pretty tricky to measure from the ground.

5.4 CoRoT and Kepler: into space for planets galore

As detecting transits is much easier from space, the European Space Agency (ESA) launched a space telescope into Earth orbit in 2006, the first space telescope dedicated to observing transiting exoplanets. This CoRoT satellite discovered its first planet, CoRoT-1 b, a few months later. A notable highlight was the discovery of CoRoT-7 b, the first exoplanet believed to have a rocky composition.

NASA's answer to CoRoT, Kepler, followed in 2009. Its mission was simple: to detect as many transiting exoplanets as possible in a single patch of sky. Because Kepler orbited the Sun rather than the Earth, it was capable of staring at the same patch of sky without a break, whereas CoRoT could only look at the same part of sky for up to 150 days at a time. Figure 5 is an artist's impression of the five-metre-long Kepler space telescope in its orbit around the Sun, trailing behind the Earth.

Figure 5 The Kepler space telescope

The bit of sky chosen for Kepler's primary mission was a part of the constellation Cygnus, the swan. Figure 6 shows Kepler's field of view – the patch of space it stared at – overlaid on an image of the night sky. It is located over one of the swan's wings. That patch of sky alone contains around half a million stars close enough to be visible to Kepler, and was covered by 42 separate detectors on the spacecraft.

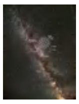


Figure 6 Kepler's field of view

After nearly a decade of planet hunting, Kepler was retired in October 2018. By this time, Kepler had discovered the transits of over 2600 planets – roughly two-thirds of all the exoplanets discovered to date – as well as many other interesting objects. In future weeks, you'll learn more about some of these planets, and about how the planets discovered by Kepler have been used to estimate the total population of planets in our Galaxy.

And in Week 8 you will learn about Kepler's replacement, TESS, which was launched in April 2018.

5.5 Mass measurements for Kepler planets

Because Kepler stared at all the stars in a particular small region of sky, most of the stars it studied are faint. The radial velocity method needs the starlight to be spread out so the tiny changes in the wavelengths of the chemical fingerprints can be measured. This is quite difficult to do when the star is so far away and consequently so faint: there is simply not enough light to spread out in this way. Radial velocity measurements require large telescopes and specialised equipment. The telescope must be dedicated to making a radial velocity measurement of only one star at a time. This is in stark contrast to a transit search like Kepler, which simultaneously measured the brightness of about 150 000 stars.

So, while Kepler has discovered a *lot* of planets, most of them have not had radial velocity measurements of their masses.

One of the most interesting new things Kepler revealed was that many stars host several transiting planets. When there are several planets, these have gravitational pulls on each other. This can cause the planets to slightly speed up or slow down in their orbit. When this happens, the planets' transits arrive slightly early or slightly late. These transit timing variations can be used to work out how strong the gravitational attraction between the planets must be. From this, astronomers can then work out how massive the planets must be.

A few of the Kepler planets do have known masses, if they are bright enough for the radial velocity method to be applied or if the method using transit timing variations can be applied precisely, but the majority have unknown masses, or masses that have considerable uncertainty. This makes it more difficult to know what the planets are really like.

5.6 The population of known transiting planets

In Week 3 you looked at the Extrasolar Planets Encyclopaedia on the Exoplanet.eu website. At that time you just investigated radial velocity planets. This time, you'll look at the planets detected by the transit method.

Activity 5 Exploring Exoplanet.eu – this time it's transits

Allow about 10 minutes

Go to the Exoplanet.eu website and click on the link labelled 'All Catalogs'. This will take you to the Catalog screen. Below the word 'Catalog' you will see a drop-down menu labelled 'Detection'. Click on this and select 'Primary Transit' to see all the transiting planets in the catalogue.

A little lower down, on the left-hand side of the screen, there is another drop-down menu that says 'Show 100 entries'. Change this to 'Show All entries'. If you scroll down the list you'll notice that many of the transiting planets were discovered by the Kepler spacecraft, and so are named 'Kepler' with a numerical identifier afterwards.

As you saw in Section 3, other groups of transiting planets are also named after the project that discovered them.

From the list of transiting planets given at Exoplanet.eu, identify some of the other transit search projects. Note their names in the box below before looking at the answer.

Provide your answer...

Answer

Transit search projects generally name their planets with a name or an acronym, followed by a hyphen that connects it to a number, which in turn is followed by a space and a lower-case letter; e.g. WASP-1 b. Projects using this naming convention include EPIC, K2, HATS, HAT-P, KELT, WASP, XO, CoRoT and Qatar.

Make a note of the number of planets discovered by:

i. their transits
ii. the radial velocity method.

Hint: use the ‘Detection’ drop-down menu to filter the results.

Provide your answer...

Why do you think so many more planets have been discovered using the transit method than any other? Why is the radial velocity technique more difficult?

Provide your answer...

Answer

Radial velocity measurements can only be made for bright stars by spreading the light. This requires large telescopes and specialised equipment that look at only one star at a time.

Transit searches observe many thousands of stars simultaneously, and are looking for a drop in the total amount of light from a star. This is an easier thing to measure than a small wavelength shift.

6 Close-in planets

In this section you will look at planets that orbit close to their parent star and you will find out how hot they are.

6.1 Close-in planets are easiest to find

One thing that really stands out about the transiting planets is how incredibly close most of them are to their parent stars. This isn't just a fluke of the systems viewed by Kepler – the same is true of other transiting planets. Remember, HD 209458 b orbits its star in just three and a half Earth days.

The following video is an animated montage of the orbits of the 726 Kepler systems with multiple transiting planets. These systems with several planets are some of the most interesting that Kepler has discovered. The orbits of the Solar System planets are shown on the same scale with dashed lines, but the planets themselves aren't to scale – there is a key showing how the sizes of the planets are represented. The colours represent the surface temperature of the planets based on the temperature and distance of their parent star.

View at: youtube:Td_YeAdygJE

Video 1 Kepler Orrery V (Please note this video has no spoken audio.)

It's very easy to see that the Kepler exoplanets orbit much closer to their stars than the planets in the Solar System, resulting in extremely compact systems.

What's going on here? Is our Solar System especially strange? No. There are probably plenty of stars out there with planets orbiting as far out as Jupiter or even Neptune. It's just much harder to spot them when they transit.

Imagine a child playing hide and seek in the garden where there's a decent-sized tree to hide behind. The child always chooses to stand directly behind the tree, instead of at a distance from the tree where the seeker could easily move a little bit to their left or right and see him or her.

The same thing happens for exoplanets in wide orbits. Unless the planet's orbit is tilted by exactly the right amount, you will not see it transit, just as the child can't successfully hide a long way behind the tree. But if the planet is in a tight orbit, like most of those found by Kepler, even if the system isn't perfectly aligned there's still a good chance it will transit. Of course, rather than hiding behind the star, the transiting planet is 'hiding' in front of the star from our point of view!

Figure 7 shows why close-in planets have a higher probability of transiting than planets which are further away from their star. Here we see that the range of angles from which we can observe the closely orbiting planet b transiting its star is much greater than the ranges of angles from which we observe transits for planet c in a wider orbit.

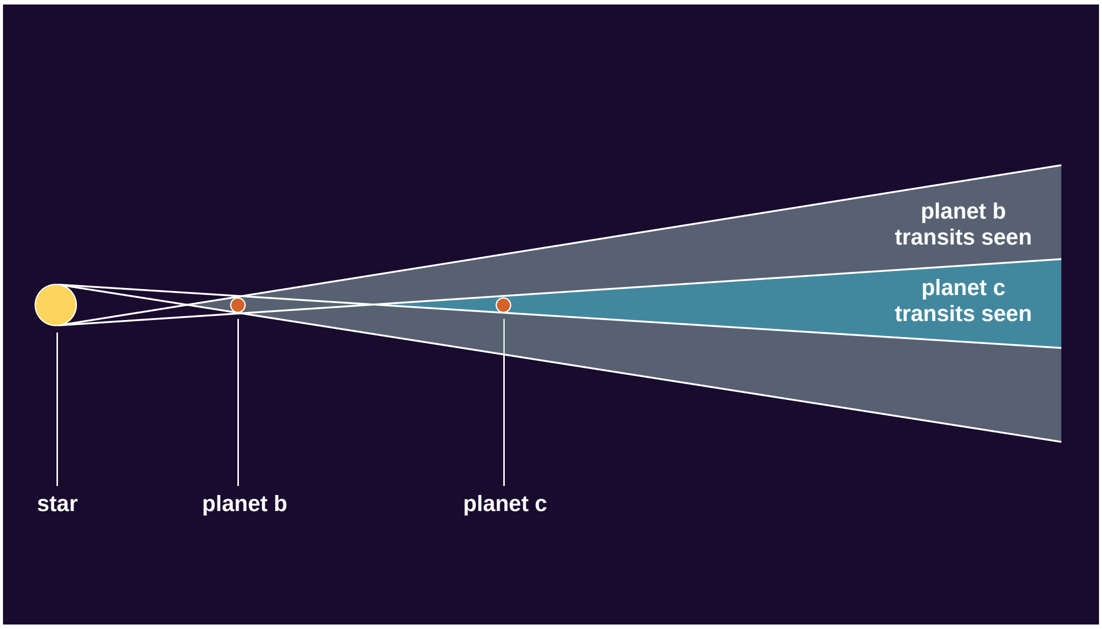


Figure 7 Transit probability

So, close-in planets are the most likely ones to transit, but there is also another reason why it's easier to find close-in planets. Like HD 209458 b, hot Jupiters have incredibly short 'years', many taking fewer than five Earth days to orbit their parent stars. Because they complete their orbits quickly, they also transit more often than planets further away from their star. Both of these facts make it particularly easy to find close-in transiting planets. So, it is no surprise that most of the ones that have been found are close-in.

6.2 Close-in planets are hot, hot, hot!

Before 51 Pegasi b was discovered, we had no idea that hot Jupiters existed. In our Solar System, we're used to small rocky planets being close to the Sun, and large, gas giant planets inhabiting the much colder regions further out. It was generally assumed that extrasolar systems would form in a similar way to our Solar System and so would be structured similarly. This idea was completely turned on its head when the first exoplanets, including HD 209458 b, were discovered.

Because these planets are very close to their stars, they are incredibly hot. Temperatures on a more recently discovered hot Jupiter, KELT-9 b, are expected to reach 4300 °C – that's hotter than the surface of many stars!

Astronomers use a different measure of temperature than degrees Celsius, °C. Instead, they measure temperature in kelvin, or K. A temperature difference of 1 K is exactly the same as a difference of 1 °C, but the starting point of the temperature scale is different. 0 °C is the freezing point of water, equivalent to 273 K. 0 K is absolute zero – the coldest anything could possibly be according to the laws of physics. This temperature scale will be used in interactive applications shortly.

Mathematically, we can convert between these two temperature scales easily: simply add 273 to a temperature expressed in °C to express it in kelvin. Alternatively, subtract 273 from a temperature expressed in kelvin to obtain the corresponding value in °C.

6.3 How hot?!

How do you know how incredibly hot these hot Jupiter planets are? You can work out an estimate based on three things: how big their parent star is, how hot their parent star is, and how far away the planet is from their parent star.

We can think about how we'd expect the temperature at the surface of the planet to depend on these three things. A bigger, hotter star releases more energy which the planet absorbs, so the planet will be hotter. A planet that is further away will absorb less of this energy from its star and so it will be cooler.

The precise relationship between these properties and the surface temperature of the planet is complicated, but the following facts will help you do a bit of detective work.

1. If the temperature of the star is four times higher, then the temperature of the planet will be four times higher – the planet temperature is *proportional* to the star temperature.
2. If the radius of the star is four times greater, then the temperature of the planet will be twice as high. (This is saying that the planet temperature is proportional to the square root of the star's radius.)
3. If the distance between the planet and the star is four times greater, then the temperature of the planet will be halved. (This time the planet temperature is *inversely* proportional to the square root of distance from the star. Inversely proportional just means that if the first thing increases then the other decreases.)

Activity 6 Hotter or colder?

Allow about 15 minutes

The interactive application allows you to calculate the temperature a planet is expected to have based on the mass of its parent star and the planet's orbital distance from the star. This temperature is called the equilibrium temperature because it is calculated assuming that the planet is in a heat equilibrium, radiating exactly as much heat as it absorbs – it depends on the factors discussed above. The interactive application assumes the star is a main sequence star, and for main sequence stars the radius and temperature on which the calculation depends are specified by the star's mass.

HD 209458 is a 1.15 M_{Sun} main sequence star. HD 209458 b has a circular orbit of radius 0.05 AU. Adjust the sliders to these parameters.

Interactive content is not available in this format.

What is the planet equilibrium temperature of HD 209458 b?

Provide your answer...

Answer

Express the equilibrium temperature of HD 209458 b in °C.

Provide your answer...

Answer

1037 °C. Remember, to do the conversion, simply subtract 273. 1310 − 273 = 1037.

What happens if you increase the mass of the star?

Provide your answer...

Answer

Both the star and the planet get hotter.

What happens if you increase the planet's orbital distance from its star?

Provide your answer...

Answer

The planet gets cooler.

Reset the sliders to the values for HD 209458 b (1.15 M_{Sun} and 0.05 AU).

Can you work out what temperature HD 209458 b should be if it was four times as far from its star? Express your answer in kelvin. Use the interactive application to find out or check your answer.

Provide your answer...

Answer

With a_{total} = 0.2 AU, the interactive application gives 657 K. This is half the temperature of HD 209458 b (give or take a few – the precision of the sliders is not perfect!), in accord with fact 3 above.

Can you find different combinations of stellar mass and planet distance that produce planets with the same temperature as HD 209458 b?

Provide your answer...

Answer

Yes, you should be able to. If you increase the stellar mass, the planet becomes hotter. Then if you move the planet further away from its star until it cools to an equilibrium temperature of 1310 K, you can get a combination that fits. By playing in this way, you should be able to find an appropriate combination for every value of the stellar mass covered by the slider in the interactive application.

Maths help

The following OpenLearn resources may help with the maths in this section. Open the link in a new tab or window by holding down Ctrl (or Cmd on a Mac) when you click on the link. Remember to return here when you have finished.

- direct proportion (Section 2.2)
- inverse proportion (Section 2.3)

7 Density is key

In Week 3 you learned about measuring planet masses by measuring the amount by which the star wobbles – this is called the radial velocity method. More recently, you learned how to measure the radius of a planet using the transit method. In Section 4 this week you applied both these methods.

Transiting planets for which you also have radial velocity measurements are extremely important. Because you know the masses and radii of these planets, you can calculate their densities. Remember, the volume of a spherical planet is equal to $4.19r^3$, and the density is equal to the mass divided by the volume.

You learned about planet densities in Week 2. The densities of rocky worlds like Earth and Venus are higher than the densities of gas giant planets like Jupiter and Saturn. Density, therefore, gives you a clue about planet composition.

The Kepler spacecraft and other programmes have found several small planets that could possibly be rocky, and therefore Earth-like. Exoplanets have given astronomers lots of surprises though. Just because all the small planets in the Solar System are rocky doesn't mean all small exoplanets are rocky. Looking at the results of density calculations for small exoplanets, you can sort out the ones likely to be rocky. For the others, where the density is different from the density of rock, you can make an educated guess at what the composition might be.

Figure 8 shows the masses (on the horizontal axis, in units of Earth mass) and radii (on the vertical axis, in units of Earth radius) of some small exoplanets. The differently coloured lines on the diagram show the masses and radii planets would be expected to have for different compositions. Going from the top to the bottom, the planets get denser, going from worlds likely to be made of water and ices, to rocky 'silicate' worlds, to worlds made of solid iron. Silicate materials are the main constituent of rocks on Earth.

Note that water is unusual in that liquid water is more dense than water-ice (in the majority of cases, solids are more dense than liquids).

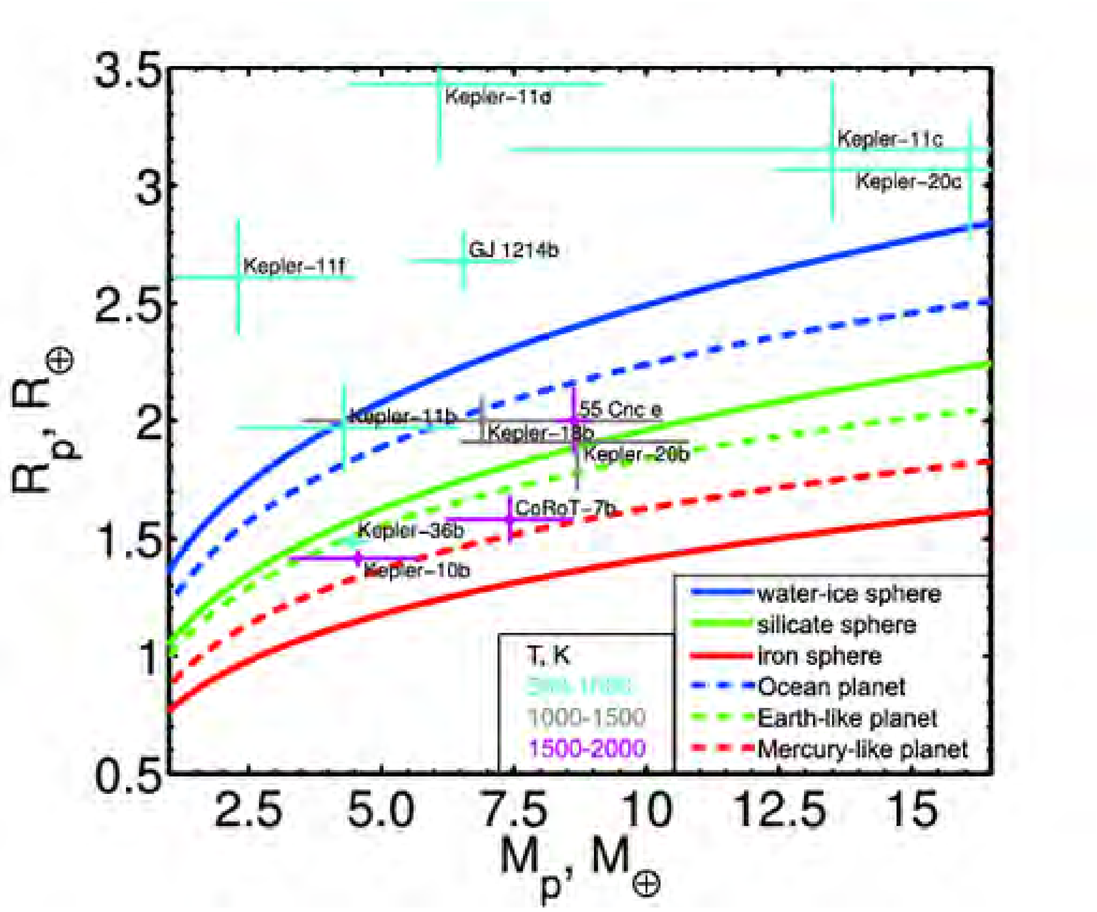


Figure 8 Densities of small exoplanets

Activity 7 Rocky or not?

Allow about 10 minutes

Based on their position on the diagram above (Figure 8), can you decide which of these planets might be rocky? (The crosshairs for each planet indicate the uncertainty in the measured mass and radius).

1. Kepler-11 c

Provide your answer...

Answer

No, it's density is less than that of a sphere composed purely of water-ice. This is shown by the fact that it's above the solid dark blue line in the diagram.

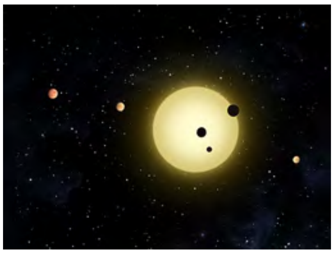


Figure 9 Artist's impression of Kepler-11 c and its five fellow planets in orbit around their host star. Five of the six planets so far discovered in the Kepler-11 system orbit well within Mercury's distance from the Sun. Sometimes more than one planet transits at a time.

2. 55 Cnc e

Provide your answer...

Answer

Yes, maybe, it's density is probably a bit less than a sphere composed entirely of silicate rock but more dense than one composed of water-ice.

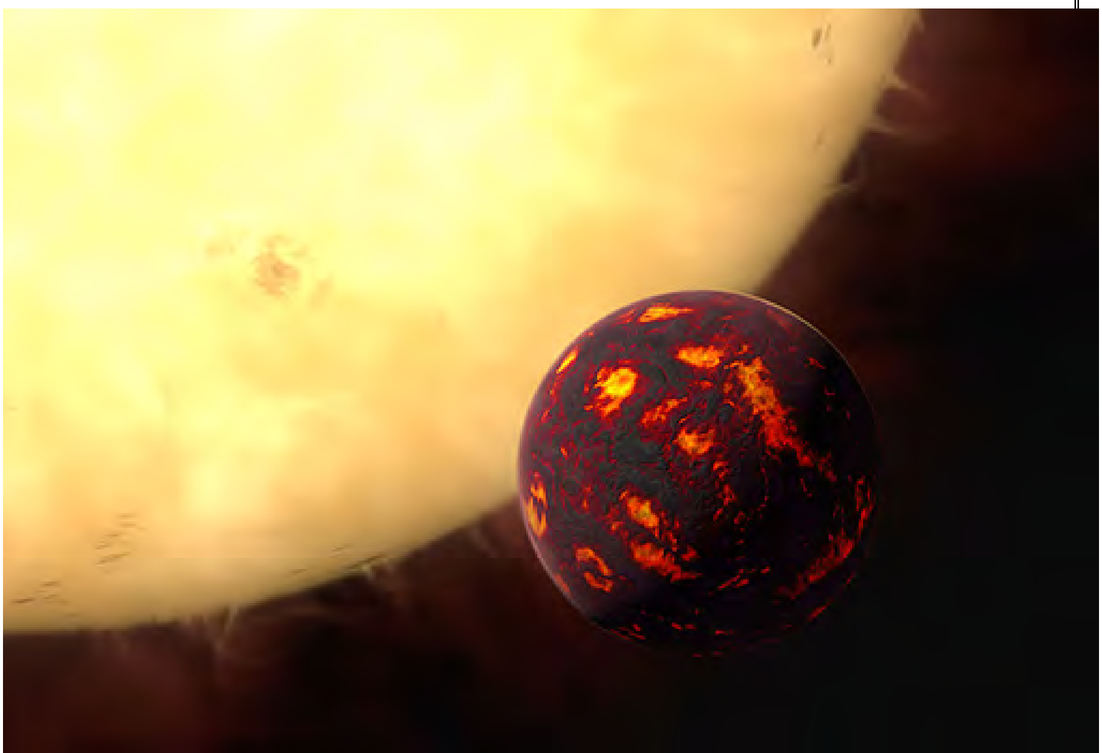


Figure 10 Artist's impression of the likely lava planet 55 Cnc e

3. Kepler-10 b

Provide your answer...

Answer

Yes, it has a density between those of Earth and Mercury.

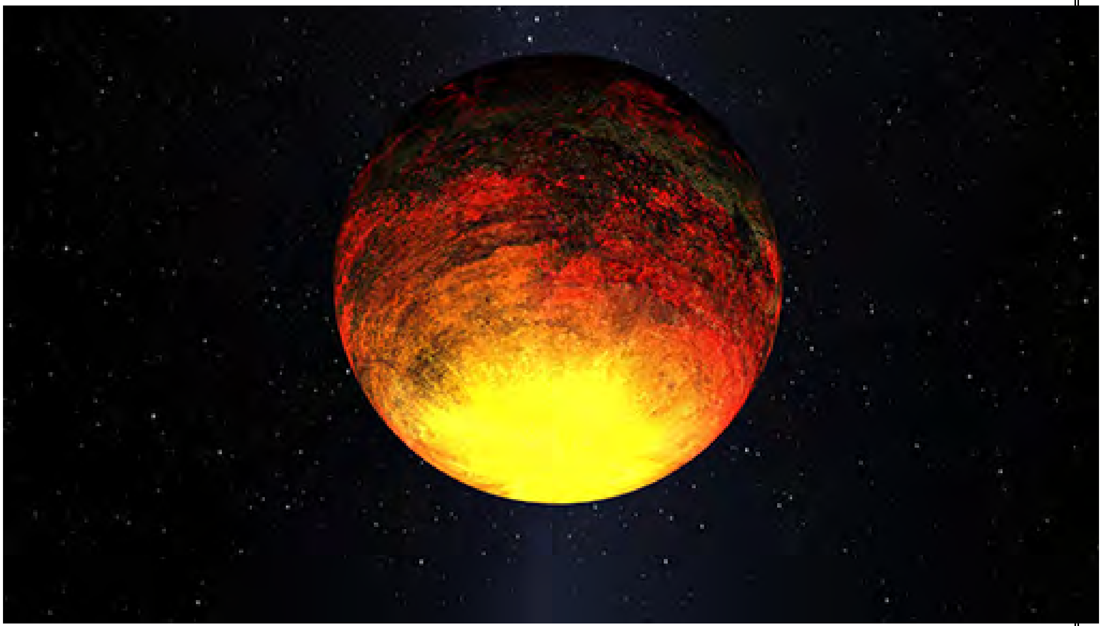


Figure 11 Artist's impression of Kepler-10 b, a rocky planet expected to be extremely hot due to its proximity to its star

4. GJ 1214 b

Provide your answer...

Answer

No, it’s density is less than that of a sphere composed purely of water-ice.

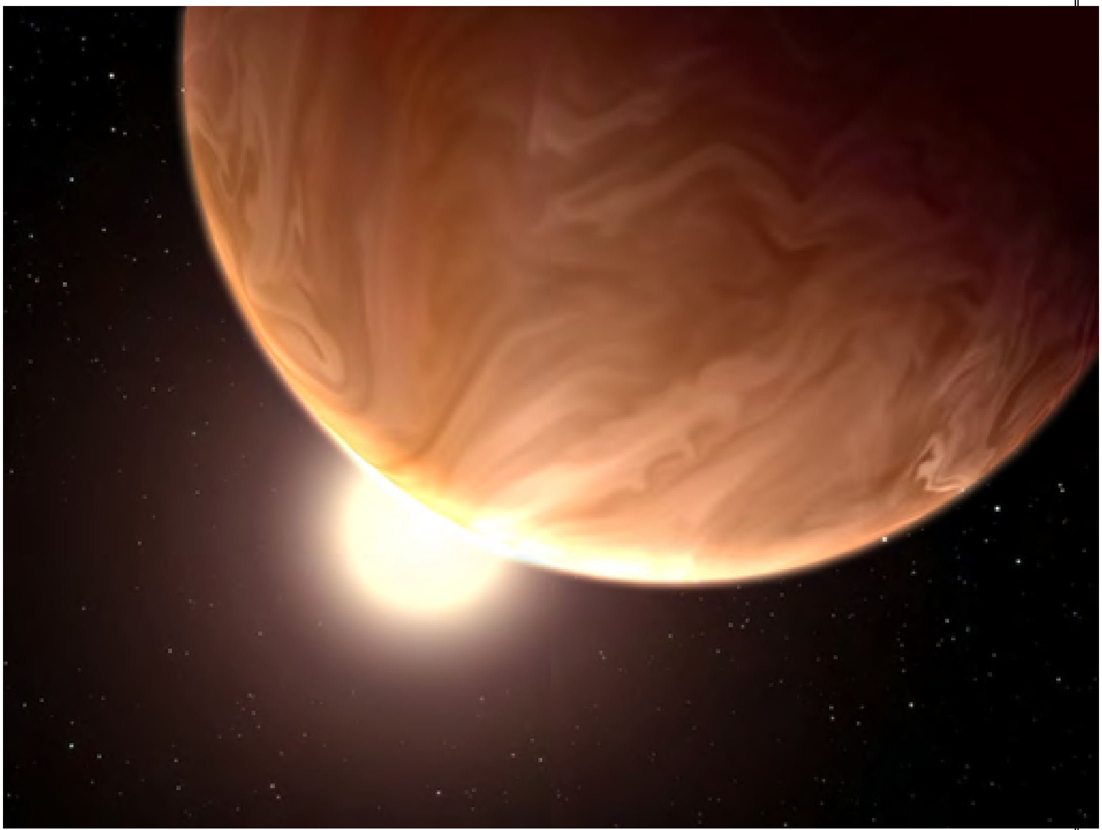


Figure 12 Artist’s impression of GJ 1214 b, a planet thought likely to be a cloudy miniature Neptune

8 This week’s quiz

Well done – you have reached the end of Week 5 and can now take the weekly quiz to test your understanding.

Week 5 practice quiz

Open the quiz in a new tab or window (by holding down Ctrl [or Cmd on a Mac] when you click the link).

9 Summary of Week 5

This week you have learned why transiting exoplanets are so important. Transiting planets are the only exoplanets with measured radii, which allows you to work out a lot more about them than you could otherwise. You have been introduced to the hot Jupiter HD 209458 b and learned about its key properties. You've also seen how efficiently you can find exoplanets using the transit method. Searching for transits from space with a purpose-built satellite called Kepler has resulted in discoveries of more than 2600 transiting exoplanets.

You should now be able to:

- know HD 209458 b was the first transiting exoplanet
- be able to explain how astronomers measure an exoplanet's size and mass
- appreciate the importance of transiting exoplanets
- be able to describe the numbers of exoplanets discovered by the transit and radial velocity methods
- know that close-in exoplanets are more likely to transit.

Next week you'll learn more about the findings from Kepler and what they mean for our understanding of planets in our Galaxy and the possibilities for extraterrestrial life.

You can now go to Week 6.

Week 6: Planets galore: the contents of the Milky Way

Introduction

Last week, you discovered how to measure the properties of exoplanets. You were introduced to some of the various surveys that have detected transiting exoplanets, in particular the Kepler spacecraft that has found around two-thirds of all the planets discovered to date. This week, you'll take a look at some of the important things we've learned from Kepler's mammoth haul of planets. This will lead on to the search for planets which may be habitable, the likelihood of finding another Earth-like planet, and ultimately, life out there.

Watch the following video to find out more about what you will be learning this week.

Video content is not available in this format.

By the end of this week, you will be able to:

- know that there are more planets than stars in the Milky Way
- explain in words how we know this
- describe the relative abundance of terrestrial and giant exoplanets

- know why some exoplanets are much easier to detect than others, using the radial velocity (RV) and transit methods for planet discovery
- understand the use of light years for measuring distance
- understand and explain in words the concept of a habitable zone
- explain why, despite their abundance, we know of relatively few terrestrial exoplanets.

1 Learning about the whole Galaxy

Kepler spent several years staring at only one relatively small region of the Milky Way. It has discovered over 2600 planets orbiting the stars in this patch of sky. We can use this information to reach conclusions about the whole of our Galaxy, not just a part of it. This is down to the sheer number and variety of stars that Kepler has monitored. Out of half a million stars available in the patch of sky Kepler stared at, 150 000 stars were selected for study by Kepler. The majority of these, around 90 000, are Sun-like G-type stars, but stars of other sizes and temperatures were also observed.

Because Kepler observed so many stars, astronomers have enough information to draw statistical conclusions about the number of different types of planets in the Galaxy. This assumes that the population of stars and planetary systems in the part of Cygnus observed by Kepler is typical of the rest of the Milky Way. This type of assumption is a common one in astronomy. It is reasonable because the laws of nature which govern how stars and planets form are the same everywhere (at least as far as we know!). To draw statistical conclusions, a large number of stars need to be studied: Kepler's 150 000 is enough.

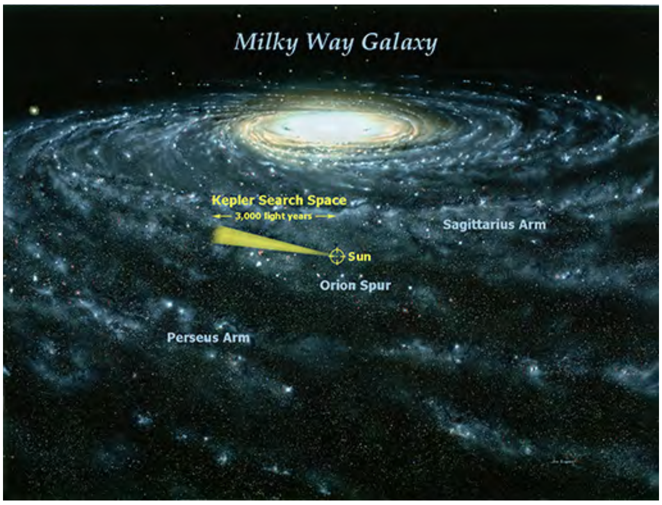


Figure 1 Kepler's search volume, shown by the yellow cone

This means that if we work out the number of planets observed by Kepler in the part of space it looked at, we can translate that to the number of planets in the whole of the Galaxy. We can also break the total planet haul from Kepler into subsets, each corresponding to a different type of planet. For example, we could count the number of small, almost certainly rocky, planets found by Kepler. From this we can work out how many rocky planets there are in our Galaxy.

2 How many planets?

So, just how many planets are there in the Milky Way? Kepler found over 2600 planets orbiting around the 150 000 stars it studied. Some of those planets are in multi-planet systems; so Kepler has found planets around fewer than 2600 stars.

It seems therefore that only a small fraction of stars have planets – 2600 is less than 2 per cent of 150 000. Yet, if you followed the headlines about Kepler's discoveries, you might have heard that there are more planets than stars in the Milky Way. So, what's going on?

2.1 Not all planets transit!

Kepler discovered planets by looking for transits. Of course, not all planets transit their parent stars from our point of view. Planetary systems are not all perfectly lined up. We know this because several planets we've discovered using the radial velocity method, like 51 Pegasi b, don't transit their stars from our viewpoint. It would also be very peculiar indeed if the orbits of all the stars in the Galaxy were lined up especially for us. Instead, it makes sense to assume that the orientation of the orbits of planetary systems are random. For each individual star and planetary system, the orientation will depend on the swirling motions of the gas cloud from which it formed, and these swirling motions are random.

The likelihood of a planet transiting relies on several factors. A key factor was introduced last week: the closer a planet is to its star, the more likely it is to be seen to transit. Basically, that just means that the system can be tilted at a greater angle before the planet no longer transits the star. Last week, this was compared to a child playing hide and seek behind a tree. It is much easier to hide if you stand close in, behind the tree, just as it is much more likely that a planet will be lined up so that it appears in front of its star if it is close to the star. Figure 2 is a photograph of a tree with two hidden children standing right behind it, with each child holding a puppet. If they had stood further back, behind the tree, it would have taken some skill to line everything up perfectly so only the puppets were visible.

Figure 2

Also, the larger the star is, the more likely it is for the planet to be seen to transit. This makes sense because if the star is bigger then there's more of a disc available for the planet to cross. In the hide-and-seek example, it's easier to hide behind a bigger tree!

Activity 1 Which planet is more likely to transit?

Allow about 5 minutes

1. Two stars, one the size of the Sun (A), and one 20 per cent larger than the Sun (B), each have a planet in orbit around them. Which planet is more likely to transit?

Answer

The planet orbiting around Star B is more likely to transit.

2. Two identical stars each host a planet. One planet takes two days to orbit its star (A), and the other takes four days to orbit its star (B). Which planet is more likely to transit?

Answer

The planet around Star A is more likely to transit as it is closer in.

3. Two stars, a G-type star and an M-type star, each host a planet in a five-day orbit. For which star are we most likely to see a transit? (Hint: you learned about star types and their relative sizes back in Section 2.3 of Week 4.)

Answer

The planet orbiting the G-type star is more likely to transit because the G-type star is bigger.

2.2 Selection effects – transits

It turns out that the probability of any particular planet in orbit around any particular star being seen to transit is generally pretty low. It's nearly 12 per cent for a planet like HD 209458 b, which is very close to its star. However, if any aliens are out there looking, there's only a 0.46 per cent chance that the Earth would transit the Sun from their perspective.

We must take this into account when we try to understand the numbers of planets found by Kepler. Scientists have done this by looking at the numbers of different kinds of planet Kepler has found, then working out how likely Kepler would be to detect this kind of planet.

It's not just the likelihood of the planet transiting that matters. Kepler's ability to detect a transiting planet also depends on the size of the planet, the luminosity of the star, the period of the planet and the distance to the star.

- The bigger the size of the planet relative to the size of the star, the larger the transit depth. Deep transits are easier to measure than shallow ones.
- For a more luminous star, Kepler is able to collect more light. This allows for more precise measurements of a transit. Big, massive main sequence stars are much more luminous than small, low-mass main sequence stars.
- Planets with longer periods have less frequent transits – there is only one transit per orbit. This makes them more difficult to detect.
- For a more distant star, Kepler collects less light and the precision of its measurement goes down.

All of these so-called selection effects combine to allow the Kepler team to work out the likelihood of detecting any given planet. A selection effect is just anything that makes it more likely to discover one type of thing than another type, in this case types of exoplanets. Selection effects need to be understood and accounted for in most areas of astronomy, and indeed in many other fields of research.

Together, all this means that it's much easier to detect large planets in close orbits around large, bright stars than any other kind of planet. Small planets in wide orbits are the hardest planets to discover using the transit method.

2.3 How many are there really?

In the next section, you will explore more about the maths involved.

How it's done

The factors discussed previously can be expressed mathematically and combined to work out the probability that a particular type of planet orbiting a particular type of star will be detected by Kepler. For a very close-in large planet orbiting a particular type of bright star, the probability might be, say, a one-in-four chance. This could also be expressed as a probability of 0.25 or 25%. Imagine Kepler studied, say, 1000 stars of exactly this type and found five such close-in large planets. A probability of 0.25 means that for every planet detected, there are probably another three which exist but are not detected – we detect only a quarter of the planets of this particular type. So, the five planets which were detected should be multiplied by a factor of four to give our best estimate of the number of such planets which actually exist. In this case, we would estimate that there are 20 of these close-in large planets orbiting the 1000 stars studied.

We can take this one step further. Say the Galaxy contains N stars (where N is a big number) of the same type as the sample of 1000 studied. We can use our estimate from the Kepler detections to calculate the total number of close-in large planets orbiting this type of star. We worked out that there are 20 close-in planets orbiting around 1000 such stars, so there are on average 20/1000 (two in every hundred) close-in planets for each star of this type. We then multiply this by the total number of such stars, N. The answer, $20/1000 \times N = 0.02 \times N$, will be the number of close-in planets which exist in orbit around this type of star in the Galaxy.

Activity 2 Planets around F-type stars

Allow about 5 minutes

Let's imagine that, out of 1000 F-type stars studied, Kepler found two planets with radii between eight and 16 times the radius of Earth, with orbital periods of less than 50 days. The probability that Kepler will detect such planets is calculated to be one-in-five, that is, 0.2 or 20%. The whole Galaxy contains 3 billion F-type stars.

Work out how many planets with radii between eight and 16 times the Earth's radius, orbit F-type stars in our Galaxy with orbital periods of less than 50 days.

Answer

Answer: 30 000 000 or 30 million

Kepler found two planets per 1000 F-type stars of the kind we are interested in, and had a one-in-five chance of doing so. This means that there is likely to be a factor of five times as many such planets than were actually detected, giving ten planets per 1000 stars, or one planet per 100 stars. So, the number of planets of this type is one per cent of the number of stars. As there are a total of 3 billion F-type stars in the Galaxy we need to find one per cent of 3 billion. This is 3000 000 000 ÷ 100 = 30 000 000.

So, the numbers given suggest there are 30 million planets in the Galaxy with orbital periods of less than 50 days and radii between eight and 16 times the Earth's radius orbiting F-type stars.

Note that this is just an example of how these calculations work: the numbers are invented!

The same logic can be applied to every combination of type of star and type of planet. Adding up all the estimates for the number of planets of each type gives an estimate of the total number of planets in the Galaxy.

The Kepler results

As you've seen, by combining the likelihood of detecting a particular kind of planet with the number that actually were detected, you can work out how many such planets exist. Using this method, Kepler scientists estimated the total numbers of different types of planet in the Galaxy. Although there is still a lot of uncertainty about these numbers, astronomers have estimated that roughly half of the stars in the Milky Way have at least one planet.

Kepler has discovered lots of stars with more than one planet. Some systems have six, seven or even eight known planets. In fact, there are probably more planets than stars.

As noted at the beginning of this course, planets are much harder to find than stars. From Kepler, we have evidence that there are many planets, but so far astronomers have only found a tiny fraction of the Galaxy's population of planets.

Selection effects for the radial velocity method

Just as there are selection effects that influence what kinds of transiting planet we can most easily find, similar effects come into play for planets detected by the radial velocity (RV) method too.

Unfortunately, those selection effects are fairly similar to those for transits – RV surveys also favour discovering larger planets orbiting close to their parent stars. The reasons are slightly different though: we don't care if a planet transits or not for a successful RV measurement, but more massive planets exert a stronger gravitational pull on their stars, meaning that the stars wobble more, thus producing a stronger radial velocity signal. This effect is also enhanced the closer the planet is to the star.

Small, Earth-sized planets are even more difficult to detect with RV measurements than with transit methods and, therefore, so far, most information about these planets comes from transit surveys. Unfortunately, that means it's difficult to be sure about the typical composition of smaller exoplanets, since we know only their radii and not their masses.

3 The Milky Way variety pack

The results from Kepler and other projects have enabled astronomers to estimate the total number of planets in the Galaxy. They also allow us to estimate how many planets of each type there are. You saw in Section 2.3 how these estimates are made. A similar type of logic can be applied to samples of stars studied to look for radial velocity (RV) variations owing to planets. For RV measurements we don't know the size of the planets discovered, but we do know about their mass.

Because Kepler has discovered many more planets than those discovered through work undertaken on any other project, it has the largest sample size to work with. Large sample sizes lead to more reliable statistics. So, we will mostly focus on the results from Kepler.

An example of Kepler's predictions for the number of planets in different size categories are shown in Figure 3. These results are for planets with orbital periods less than 85 days, roughly that of Mercury orbiting the Sun. The numbers on the vertical axis show how many planets of a particular size there are for each star. So, for example, for each star there are 0.06 planets with orbital periods less than 85 days and radii between 2.8 R_E and 4 R_E, or equivalently, 6 such planets for every 100 stars. The vertical 'error bars' show the experimental uncertainty in the figures.

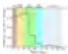


Figure 3 Planet population by size derived from Kepler discoveries

Kepler's results have shown that small planets are much more common than giant planets.

The likelihood that small, Earth-sized planets are common should be good news for scientists who are interested in the possibility of finding another planet like Earth, or even one that's inhabited – the more planets that are out there, the more likely it will be that we'll find one. But finding Earth-sized planets is difficult, and space is really, really big.

4 The light year

Because space is so big, we need to use another measurement of distance to think about the distances between stars. To recap, so far, we've measured:

- planet sizes in units of R_E and R_J
- star sizes in units R_{Sun}
- distances within planetary systems in units of AU, which is the distance between the Earth and the Sun.

To measure distances between stars, we use a unit called the 'light year'.

The light year is simply the distance light can travel in a year. To us, it looks as though light travels instantaneously, but actually it's just extremely fast. Light travels at a speed of nearly 300 000 kilometres every second – fast enough to take it over seven times around the Earth in just one second!

This is the fastest known thing in the Universe. Based on existing scientific theory, it's actually impossible for anything to travel faster than the speed of light. Even so, it still takes light eight minutes to travel from the Sun to us, and the light we see from our nearest neighbouring star, Proxima Centauri, left over four years ago (Figure 4).

There are 31.5 million seconds in a year, so light can travel a distance of 300 000 × 31.5 million km in a year. A light year works out as approximately 9.5×10^{12} km (remember, 10^{12} is 1 with 12 zeros after it – 1000 000 000 000, or 1 million million, or 1000 billion, or 1 trillion, though scientists don't tend to use the word 'trillion').

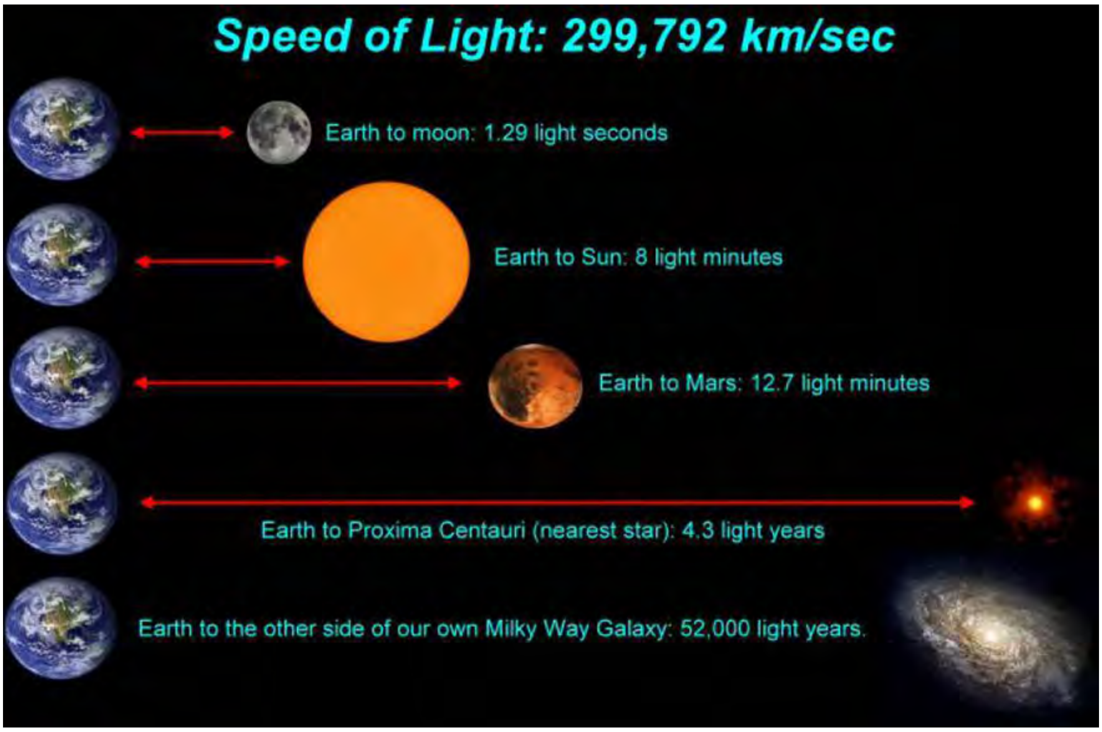


Figure 4 Light-speed distances

Activity 3 Light-speed distances

Allow about 15 minutes

If each of the distances in Figure 4 was drawn to the same scale, with, say, 1 cm representing the distance from Earth to the Moon, then the distance across the Milky Way Galaxy should be represented by a line 13 million kilometres long!

Can you work out and explain how we get 13 million km from the information in Figure 4?

Answer

First, we need to convert 52 000 light years into light seconds so we can compare it with the Earth–Moon distance in the same units, light seconds. To do this we must multiply by the number of days in a year and the number of seconds in a day. So, the distance across our Galaxy in light seconds is:

52 000 light years × (365.25 × 24 × 60 × 60) seconds per year

= 1640 995 200 000 light seconds

= 1.6×10^{12} light seconds.

Since the distance to the Moon, 1.29 light seconds, corresponds to 1 cm, the scale would be 1.29 light seconds per cm. We need to divide the distance across the Galaxy by the 1.29 light seconds per cm to work out the width of the figure in cm if drawn to scale:

1.6×10^{12} light seconds ÷ 1.29 light seconds per cm

= 1.3×10^{12} cm.

This is a very big number, so it makes sense to express the answer in km rather than cm. There are 100 cm in 1 m and 1000 m in 1 km, so our answer is:

1.3×10^{12} cm ÷ 100 = 1.3×10^{10} m

1.3×10^{10} m ÷ 1000 = 1.3×10^{7} km.

Since 1 million is 1×10^{6}, 1.3×10^{7} is the same as 1.3 × 10 × 1 million. So, our answer 1.3×10^{7} km is more elegantly expressed as 13 million km.

That is, if Figure 4 was drawn to scale in which the distance to the Moon is 1 cm, then we would need a piece of paper 13 million km long!

As we said, space is really, really big! This is why some pictures in astronomy are not drawn to scale.

What is the true distance from Earth to the other side of the Milky Way in kilometres?

Answer

Answer: 5×10^{17} km

A light year is a distance of 9.5×10^{12} km, so 52 000 light years is a distance of $9.5 \times 10^{12} \times 52\,000 = 5 \times 10^{17}$ km.

That's 5 hundred thousand million million – phew!

In fact, recent studies of the outermost stars in the Milky Way have suggested that it may be even bigger than that.

And that's just the distance across our own Milky Way Galaxy! There are many billions of other galaxies out there.

Activity 4 How long would it take the light to get here?

Allow about 10 minutes

In Figure 4, you've been shown how long it would take light to reach the Earth from different objects. Based on those numbers, see if you can work out how long it would take light to come from elsewhere.

1. If Mercury is about half the distance from the Earth to the Sun, how long does it take light from the Sun to get to Mercury?

Answer

4 minutes

---

2. The International Space Station (ISS) is about 1000 times closer to the Earth than the Moon is. Approximately how long does it take light to reach us from the ISS?

Answer

About 1/1000th of a second

---

3. HD 209458 b, the planet we learned all about last week, is nearly 40 times further away from us than our closest star, Proxima Centauri. Approximately how long does it take the light from the star HD 209458 to reach us?

Answer

Approximately 160 years

---

5 The habitable zone

Earth is currently the only place in the whole Universe we know of that harbours life. Further discoveries in our Solar System or beyond may come in the not too distant future, but for now it makes sense to assume that 'Earth-like' planets are the best places to look for signs of life.

From current theories about planetary formation and structure, as well as from studies of exoplanets with known densities, scientists believe that rocky, terrestrial planets must be relatively small. Planets larger than about 1.5–2 R_E would be expected to accumulate a substantial gaseous envelope and so be more akin to Neptune.

As well as a planet being small and rocky, there are other things we need to consider when we're deciding whether or not it's likely to be habitable.

Habitability is a very complicated issue because we still don't know exactly what conditions were necessary for life to evolve on Earth, but one thing scientists think is likely to be very important is the presence of liquid water. All living things on Earth need liquid water to survive, and the average human body is made up of around 60 per cent liquid water.

5.1 The Goldilocks effect

Water doesn't exist as a liquid under all conditions. We know this, because in winter when the temperature drops below 0 °C it freezes and becomes a solid. If you're boiling vegetables and you don't put the lid on the pan, eventually the pan will boil dry because all of the water will turn into a gas and escape. So, the temperature of a planet is going to be really important in determining whether or not it is habitable.

You explored the factors which govern the temperature of a planet in Week 5, Activity 6, 'Hotter or colder'. The distance to its star is the main thing which determines how hot a planet is. A camp fire provides enough heat to keep you warm when you sit next to it, but has little effect if you sit 20 metres away. The heat from a star behaves similarly.

Planets which are too close to the star are too hot; planets which are too far away are too cold. But some planets, like Earth, have just the right conditions for liquid water to be present on their surfaces. Scientists define the habitable zone of a planet as the range of distances it could be from its star for which water could exist as a liquid. This is often colloquially referred to as the Goldilocks Zone.

5.2 The perfect distance depends on the star's type

For smaller, cooler stars, the habitable zone will be closer to the star, and for hotter stars it will be further away (Figure 5). In our camp-fire analogy, high-mass luminous stars are like huge, well-fed, blazing fires, while low-mass stars are like small, feeble camp fires burning little fuel. You would need to huddle close to a small fire to keep warm, while you might have to back away from a big fire to avoid sweating.

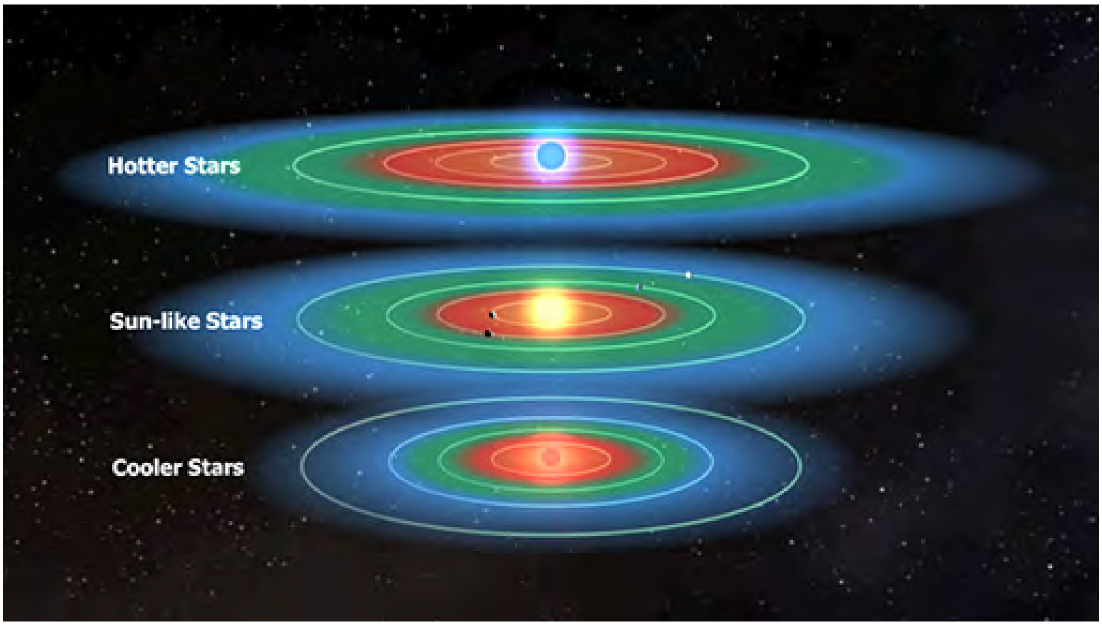


Figure 5 The habitable zones (green) for different temperatures of star. The orbits of the Solar System terrestrial planets are shown.

Astronomers want to find and study planets in the habitable zones of their stars because they may be potential habitats for life. The possibility of life elsewhere is something that has fascinated people for centuries. The study of exoplanets provides us with the opportunity to, maybe, find evidence for it.

Activity 5 Is your planet habitable?

Allow about 10 minutes

This interactive application allows you to determine whether a planet is orbiting at the right distance for liquid water to be present on its surface. The habitable zone, where this is possible, is indicated in green. Closer to the star is coloured red: too hot, while further from the star is coloured blue: too cold.

As noted in Week 5, Activity 6, 'Hotter or colder', the stellar properties which determine how hot an orbiting planet gets are the temperature and the radius of the star. For main sequence stars these depend only on the star's mass.

Interactive content is not available in this format.

Change the star's mass and watch how the three zones change. As with previous interactive applications, you can also use the arrow keys on the keyboard to amend the values. You will need to adjust the zoom using the + and − buttons for all three zones to be visible for different choices of stellar mass.

The second slider allows you to change the planet's distance, a_{total}, from the star. You can choose a value of a_{total} to place the planet in one of the three zones.

For a more massive and therefore hotter star, does your planet have to move further away or closer in? For the very coolest stars, how close would a planet have to get? (Remember that the least massive stars are 0.08 solar masses.)

As in Week 5, the star and planet parameters are used to calculate an 'equilibrium temperature' for the planet. This is a calculation of the planet's surface temperature based on the assumption that it is a simple sphere, and that the amount of energy it absorbs and re-emits is balanced.

Set the slider values to correspond to the Sun and Earth.

Answer the following questions:

1. What values do you need to choose?
2. In which zone is the Earth and what is the value of its equilibrium temperature? Convert this from kelvin (K) into degrees Celsius (°C) and comment on your findings.

Answer

1. M_{star} = 1 solar mass and a_{total} = 1 AU.
2. The Earth falls in the blue region, outside the habitable zone. The equilibrium temperature is 255.5 K. To convert this to °C you need to subtract 273, which gives a temperature of −17.5 °C. Water is not a liquid at this temperature: it freezes at 0 °C. Clearly the Earth is warmer than the interactive application is saying.

5.3 Why isn’t the Earth frozen?

Clearly the interactive application in Activity 5 is not telling the whole story. It makes a simple calculation assuming all the sunlight heats the surface of the Earth, which then cools according to the simplest equation describing how warm objects cool. In fact, all the sunlight does *not* reach the surface of the Earth: the Earth’s atmosphere absorbs and scatters some of the sunlight. But the atmosphere also absorbs heat energy from the surface that would otherwise escape directly back into space, as shown in Figure 6. This keeps the surface warmer than it would otherwise be. This is the ‘greenhouse effect’, the importance of which has been widely discussed in recent years. It is now clear that the Earth is gradually warming because human industry is changing the mix of gases in the Earth’s atmosphere.

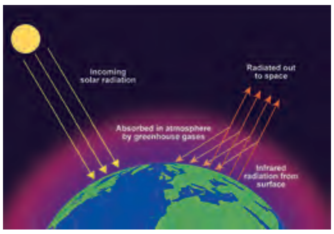


Figure 6 The greenhouse effect. Heat energy in the form of ‘infrared radiation’ is given off by the Earth’s surface and absorbed by gases in the atmosphere.

Activity 6 With a greenhouse effect, is your planet habitable?

Allow about 10 minutes

This interactive application includes the effect of an atmosphere which causes a simple greenhouse effect. It appears similar to the one you encountered in Activity 5, but the equations used to calculate the planet’s average surface temperature are different. Consequently, the results it displays are different. As before, the habitable zone, where the presence of liquid water is possible, is indicated in green.

Interactive content is not available in this format.

Change the star's mass to explore again how the location of the habitable zone can change for different stars.

Set the slider values to correspond to the Sun and Earth.

Answer the following question:

In which zone is the Earth, and what is the value of its surface temperature? Convert this from K into °C and comment on your findings.

Answer

The Earth falls in the green region, the habitable zone. The average surface temperature is 296 K. To convert this to °C you need to subtract 273, which gives a temperature of 23 °C. Water is a liquid at this temperature. The Earth has a temperature similar to that reported by this interactive application.

Once the greenhouse effect is included, the temperature of the planet does not depend only on its distance from the star. The properties of the planet's atmosphere are crucial in determining the planet's temperature. This is one reason why astronomers are very keen to detect and measure the composition of exoplanet atmospheres. You'll find out how next week.

Explore how much the mass of the Sun would have to change before Earth was no longer in the habitable zone.

5.4 Fighting climate change with paint

There are other factors too, which are crucial in determining whether a planet is the right temperature to be habitable. One of them is how reflective the planet is. A very reflective planet will reflect starlight, and will be cooler than an otherwise identical planet whose surface absorbs all the starlight. Things like rock type, cloud cover, snow and ice, and whether there are large oceans all affect how reflective a planet is.

Since industrialisation started about 200 years ago, the composition of the Earth's atmosphere has gradually changed. The amount of carbon dioxide has increased, which is a very effective greenhouse gas. The average temperature of the Earth is rising as a result. One consequence of this is that glaciers are melting. This is bad, because glaciers are reflective, while the rock underneath them isn't. A consequence of melting glaciers is that the Earth absorbs more sunlight, which makes global warming worse.

The glaciers in the Peruvian Andes have melted. The local people are suffering as a result: glacial meltwater is no longer available for their crops. Villagers in Licapa have been whitewashing the mountain above their village. The hope is that it will absorb less sunlight, cool, and a glacier might be re-established.

Figure 7 Whitewashing a mountain

5.5 Lots of habitable planets!

Applying the methods you learned about in Sections 2 and 3, astronomers have reached startling conclusions about the number of potentially habitable planets there may be in our Galaxy. This draws on everything we know about the exoplanets discovered so far, and uses the correction for the probability factors. The conclusion is that there is likely to be a rocky planet in the habitable zone of one star in five!

6 Where are the aliens? The Drake equation

Kepler's results about the numbers of planets, especially small ones, are important for assessing the likelihood of life elsewhere in our Milky Way Galaxy. The Drake equation gives this likelihood in mathematical terms. This equation, invented by astronomer Frank Drake, is a way of estimating the number of active, communicative civilisations in the Milky Way. Basically, it's an estimate of how likely it is that there is an advanced alien race somewhere out there that we might be able to detect signals from. The number of these civilisations is worked out by a long multiplication of lots of different factors, illustrated in Figure 8:

Number of civilisations =

Rate of star formation

× fraction of stars with planets

× average number of planets per star that can support life

× fraction of those planets that develop life

× the fraction of planets bearing life on which intelligent, civilised life evolves

× the fraction of these civilisations that have developed communications technologies that release detectable signs into space

× the length of time over which such civilisations release detectable signals.

A lot of the latter factors are things we don't really know the answers to, especially things like the fraction of planets that develop life, but the results from Kepler have helped us to get a handle on the second and third points – the average number of stars with planets, and the average number of planets per star that can support life.

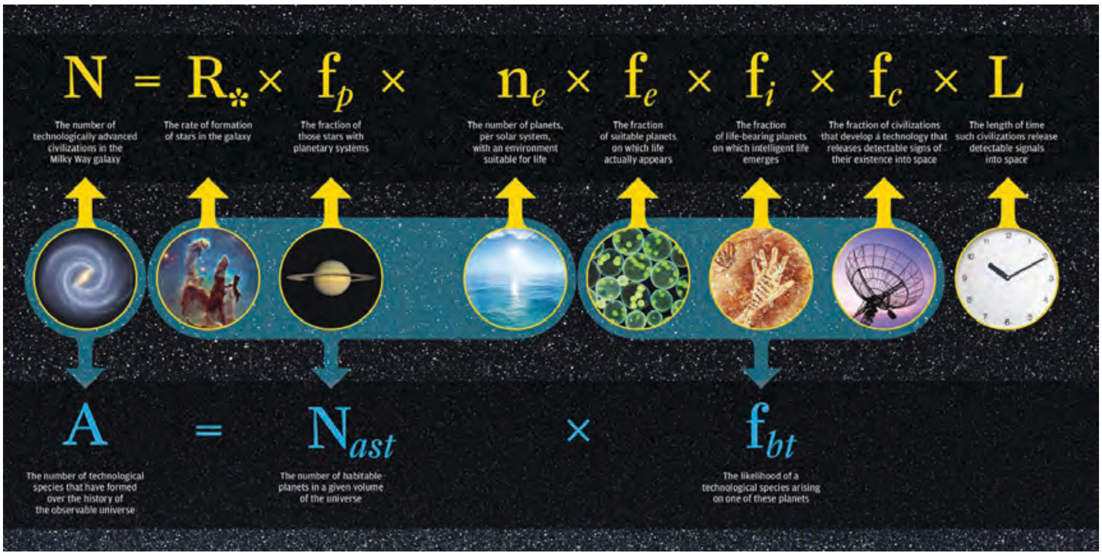


Figure 8 The Drake equation. If you are struggling to see the labels even in the larger version, try viewing an even larger version here.

Activity 7 Is anyone out there?

Allow about 15 minutes

Visit the following BBC web page on the Drake equation How many alien worlds exist?

On this interactive site, you can change each of the values in the Drake equation and find out how that affects the chance of there being other civilisations nearby.
Remember, the Milky Way is very big – even if there might be thousands of intelligent species on planets throughout the Milky Way, there may not be any close enough for us to communicate with. The Milky Way has a diameter of something like 200 000 light years – that's about 2×10^{18} km – and so covers an area of the order of 10^{36} km^2. A few thousand civilisations would be spread pretty thinly across that area, and with current technology we won't be paying them a visit any time soon! Remember, even if we could travel at the speed of light (which we can't!) it would still take four and a half years to travel just to our nearest star.

Click on the preset settings for 'today's optimistic estimate'. How many communicating civilisations would there be in the Galaxy?

Answer

Answer: 72 800

Note that this requires a reasonable percentage of all planets to be habitable, and for each habitable planet a virtual certainty of intelligent life evolving. We'd probably have to be quite lucky (or unlucky?) to encounter another intelligent civilisation.

7 Kepler's small planets

The 'holy grail' in the early years of exoplanet discovery was a rocky planet located in the habitable zone of its star. Remember, the first exoplanets to be discovered were the much more easily detectable 'hot Jupiters' – too large to be rocky and too close to their star for liquid water to exist.

But as more technology, like Kepler, was applied to exoplanet research the size of planets being discovered rapidly decreased. Scientists expect planets that have a chance of hosting life to be rocky, so the small planets discovered by Kepler are especially important for the Drake equation.

The planets found so far by Kepler and other planet searches tell us that rocky planets are common companions of M-type stars – the smallest, coolest type of main sequence star. These are often referred to as red dwarf or M dwarf stars. These stars are very common – much more common than bigger, more luminous stars like the Sun. In fact, about 70 to 80 per cent of the stars in the Galaxy are M dwarf stars.

Because they are relatively very dim, the habitable zone lies very close to M dwarf stars, closer than Mercury is to the Sun. Studies of the Kepler data indicate that there could be at least one Earth-sized, potentially habitable, planet for every six M dwarf stars in the Milky Way. That could work out at around 50 billion!

So, we now know our Galaxy must be swarming with small planets in the habitable zones of small stars. There are plenty of small stars in our immediate neighbourhood – in fact, there are 50 within 15 light years from us. This means we could expect to have eight or more very close Earth-sized planets that are potentially habitable. By 'close', here, we mean in the context of the size of our Galaxy: a planet 15 light years away is not close in our everyday sense!

Kepler found hundreds of Earth-sized planets, some of which might be in the habitable zones of their stars. The first one of these, announced in 2014, was Kepler-186 f – the fifth planet in the Kepler-186 system. The star, Kepler-186, is about half the size of the Sun, so it is cooler. Kepler-186 f takes around 130 days to orbit its star, so its discovery required analysis of three years of observations.

Figure 9 Artist's impression of Kepler-186 f

However, we may never know whether Kepler-186 f and many of the other small Kepler planets are really habitable. We may not even know if they're really rocky. Unfortunately, their host stars are too faint and far away from us. The planets are not big enough for us to measure their masses using the radial velocity technique: the signals would simply be too small. It will also be very difficult to study other properties of these planets in more detail.

8 The search for Earth's first cousins

Kepler's small planets may be too distant for us to learn more about them, but the measurements have told us that we can expect several small planets to be in orbit around cool stars in much closer parts of the Galaxy. If they are close enough, then we may be able to measure their masses to determine whether or not they are rocky, and we might even be able to go further and find out what they are really like.

8.1 The MEarth survey

While Kepler was surveying more distant regions of the Galaxy from space, a team of astronomers from Harvard University were looking at nearby small stars in the hope of discovering a planet close enough to learn much more about. This was the MEarth survey (pronounced 'mirth') – looking for Earths around M dwarf stars.

Figure 10 MEarth observatory

The MEarth observatory consists of eight small telescopes. These telescopes monitor the brightness of M dwarfs close to the Solar System to detect any transiting planets.

The search was rewarded in 2009 when the first MEarth planet was discovered – a planet around 2.5 times the size of Earth orbiting the star GJ 1214. This star is only 48 light years away from us. As one of the closest planets so far discovered, GJ 1214 b was an exciting result, but follow-up radial velocity measurements of the planet's mass indicated it is not dense enough to be rocky. The search was still on for an Earth-like neighbour.

After several years yielding no results, a second planet was eventually found by MEarth in 2015, and this one looked more promising. GJ 1132 b, which is about 20 per cent larger than Earth, is still not a habitable planet, probably hitting the thermometer at more than 300 °C, but it has a density consistent with a rocky planet. Astronomers have speculated that this world might be similar to Venus – so, slowly, MEarth is helping us get closer to finding Earth's cousin. You'll learn more about MEarth's first two planets next week.

Figure 11 Artist's impression of GJ 1132 b, with its parent star in the background

8.2 TRAPPIST planets

With two successful discoveries by MEarth, other teams have also decided that cool stars are the way to go. The TRAPPIST survey (TRAnsiting Planets and PlanetesImals Small Telescope) is operated by a team from the University of Liège in Belgium. It announced its first discovery in May 2016 – not one, but *three* Earth-sized planets orbiting a nearby ultra-cool dwarf star. It doesn't stop there: an additional four Earth-sized planets were later found in the same system. And, three of TRAPPIST-1's planets could be in the habitable zone. You'll learn more about this remarkable system, and other special exoplanets, next week.

8.3 Radial velocity searches for small worlds

As discussed earlier, small planets are difficult to find with radial velocity (RV) searches, just as they are with transit surveys. But looking at small stars can help with this technique too. Remember, in the see-saw example from Week 3 the star doesn't move much because it is so much more massive than the planet. If the star is a little bit less massive, then it will wobble more for the same mass of planet.

Astronomers have been making use of this fact by searching for small planets in the RV wobbles of nearby M dwarfs, using instruments such as HARPS installed on the European Southern Observatory's 3.6 m telescope in Chile. To date, HARPS (High Accuracy Radial velocity Planet Searcher) has found well over one hundred planets, making it the most successful ground-based planet hunter.

HARPS astronomers have assessed the likelihood of there being habitable planets around M dwarfs by observing a carefully chosen sample of such stars, some of which were found to harbour planets. They concluded that there is probably a planet with a mass lower than 10 M_E in the habitable zone of about 40 per cent of such stars in the Milky Way. The logic underpinning this conclusion is similar to that used in Section 2.3, but the conclusion is based on completely different observations. The two results agree and seem to confirm that there are probably lots of Earth-like worlds out there.

Figure 12 is an artist’s impression of one of the potentially rocky planets found using HARPS. This planet, Gliese 667 C c, is only 24 light years from Earth and orbits an M dwarf star which is itself in orbit around two stellar neighbours.

Figure 12 An artist’s impression of a potentially rocky planet orbiting the M dwarf star Gliese 667 C. Like the nearest star to the Sun, Proxima Centauri, Gliese 667 C is part of a triple-star system. The other two stars in the system are visible in the planet’s sky.

In Week 8 you will learn about the recent discovery of an even closer potentially rocky planet. This one is extremely interesting, and has important implications for the Drake equation.

8.4 Habitable planets around M dwarfs

Because M dwarf stars are dim, a planet in the habitable zone needs to be close to its star. This means that the orbital period of a potentially habitable M dwarf planet is much shorter than an Earth year.

Activity 8 The habitable zone of an M dwarf star

Allow about 10 minutes

Interactive content is not available in this format.

The interactive application above is the same as the one you used in Activity 6, but the range of values on each slider has been changed to allow you to focus on the lowest-mass stars. M dwarfs have masses up to about half the Sun's mass. As before, it includes a greenhouse effect in the calculation of the planet's surface temperature.

Adjust the stellar mass slider to 0.5 solar masses, representing one of the most massive M-type stars. Adjust the distance of the planet from the star until the planet surface temperature is about 300 K. You can also use the arrow keys on the keyboard to amend the values.

How long is the planet's orbital period?

Answer

You should obtain an orbital period close to 0.17 Earth years.

How long is the planet's orbital period in Earth days?

Answer

Multiplying by the number of days in an Earth year, this is equivalent to about 62 Earth days.

Even for the most massive, most luminous M-type star, and assuming a greenhouse effect, a planet in the habitable zone would be so close to its star that it completes an orbit in about two Earth months.

Adjust the stellar mass slider to 0.12 solar masses, representing Proxima Centauri, the Sun's closest neighbouring star. It is a low-mass M-type star. Adjust the distance of the planet from the star until the planet surface temperature is about 300 K.

How long is the planet's orbital period?

Answer

For 303 K, the orbital period is 0.023 Earth years.

How long is the planet's orbital period in Earth days?

Answer

Multiplying by the number of days in an Earth year, this is equivalent to between eight and nine Earth days.

Activity 8 showed that for a low-mass M-type star like Proxima Centauri, a planet in the Goldilocks habitable zone would be so close to its star that it completes an orbit in not much more than an Earth week.

The proximity has another effect too: have you noticed that we only ever see one side of the Moon from Earth? This is because the Moon is so close to the Earth that it is forced by Earth's gravity to keep the same face pointed at Earth. We say that it is 'tidally locked' – it doesn't rotate on its own axis independently of the Earth. Its period of rotation is just the same as its orbital period around the Earth. This same gravitational effect between the Earth and the Moon causes the tides.

A planet in the habitable zone around an M dwarf star suffers the same tidal locking effect. The same side of the planet always points at the star it orbits around. This means the star is fixed in the planet's sky. As time passes there is no cycle between day and night. Someone living on one of these planets would never see a sunrise or a sunset unless they travelled between the light and dark side of the planet.

So, the potentially habitable planets of M dwarf stars are quite different from Earth. They are cousins of our world, not twins. You'll learn about how we hope to find Earth's twins in Week 8.

9 This week's quiz

Well done – you have reached the end of Week 6 and can now take the weekly quiz to test your understanding.

Week 6 practice quiz

Open the quiz in a new tab or window (by holding down Ctrl [or Cmd on a Mac] when you click the link).

10 Summary of Week 6

This week, you've learned about the planetary population of the Milky Way. The large sample of stars studied by the Kepler space telescope has given us a lot of information about the kinds of planets that are likely to be in the Milky Way. You've also learned why these numbers are important for scientists trying to predict whether there are other habitable worlds out there. You've even seen an introduction to the scientific assessment of whether alien life is likely.

You've learned that it's more difficult to detect some types of planets than others. In particular, it is difficult to find small planets in wide orbits. It is relatively easy to find large planets in close orbits, so the numbers of each type of known planet are very heavily biased. Fortunately, we can correct this by using the probability of detection. This allows us to work out what the Galaxy's population of planets is truly like. All else being equal, it's also much easier to detect and find out about planets orbiting stars that are relatively near. Recently, surveys have started to look for small, potentially habitable planets around nearby cool stars. These surveys have met with some success.

You should now be able to:

- know that there are more planets than stars in the Milky Way
- explain in words how we know this
- describe the relative abundance of terrestrial and giant exoplanets
- know why some exoplanets are much easier to detect than others, using the radial velocity (RV) and transit methods for planet discovery
- understand the use of light years for measuring distance
- understand and explain in words the concept of a habitable zone
- explain why, despite their abundance, we know of relatively few terrestrial exoplanets.

Next week, you'll be studying some of these small planets, as well as the most interesting of other larger planets.

You can now go to Week 7.

Week 7: The Special Ones

Introduction

Last week, you learned what we've been able to learn from large exoplanet surveys like Kepler, and how we've been able to use our findings to understand the likely population of planets in the Milky Way. You also looked at the Drake equation and efforts to find nearby habitable worlds. This week, you're going to focus on a few special exoplanets that have been studied in detail. You'll learn how astronomers are using some pretty nifty science to discover what planets that can't even be seen are like.

Start by watching the following video with Carole Haswell.

Video content is not available in this format.

By the end of this week, you will be able to:

- have a qualitative appreciation of how transmission spectroscopy tells us which atoms and molecules are present in exoplanet atmospheres
- appreciate why astronomers can get better measurements when an object is nearby
- recognise the importance of:
    - HD 189733 b, HD 209458 b and WASP-12 b
    - GJ 1214 b and GJ 1132 b
    - Kepler-1520 b
    - the TRAPPIST-1 system.

1 Spectra: how we learned what stars are made of

Back in Week 3 you learned about a technique called spectroscopy. This is the way that astronomers use light to determine the presence of chemicals in the atmosphere of an object. In Week 3, you learned about doing this for a star – but it works just as well for planets.

Remember, this is what the spectrum of the Sun looks like:

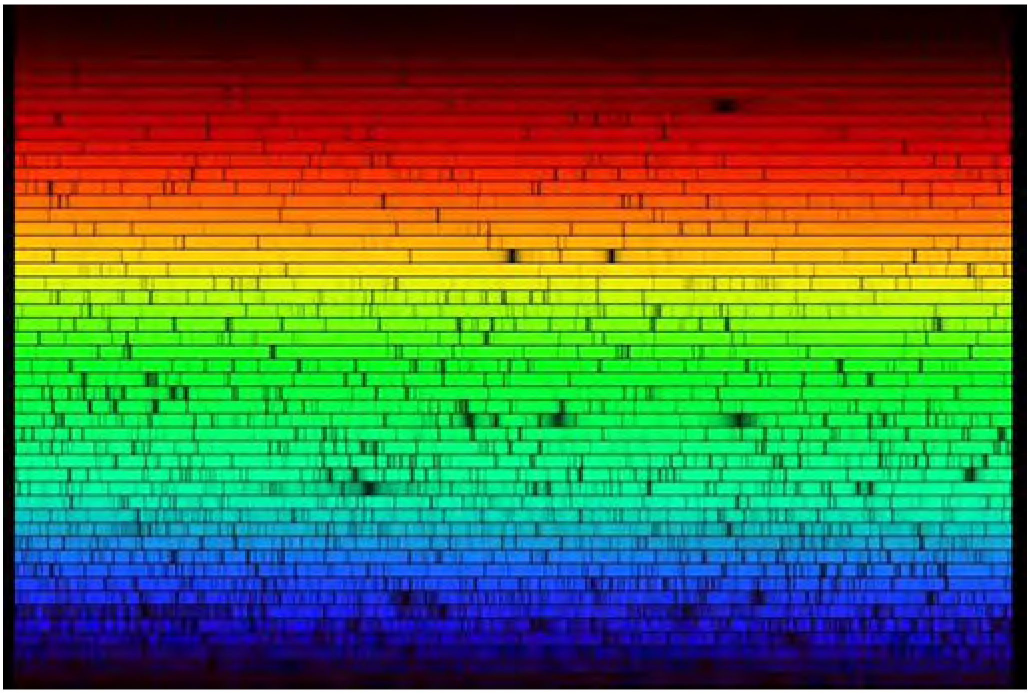


Figure 1 Solar spectrum, in which the light has been spread out to a very high degree over many horizontal strips

When the light from the Sun is split up into its constituent colours, some of those colours are missing because gases in the outer regions of the Sun absorb those specific wavelengths of light, stopping them from making their way to us.

In Week 3, you learned about using the precise positions of the dark absorption lines in a star's spectrum to measure the 'wobble' of a star with a planet in orbit. But long before astronomers searched for exoplanets, these lines were used to learn about what stars are made of. In the early 1800s, scientist Joseph Fraunhofer made very careful measurements of the positions of the black lines in the Sun's spectrum. Later that century, Sir William Huggins matched measurements of dark lines in other stars with the known absorption features of substances that had been studied on Earth: modern astronomical spectroscopy was born. As you learned in Week 3, this was how helium was discovered: after all the lines had been matched up with the chemicals known on Earth, a few lines seen in the spectrum of the Sun and in the spectra of other stars remained. These lines were due to helium.

You studies different types of star in Week 4. These different types of star are distinguished from each other by their spectra. Stars of different temperatures have absorption lines due to different gases. Stars were first categorised in this way in the early twentieth century, with most of the work being undertaken by Annie Jump Cannon, one of the earliest recognised female astronomers.

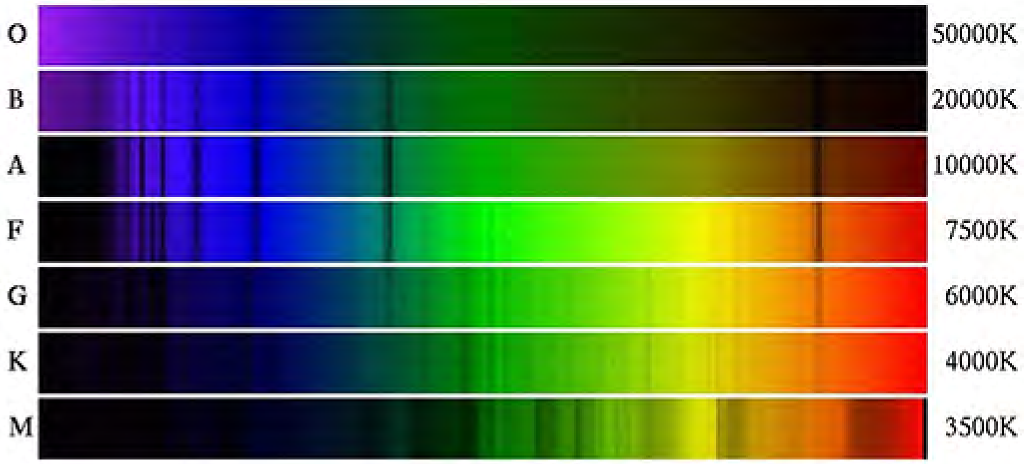


Figure 2 Spectra of different star types

The dark absorption lines in the spectra in Figure 2 can be identified as belonging to various gases. As the stars get cooler, you can see that the number of lines changes, and also the overall colour of the star changes. Hot O stars are much bluer and have fewer lines, whereas the coolest M stars are redder and have lots of lines. In fact, a great deal of the light that M stars emit is so red that we can't actually see it at all.

1.1 The electromagnetic spectrum

You know that the light you see can be split up into the colours of the rainbow, just as in the stellar spectra shown in Figure 2. If you have a prism, a clear precious stone in a ring, or even a watch face with sharp edges, you can often see this effect – your ring or watch will throw rainbows onto a wall if it catches bright sunlight at the right angle.

In reality, however, the colours don't stop with red and violet. Light extends further in both directions – it's just that our eyes are not sensitive to those colours. The Sun emits most of its light in colours from red to violet, so our eyes evolved accordingly. The whole spread of different colours of light, those we can see as well as those we can't, is called the 'electromagnetic spectrum'.

Much of what we know about the coolest stars comes from looking at the part of the spectrum *after* the colour red. This is aptly named the 'infrared' region. You come across infrared 'light', or radiation, quite often in day-to-day life. For example, it's what browns your toast; it's what allows naturalists on television to show videos of animals and birds at night. Infrared-sensitive cameras track the heat from their bodies, rather than relying on sunlight to illuminate them.

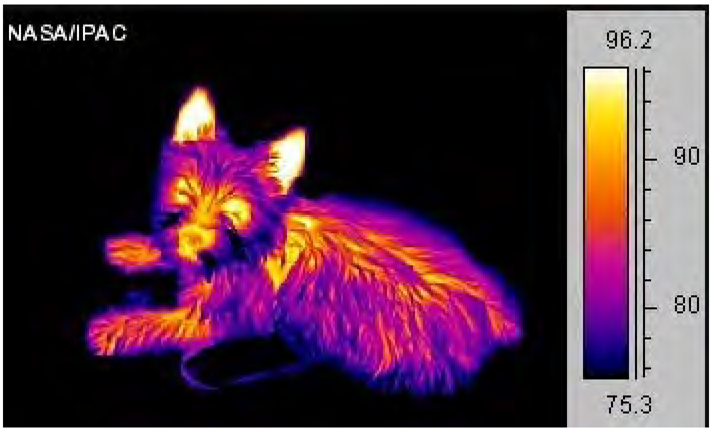


Figure 3 Infrared picture of a dog

The infrared is very useful for scientists who want to look at cool M-type stars, and also at planets. We've already said the Sun emits most of its light in the visible part of the electromagnetic spectrum. Cooler stars emit most of their light in the infrared instead. Other things at moderate temperatures, like humans and the dog in Figure 3, also emit infrared light.

2 Atmospheres of planets and their climates

If we can tell what stars are made of by looking for the missing colours, or wavelengths, of light in their spectra, then in theory we can do the same for planets. In both cases, what we can learn directly is restricted to the contents of the outer layers (i.e. the atmospheres of stars and planets). However, there's one thing which makes applying this technique to planets really difficult. Stars are big and bright, so we can see them even when they're a long way away, but planets are small and faint. It's extremely difficult to detect the light coming directly from a planet, let alone split it up into all its various colours.

Instead, astronomers do something ingenious with transiting planets. When a planet transits, it blocks some of the starlight. You learned about this back in Week 4, and you also learned that the amount of light blocked tells you how big the planet is relative to the size of the star.

Remember, this is how the transit depth is calculated:

When you studied transits in Week 4, the calculations assumed that the planet was solid. A lump of rock is completely opaque: no light gets through it. But even a planet like Earth – a rocky planet – is more than just a lump of rock. Except for Mercury, the rocky planets in our Solar System are surrounded by a shell of gas called an atmosphere.

2.1 Why are atmospheres important?

What a planet's atmosphere consists of is very important if we want to understand the conditions prevailing on a planet. For example, the principal gases in Earth's atmosphere are essential for life as we know it. Nitrogen is the most abundant, and is a key chemical in our cells and in plant cells. As a gas in the atmosphere nitrogen is very unreactive, so we rely on special bacteria to covert it into a form that other life can use.

Around a fifth of the Earth's atmosphere is made of the gas oxygen. Plants produce oxygen, which humans and other animals then inhale – without it, we couldn't survive. Scientists think that finding oxygen in another atmosphere could be key to finding another planet that hosts life, and you will revisit this idea next week.

2.2 The greenhouse effect

Earth's atmosphere also has a small amount of carbon dioxide, a so-called 'greenhouse gas'. Carbon dioxide is very good at absorbing infrared light – the kind described earlier, which is given off by warm things. Because the Earth is also a warm thing, it gives off infrared light, which the carbon dioxide in the atmosphere absorbs and partially re-radiates back towards the Earth. Figure 4 reminds you of this idea. You saw in Week 6 that this 'greenhouse effect' plays a vital role in making our planet habitable – without it our world would be frozen.

The problem is that gradually over time we are increasing the amount of carbon dioxide in the atmosphere by burning fossil fuels, and this is stopping the Earth from losing the heat it needs to maintain a constant temperature. That is why we talk about 'global warming' – the Earth is gradually warming up because the greenhouse gases in the atmosphere are increasing.

Because Venus's atmosphere comprises so much carbon dioxide, it is actually the hottest planet in the Solar System – even hotter than Mercury, despite the fact that Mercury is closer to the Sun. So, atmospheres are very important for determining the surface conditions.

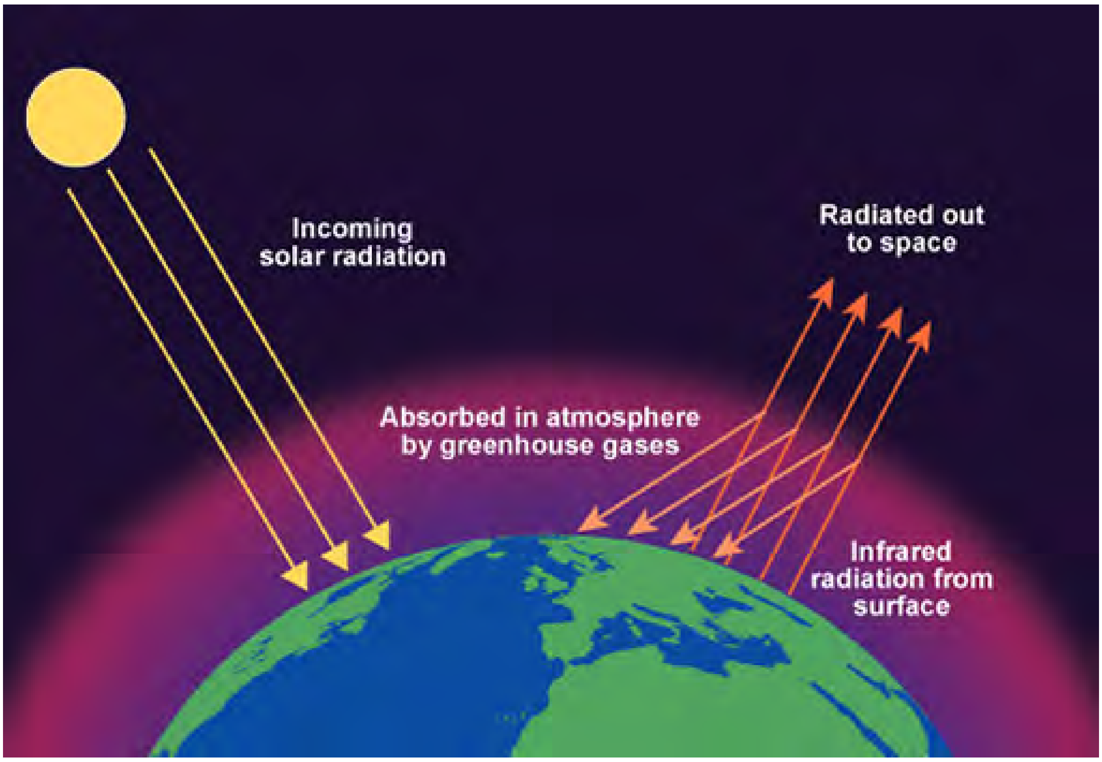


Figure 4 The greenhouse effect

2.3 Atmospheres and transits

When an exoplanet transits its star, of course the planet's atmosphere passes in front of the star too. But the atmosphere isn't completely opaque, so some of the starlight actually passes right *through* the atmosphere on its way to us, as shown in Figure 5. This means that the gases in the planet's atmosphere can leave exactly the same sort of fingerprints on the starlight as we saw in Week 3, shown schematically in Figure 6. These fingerprints can help astronomers to work out what the planet's atmosphere is made up of.

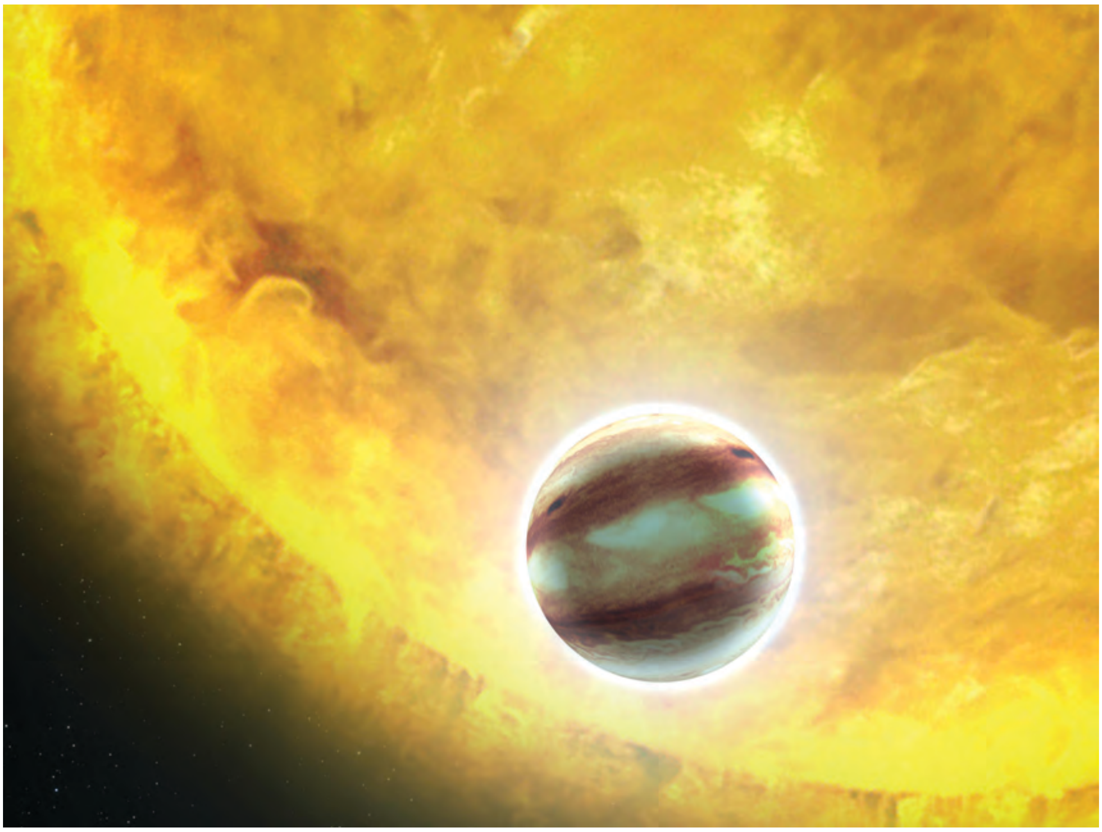


Figure 5 Artist's impression of a hot Jupiter and its atmosphere in transit

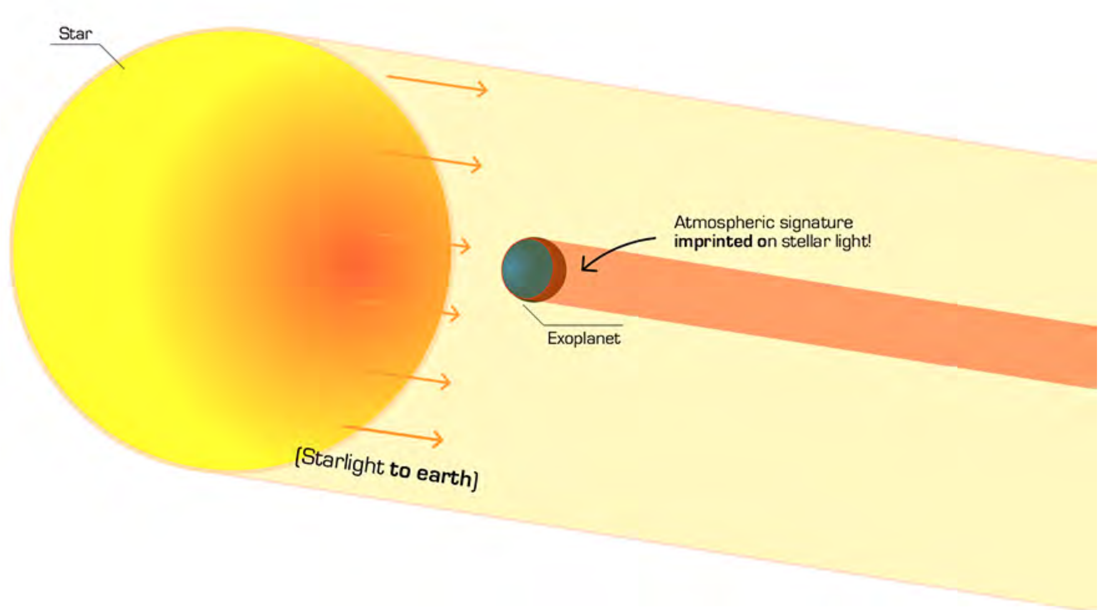


Figure 6 The starlight passing through the exoplanet's atmosphere is imprinted with the spectral signatures of the gases in the atmosphere

Of course, the fraction of starlight that passes through the planetary atmosphere itself is tiny, making this a technically very challenging task that requires meticulous observation and data processing. For a hot Jupiter transiting a Sun-like star this fraction might be 0.01%, but for an Earth-sized planet it could be just 0.00001%!

How can we extract the weak spectral signatures of the planet from the overwhelming starlight? One key method is transmission or transit spectroscopy. The fingerprints appear as tiny differences in the transit depth for different colours of light. For colours that are absorbed by atoms and molecules in the planet's atmosphere, the transit is a tiny bit deeper – the planet appears to be bigger because the atmosphere is blocking a bit of extra starlight. The resulting spectrum, plotting transit depth for different colours, is shown schematically in Figure 7.

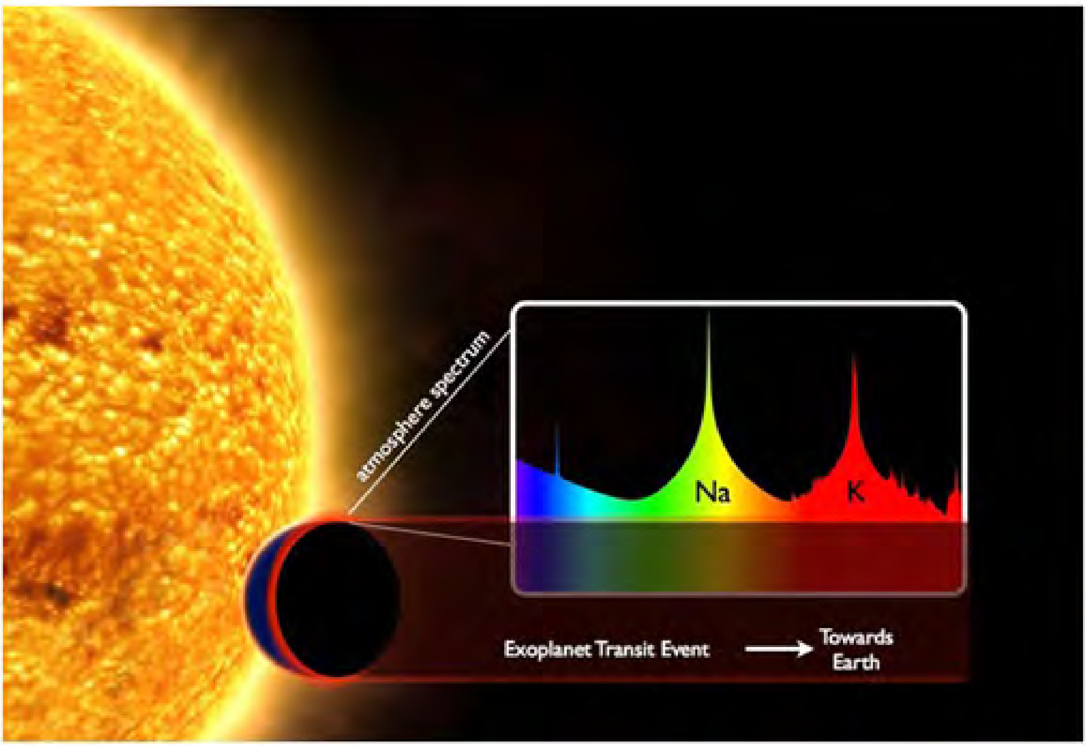


Figure 7 Transmission spectroscopy: as the light from the star passes through the planet's atmosphere, certain specific colours are absorbed by gases in the atmosphere, changing the transit depth for those colours

2.4 Being an atmosphere detective

A transmission spectrum is a graph of transit depth plotted at different wavelengths. Remember that the wavelength of light corresponds to its colour. The tiny differences in transit depth appear as little wiggles in this graph. The graph in Figure 8 shows how the transit depth changes with wavelength for a planet you've already studied – HD 209458 b. Remember, HD 209458 b is a hot Jupiter – a big ball of hydrogen and helium gas, with traces of a few other gases mixed in. It's nothing like the Earth, so we're not expecting to see oxygen, and we don't. We see evidence of water vapour – water in its gaseous form – which might not seem too strange, but we also see sodium and potassium. Sodium and potassium are both metals and they're solid in normal conditions on Earth, but in the atmospheres of these planets they are hot enough to be gases.

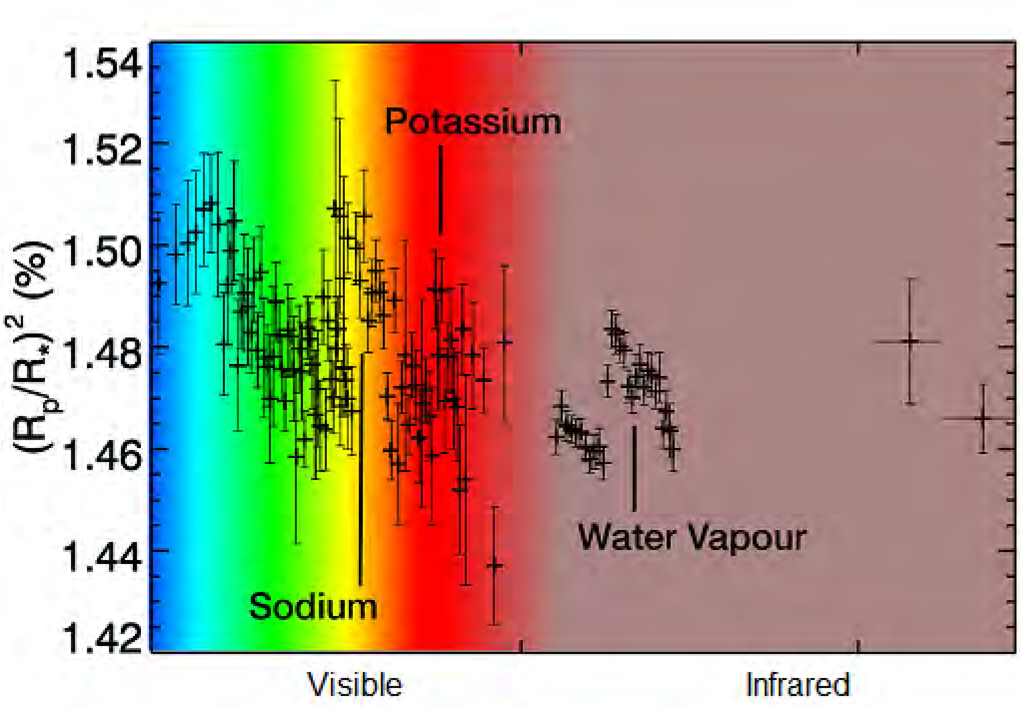


Figure 8 Transmission spectrum of HD 209458 b

Each point in the transmission spectrum of HD 209458 b is a measurement made in a particular colour of light, and the vertical bars show the level of uncertainty on each measurement – it expresses a possible range of values that measurement can occupy. The transit depth is plotted on the vertical axis, expressed as a percentage. Note that the numbers towards the top of the axis are bigger, corresponding to a deeper transit, and hence more absorption of that particular colour of light. You can see small bumps in the spectrum where sodium, potassium and water vapour absorb some of the starlight. There are gaps in the spectrum because instruments on spacecraft can only observe limited ranges of colours.

You may be wondering where the hydrogen is – after all, hydrogen is by far the most plentiful element in the Universe and is expected to be the main constituent of gas giant atmospheres, as it is for Jupiter. Although there is a lot of hydrogen, it doesn't absorb light when in molecular form. This is the form it would take in planetary atmospheres and so it is very difficult to detect.

From these kinds of atmospheric studies astronomers have inferred that HD 209458 b and other hot Jupiters have 'puffy' atmospheres. This is due to the intense heating from their close parent stars (Figure 9). You may recall that in Week 5 you calculated that HD 209458 b is less dense than Jupiter, and this is probably the reason.

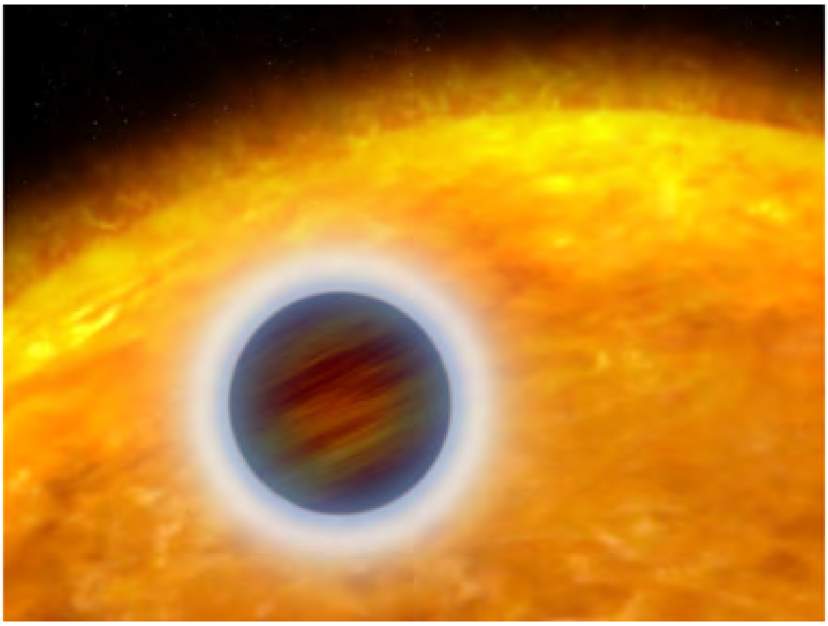


Figure 9 Artist's impression of a hot Jupiter like HD 209458 b with a puffed up atmosphere

Activity 1 Atmosphere detective

Allow about 15 minutes

Now it's your turn to see if you would be a good atmosphere detective. You'll be shown four different spectra with different combinations of the gases sodium, potassium and water vapour detected. It's your job to identify which of these gases are present in the atmosphere of planets. Take a look at the example in Figure 10 to help you decide.

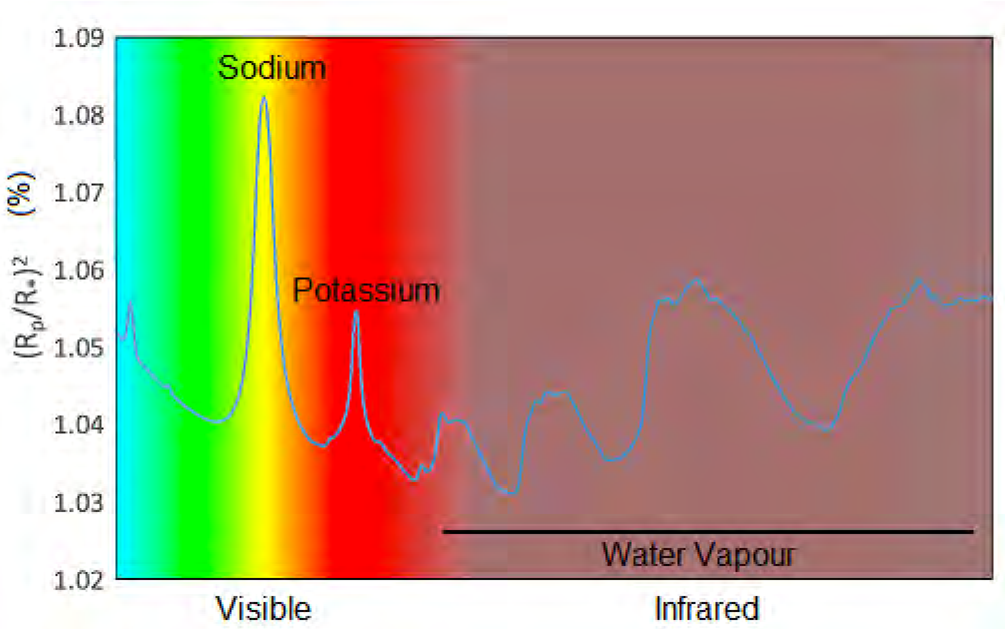


Figure 10 Template spectrum

This is a template showing features due to sodium, potassium and water vapour. Sodium and potassium each have one prominent feature, whereas water vapour has several broader features.

Identify the gases in the spectrum in Figure 11.

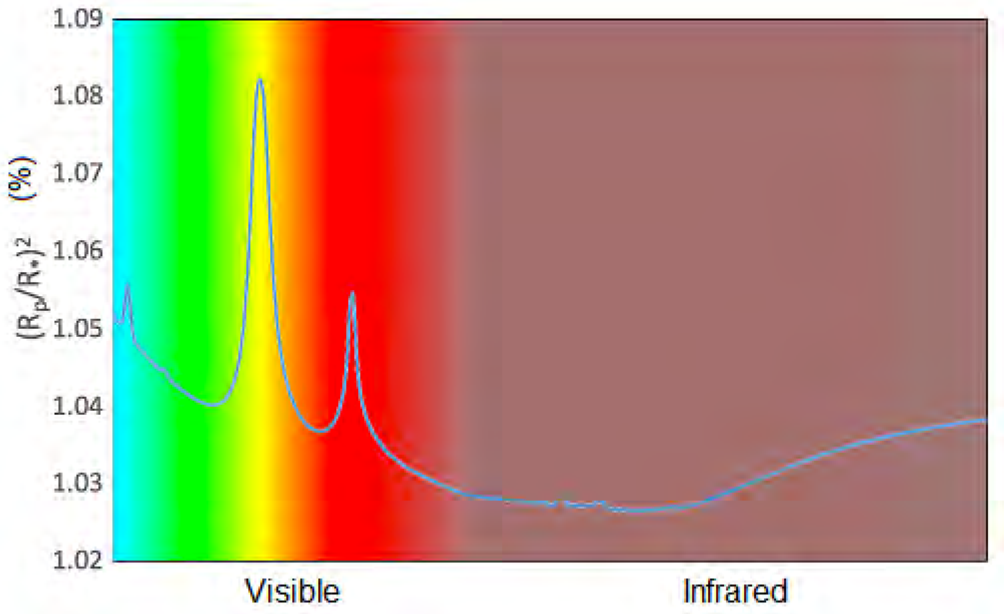


Figure 11 Activity spectrum

Answer

Sodium and potassium

Identify the gases in the spectrum in Figure 12.

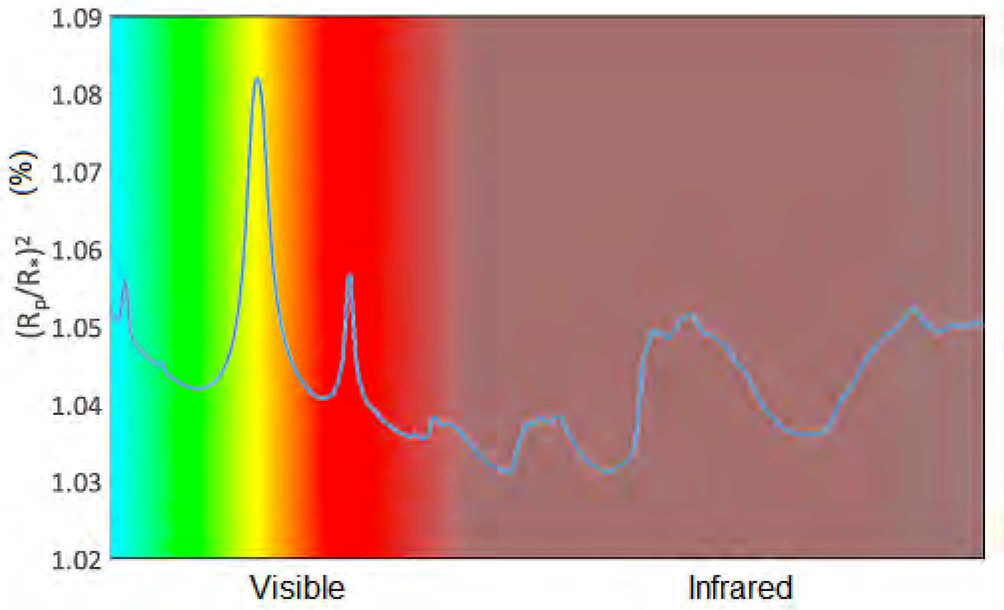


Figure 12 Activity spectrum

Answer

Sodium, potassium and water vapour

Identify the gases in the spectrum in Figure 13.

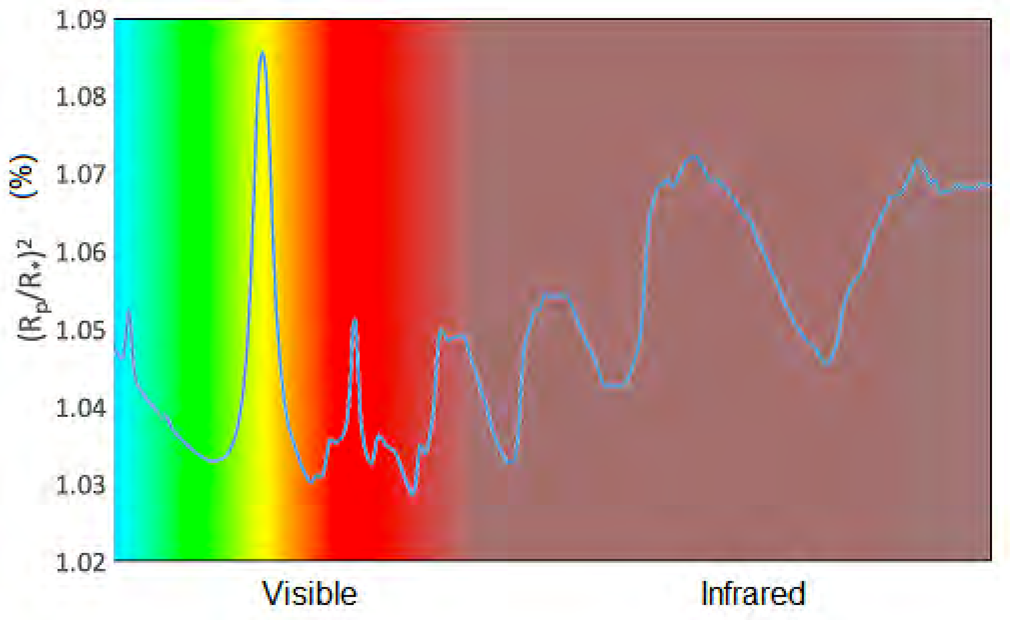


Figure 13 Activity spectrum

Answer

Sodium, potassium and water vapour

Identify the gases in the spectrum in Figure 14.

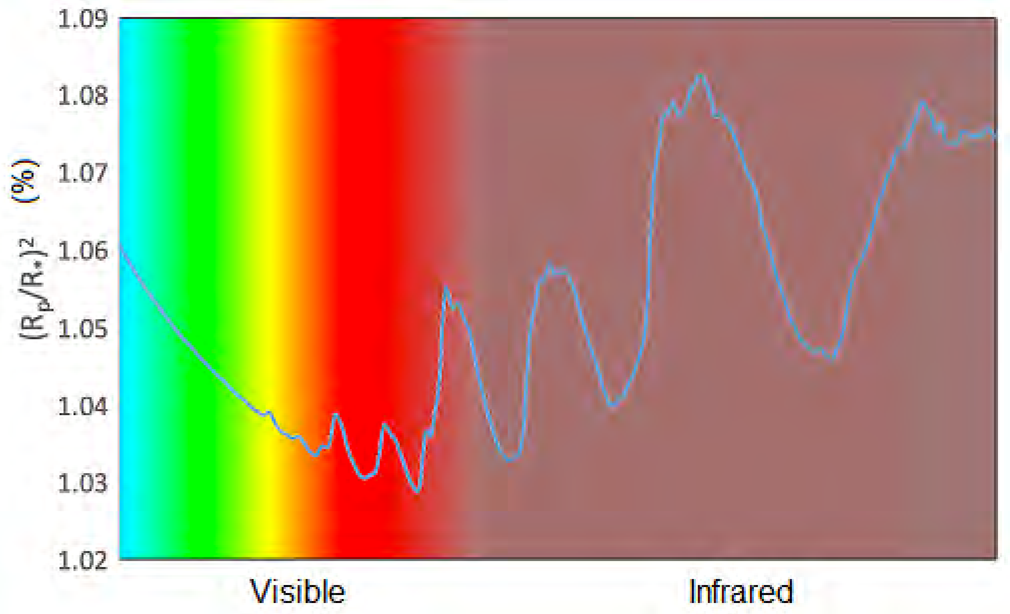


Figure 14 Activity spectrum

Answer

Water vapour

3 Measurements and uncertainty: why great distances are bad news

When you looked at the transmission spectrum of HD 209458 b in Section 2.4, you'll have noticed that the measurements of each colour were shown with an uncertainty. This uncertainty is sometimes called the 'experimental error', though this *doesn't* mean there was a mistake in the measurement. It is very important for measurements in all branches of science to carefully specify the range of possible values the measurement indicates. When you use a ruler to measure something, you can probably only make a reading to the nearest millimetre or so. If you use a ruler to measure a line which is exactly 13.163 cm long, you might record a value of 13.2 cm, or if you are very careful and have good eyesight you might record a value of 13.15 cm. Your value has an uncertainty of about 0.05 cm, and experimenters would record it as (13.15 ± 0.05) cm. This gives the value and an indication that the experimenter's uncertainty range is from 13.10 cm to 13.20 cm. Rather than meaning that scientists don't know the answer, it's a way of showing how confident they are in the measurement they have made. You might think that it is obvious that the uncertainty in a length measurement is about this much, but it depends entirely on how you make the measurement. If you use specialised equipment, it is possible to make much more precise measurements, so the uncertainty range is a very important part of the measurement value.

The uncertainty of the measurements made by astronomers comes from a range of sources. There is a fundamental limit to how precisely astronomers can measure the properties of anything they observe. This limit arises from the properties of light. Light is transmitted as individual wave packets known as 'photons'. When these photons are captured by a research telescope they are counted by a detector. The more of these packets of light that are detected, the more certain scientists can be about their measurement – but if there are few packets of light in the signal, the measurement can start to look very uncertain. Scientists call this unavoidable uncertainty 'noise'. Figure 15 shows the effect of noise in photographs – the less light that is collected the less sharp and clear the picture is. Generally the effects of noise can be minimised by collecting more and more photons from the source being studied.

Figure 15 Photon noise

This fact is very important when astronomers want to make measurements, because more light (and therefore more individual light packets, i.e. photons) is received from closer stars than from stars that are further away. A candle seems quite bright when you are close to it, but if it is 100 metres away it seems dim. So when astronomers are trying to make precise measurements of a planet's atmosphere, it's much easier if the star is nearby. That's why we still know so little about most of the many planets discovered by the Kepler spacecraft: they are simply too far away. This is one of the reasons why astronomers get particularly excited about discovering exoplanets orbiting nearby stars. The closer the planet, the more light astronomers should be able to collect. More light allows for more detailed measurements of the planet's properties. For nearby planetary systems, these measurements should have relatively small uncertainties.

4 Special planets

Although we can't easily find out much about many of the discovered exoplanets, there are some, mostly orbiting nearby stars, that we already know quite a bit about. We are realising that what we knew about planets from just our own Solar System has barely scratched the surface. To round up this week, the following sections take a look at some of the most exciting exoplanets.

4.1 The hot ones: HD 189733 b, HD 209458 b and WASP-12 b

The majority of the exoplanets that astronomers have managed to look at in detail fall into the class of planet called 'hot Jupiters'. Three of the best known are the first transiting planet discovered, HD 209458 b; its similar cousin HD 189733 b, which was found not long afterwards; and WASP-12 b, one of the hottest hot Jupiters we know of.

You've already taken a look at the spectrum of HD 209458 b (shown again below), so you know that water vapour, sodium and potassium were all identified in its atmosphere. The same gases have also been found in HD 189733 b – but also something even more exciting.

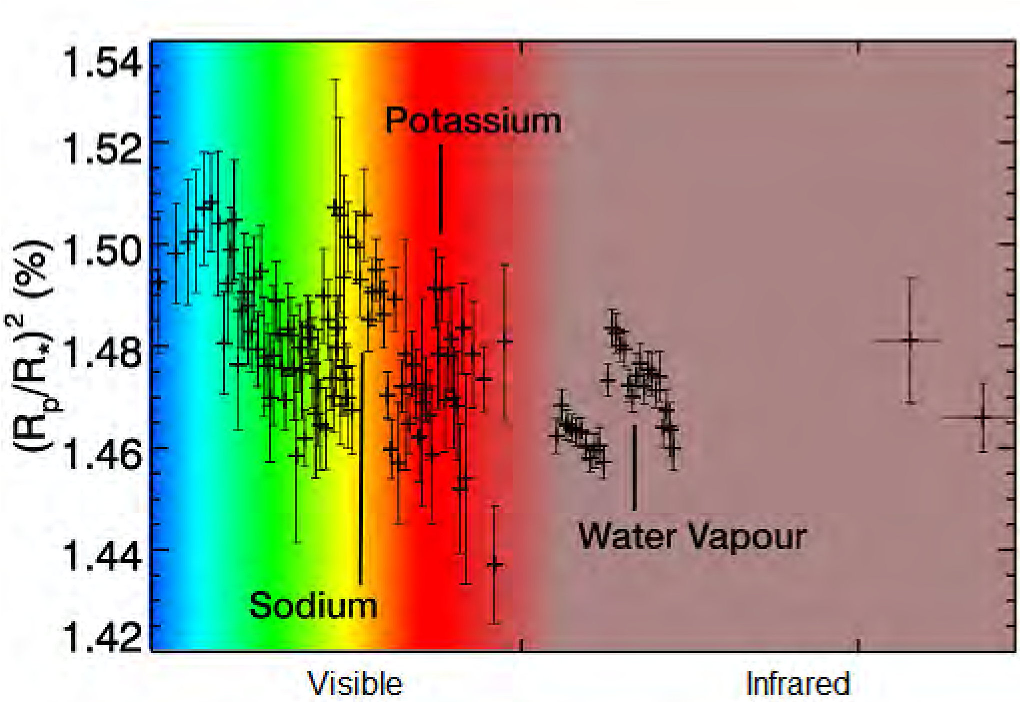


Figure 16 HD 209458 b transmission spectrum

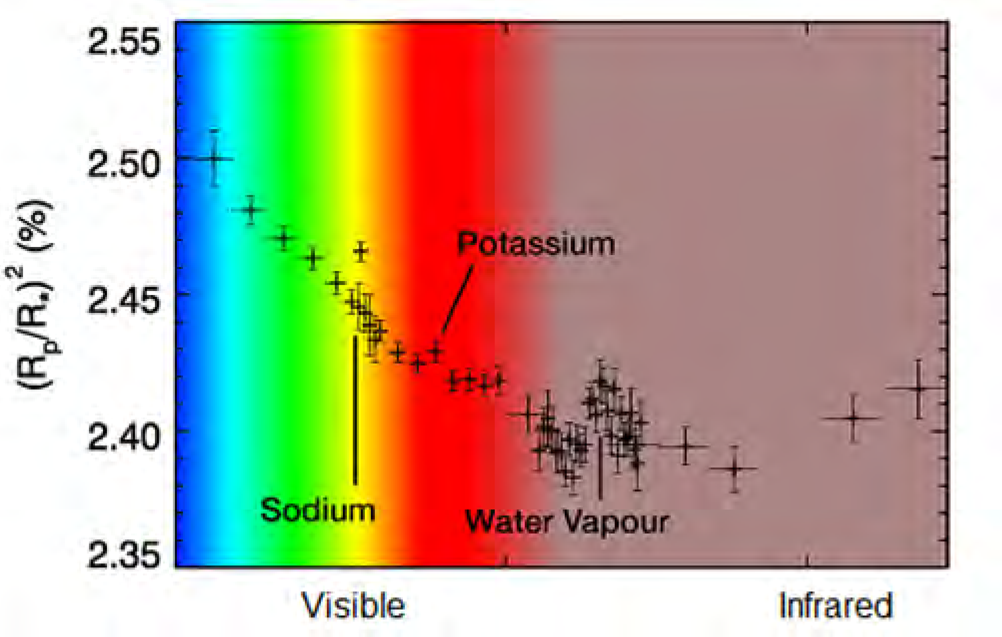


Figure 17 HD 189733 b transmission spectrum

Figure 17 shows the measured transmission spectrum for HD 189733 b. You can see that, as in the HD 209458 b spectrum, sodium, potassium and water vapour are all identified, but their signatures look very different. The sodium and potassium signatures in particular are tiny.

Why is this? Scientists think the answer is *clouds*. Clouds high up in an atmosphere can stop starlight from passing through so easily, making the planet look a bit bigger, and also masking the little bumps and wiggles in the transmission spectrum caused by gases. Nobody should really have been surprised by this, as most of the Solar System's planets have clouds, but no one had really thought much about what clouds might be made of on a 1000 °C planet!

But what do we actually mean by *clouds*, particularly on other planets? Clouds are made of tiny liquid or solid particles that have formed from atmospheric gases. These particles are suspended in the atmosphere to form a visible mass. On Earth, water vapour in the atmosphere condenses to form cloud particles of liquid water or ice crystals. Clouds don't have to be made of water though. In Week 2 you saw Jupiter's clouds, the highest of which are made from ammonia ice. You also saw Venus' sulfuric acid clouds.

Now certainly the temperatures on hot Jupiters are much too high for water to exist in liquid or solid form. Instead, their clouds could be composed of silicate minerals, chemical compounds like aluminium oxide, or even metals, like iron. And just as clouds produce rain on Earth, clouds on hot Jupiters could produce some very exotic and unpleasant rain, perhaps even rain of molten metal.

Inspired by this result, scientists decided to see if they could measure the tiny amount of light that is reflected from the cloudy atmosphere of HD 189733 b. To do this, they looked at what happened when the planet disappeared behind the star, halfway around its orbit from the transit. Sure enough, as the planet disappeared they saw a little bit less blue light coming from the system, but the amount of red light they saw didn't really change. This told them that the planet HD 189733 b would look blue if we could see it up close, perhaps looking like the image in Figure 18.

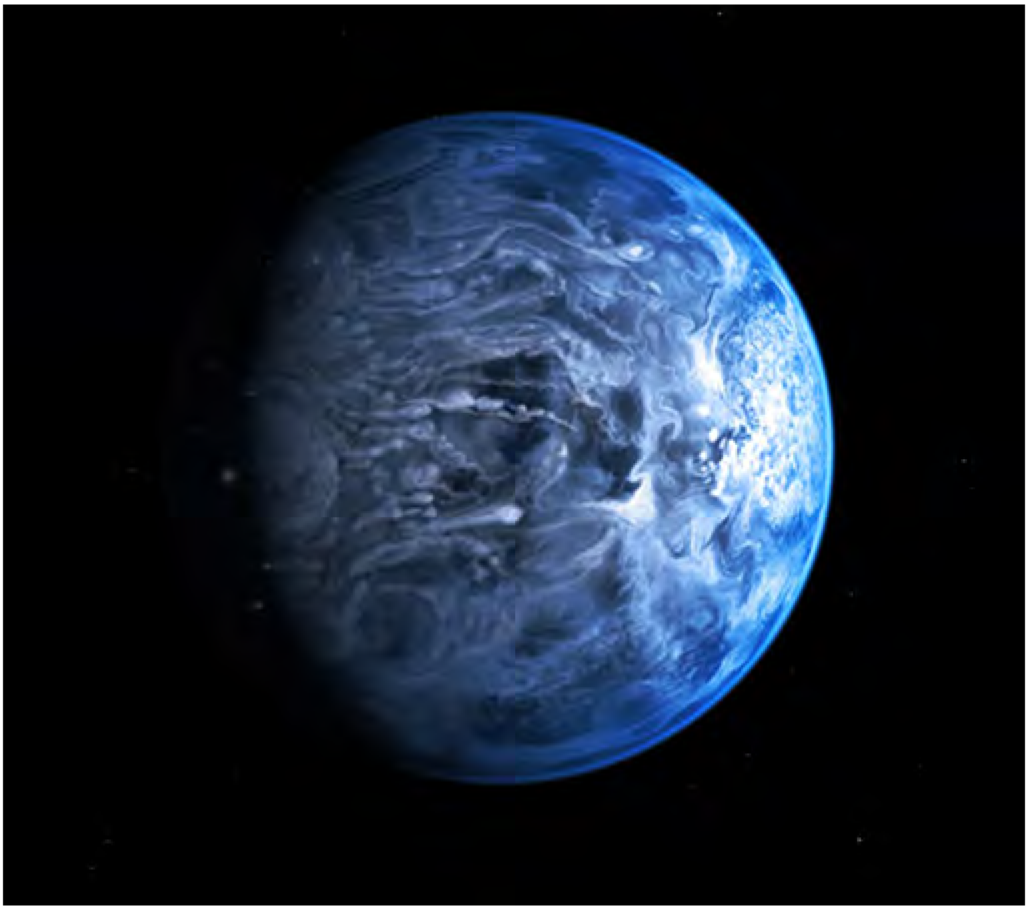


Figure 18 Artist's impression of the deep-blue, cloudy planet HD 189733 b. The clouds are expected to be made of material similar to molten glass because the planet is so incredibly hot.

Our final 'hot one' is WASP-12 b. This is a strange planet, about 1000 °C hotter than HD 189733 b and HD 209458 b. Because it's being 'cooked' so much by its star, astronomers think that it's in the process of losing its atmosphere. The heated gas expands so much that it escapes the planet's gravity; some of it falls onto the star and some diffuses outwards to shroud the entire planetary system in a wispy gas. This phenomenon was discovered by researchers at The Open University using the Hubble Space Telescope, by looking at how spectra of the system changed as the planet and its vastly expanded atmosphere transit its star. In effect, the star is consuming its planet.

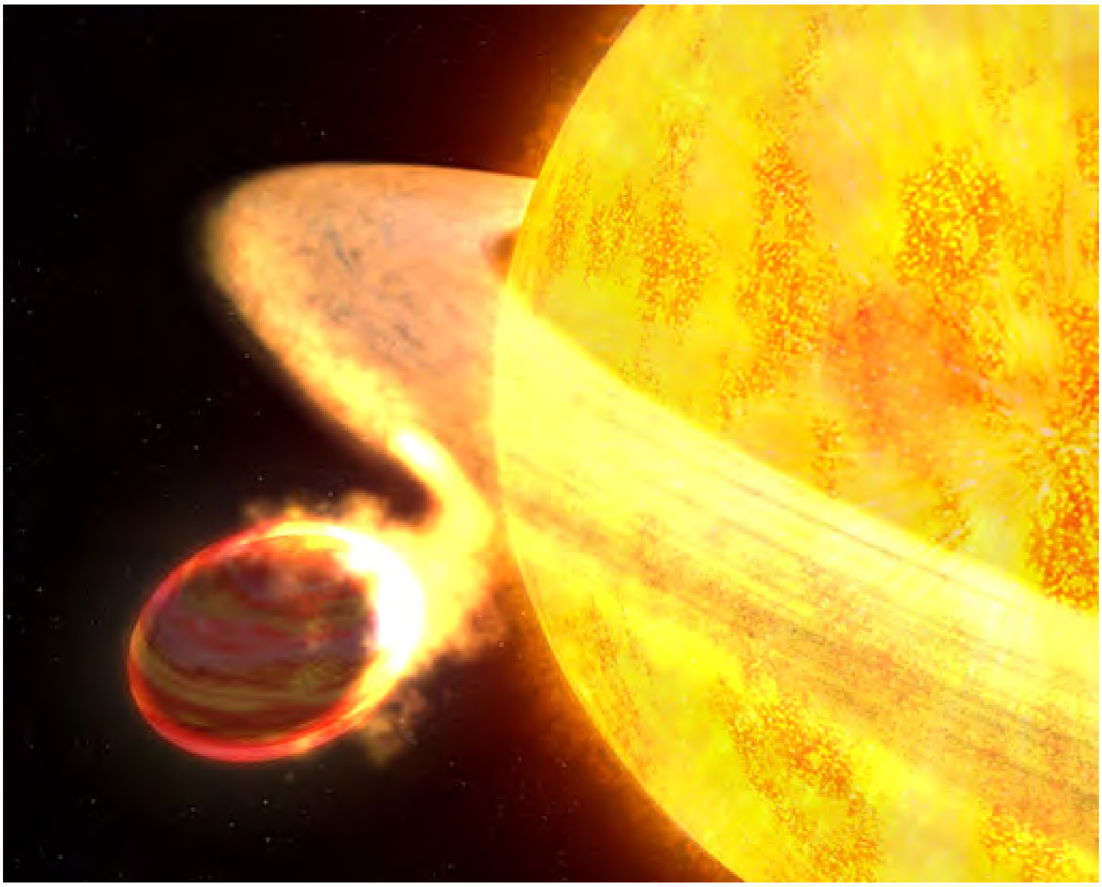


Figure 19 Artist's impression of the shrouded WASP-12 planetary system. The super-hot planet WASP-12 b is being heated to such an extent that it is losing its outer gaseous layers, feeding its star and creating a diffuse gas cloud surrounding the entire planetary system.

Activity 2 Pick your favourite planet

Allow about 20 minutes

Pick one of the hot Jupiters HD 209458 b, HD 189733 b and WASP-12 b and look it up online. There's quite a lot of information about all three, since all have made the newspapers at some point. You can also look them up on Exoplanet.eu. See if you can find out when your chosen planet was discovered, how big it is compared with Jupiter, and how hot it is. What is the fact that most surprises you about your planet?

4.2 The small ones: GJ 1214 b and GJ 1132 b

Although it's generally easier to find and measure large planets, there are a few smaller planets that have been looked at in detail. One of these is the super-Earth GJ 1214 b.

As you learned in Week 6, GJ 1214 b was discovered in 2009 by the MEarth survey. Its discovery generated a lot of excitement, because at the time it was one of the smallest exoplanets found. It is only about 2.5 times the radius of the Earth, so it is somewhere between Earth and Neptune in size. It is also much cooler than most of the hot Jupiters found, at only around 200 °C – although it's still a bit on the toasty side compared to Earth!

Because it orbits a relatively nearby, small, cool star, GJ 1214 b was a perfect target for transmission spectroscopy. Remember, nearby stars, and stars that are small, make it much easier to detect a planet and then make precise measurements. Virtually every available instrument was used to observe GJ 1214 b, and, at first, results seemed to be promising but inconclusive. There were hints of wiggles in the spectrum, but no gas was firmly identified.

The shock came when a team of astronomers from Chicago watched GJ 1214 b transit on 12 separate occasions, and combined the results. Suddenly, what they were looking at was a completely flat, featureless spectrum (Figure 20). That wasn't the plan at all!

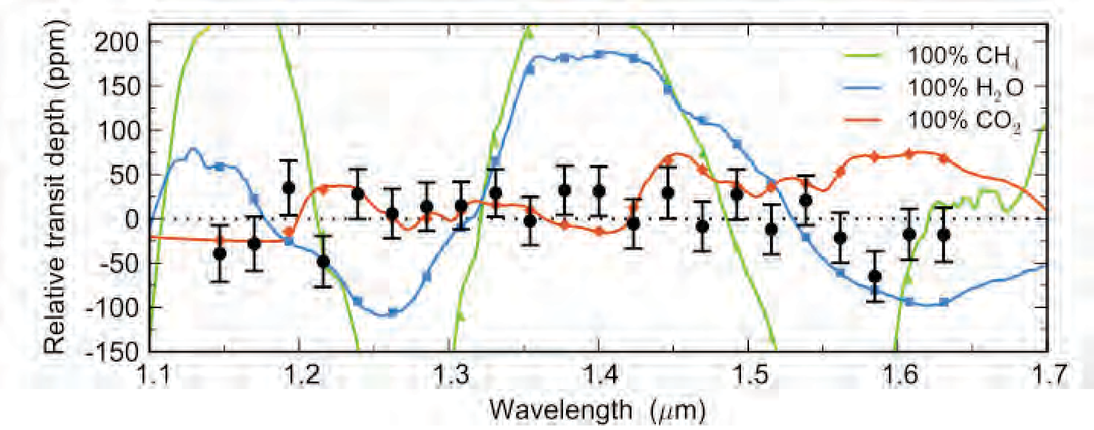


Figure 20 GJ 1214 b transmission spectrum. The measurements are shown as black circles (with error bars). The coloured lines are models for different atmosphere compositions used as a comparison. The changes in transit depth are so small that they are measured in a unit called 'parts per million' (ppm) – ten thousand times smaller than our more familiar percentage measure ('parts per hundred').

If GJ 1214 b has an atmosphere, its transmission spectrum is expected to be wiggly, like those of the hot Jupiters you looked at. So why is it so flat? Maybe GJ 1214 b doesn't have an atmosphere at all? If it is just a bare lump of rock then its spectrum would look that flat.

Activity 3 Does GJ 1214 b have an atmosphere?

Allow about 5 minutes

In Week 2, you learned about planet density. For GJ 1214 b to be rocky, it must have a suitable density for a rocky planet. But does it? You decide.

The density of GJ 1214 b is 1.6 g/cm^3. Can you remember the typical densities of planet types you met earlier in the course? Which type of Solar System planet is GJ 1214 b more likely to resemble?

Answer

The density of GJ 1214 b is much lower than the density of Earth (5.5 g/cm^3). In fact, it has the same density as the ice giant Neptune, and so it is probably not a rocky planet.

You probably decided that GJ 1214 b isn't dense enough to be rocky. So that's not a good explanation for why its spectrum is so flat. What other reason could there be?

It turns out that the clouds struck again – GJ 1214 b is just a very cloudy planet. If a planet is cloudy enough and the clouds are high up, it can stop almost all starlight from getting through the atmosphere. That means that there are probably gases there, we just can't see the wiggles.

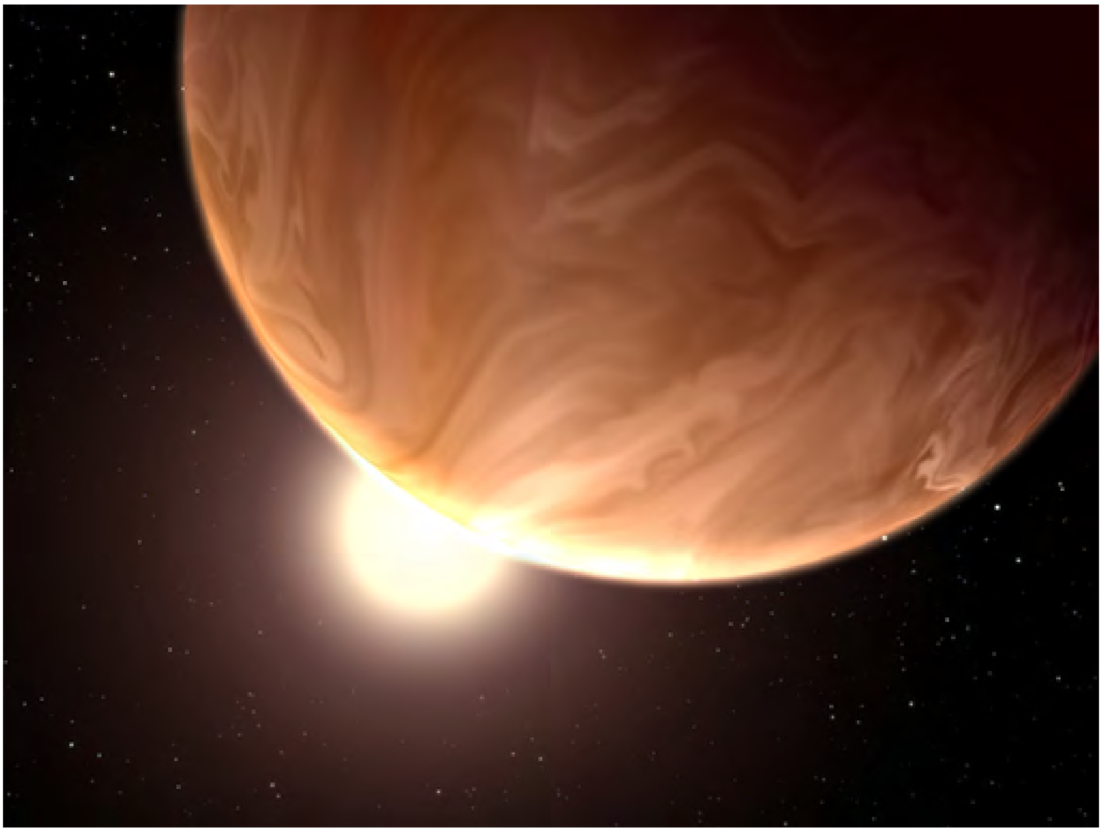


Figure 21 Artist's impression of the cloudy planet, GJ 1214 b

The MEarth survey found another small planet in 2015, called GJ 1132 b. Unlike GJ 1214 b, this planet is closer to being Earth-sized – it's radius is 1.2 R_E – and its density indicates that it is probably rocky. GJ 1214 b may not have turned out to be the super-Earth everyone wanted, but GJ 1132 b looks more likely to fulfil expectations. Like GJ 1214 b, it is close by so is an exciting prospect for detailed study. Its temperature is likely to be similar to that of Venus – so over the next years we might have the opportunity to study a Venus twin in detail. Of course, Venus is very cloudy, so transmission spectroscopy of GJ 1132 b may also give us a flat line. Initial spectroscopic studies are giving differing results and we will probably have to wait for new technology that you'll learn about in Week 8 to really know what GJ 1132 b is like.

Incidentally, the record to date for the smallest exoplanet goes to Kepler-37 b, with a radius of 0.34 R_E, smaller than Mercury and only just a little larger than our Moon. This 'sub-Earth' is thought too small and too hot to hold onto any atmosphere though.

4.3 The disintegrating one: Kepler-1520 b

This is one of the most fascinating 'planets' discovered to date. When it was first discovered, Kepler-1520 b was known as KIC 12557548 b, and it took a while for it to be officially acknowledged as the 1520th planetary system named by the Kepler team. The reason for this is that it is very unusual, and no similar planet had ever been found previously, or even predicted.

Kepler-1520 b is probably roughly the size of Mercury, and is likely to be a rocky planet, but the transits don't look normal. The depths of the transits change a lot, which makes astronomers think they are caused by a cloud of dusty material around the planet. Different amounts of dust are seen each time the planet transits. Obviously a solid spherical planet cannot produce a changing transit depth because the cross-section of the planet would always be the same. Only something which changes size can change the amount of starlight being blocked, to create a transit depth which is different from one orbit to the next. This led astronomers to the dust-cloud explanation.

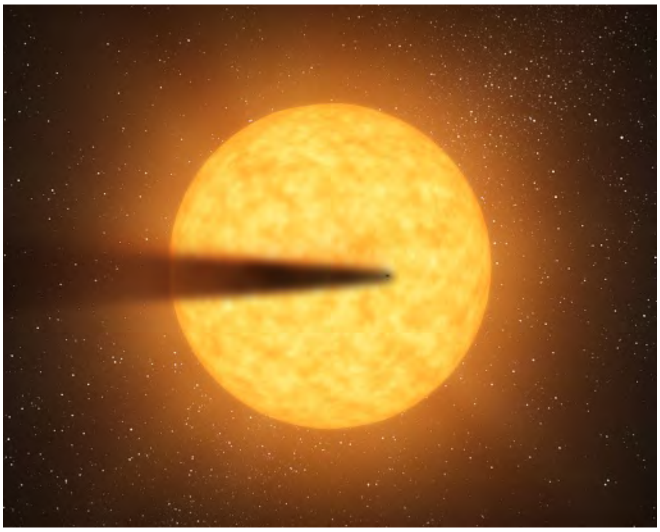


Figure 22 Artist's impression of Kepler-1520 b with a dusty comet-like tail of debris as the planet is gradually vaporised

If the transits are caused by a transiting dust cloud, each individual transit should be very slightly deeper in blue light than red. This prediction comes about because dust scatters and blocks blue light far more effectively than it scatters and blocks red light. This same property causes sunlight to appear red at sunrise and sunset: at these times we see the Sun through a long, almost horizontal path through Earth's atmosphere. The long path takes the light through a lot of dust, and many of the blue photons are scattered, while the red photons pass through. In 2015, researchers from The Open University detected the difference in depth between the red and blue transits of Kepler-1520 b, confirming the dust-cloud hypothesis.

Where this dust is expected to come from is quite remarkable. Kepler-1520 b's proximity to its star would result in surface temperatures of around 2000 °C and astronomers believe the rocky surface facing the star is being turned directly to vapour, perhaps having already lost much of its original mass.

The compelling thing about Kepler-1520 b is the way the material from the planet is spread over a large distance. This may allow astronomers to use transmission spectroscopy to measure the composition of the disintegrating rocky surface. Unfortunately, Kepler-1520 b is very distant and so appears faint. It would be really exciting if we could find a similar disintegrating planet orbiting a bright, nearby star.

4.4 The habitable ones? TRAPPIST-1 planets

In May 2016 one of the most remarkable exoplanet discoveries to date was announced, to surprisingly little fanfare. As you saw in Week 6, the ground-based telescope TRAPPIST had discovered its first planetary system with not one but three Earth-sized planets. They were orbiting a particularly small, cool M dwarf star within 40 light years of the Solar System. Further announcements increased the count to seven planets, all terrestrial-sized, the most of any system so far. All seven planets were transiting (Figure 23).

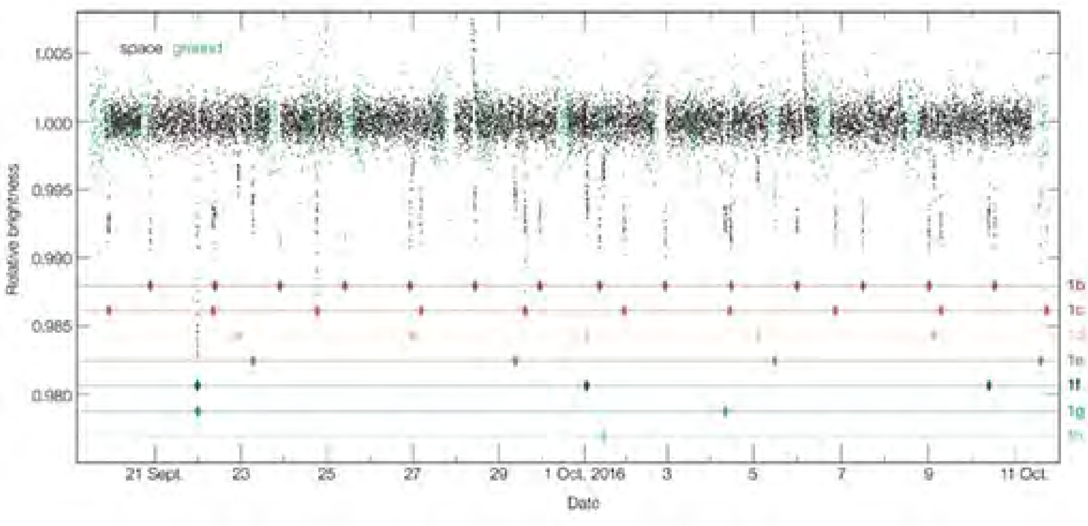


Figure 23 Light curve of the TRAPPIST-1 system, showing the wonderfully complex pattern of dips in brightness due to the seven transiting planets. The planets are indicated in the bottom half of the figure. The data was assembled from several ground-based telescopes and NASA's Spitzer Space Telescope.

Kepler had found many Earth-sized planets before, so why was this one so exciting? TRAPPIST-1 is close enough for there to be a realistic chance of obtaining transmission spectra of the planets – and three of them are considered to be in the habitable zone of the parent star. In Week 6, you learned about the habitable zone – it means that liquid water might be present on the surface of that planet, and so there is a possibility that the planet has an Earth-like atmosphere and conditions.

Figure 24 Artist's impression of the TRAPPIST-1 system from the surface of the outermost planet

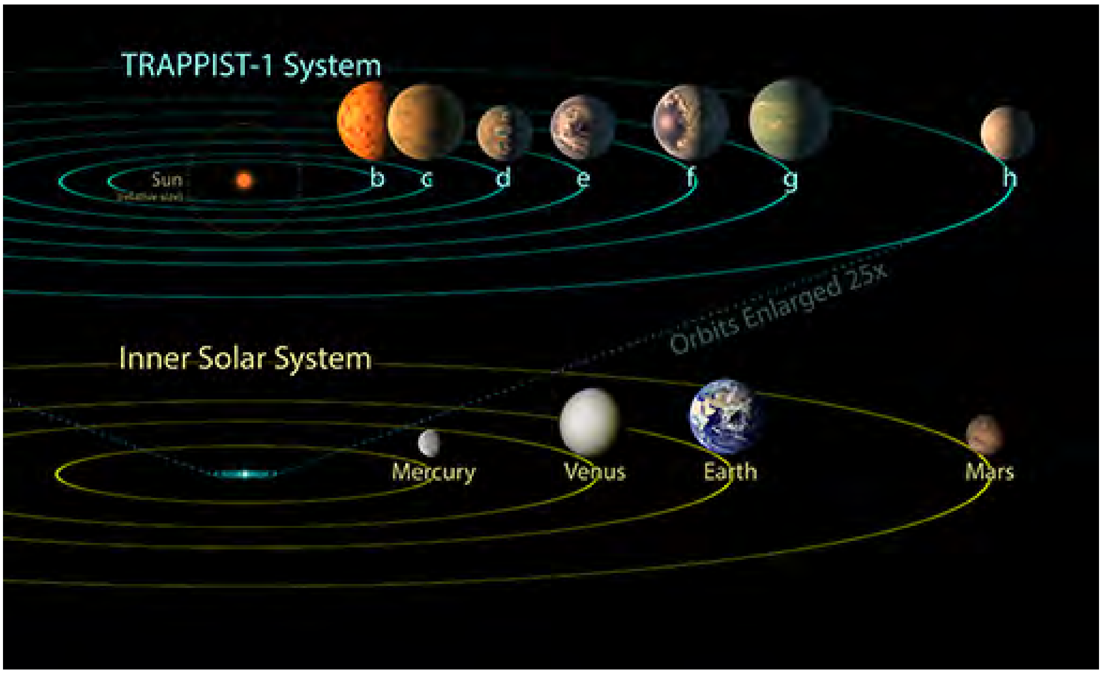


Figure 25 Comparison of the scale of the TRAPPIST-1 planetary system with the Solar System. The orbits of all of the seven planets discovered to date could easily fit within Mercury's orbit.

Astronomers rushed to conduct the first spectroscopic study of the planets, using the Hubble Space Telescope. These preliminary investigations left a number of scenarios that would be consistent with the results, but they pave the way for the future. As with GJ 1132 b, it seems we will have to be patient, but it's likely that we will be able to improve on these studies in just a few years' time.

The TRAPPIST-1 planets lead nicely into next week's work when you will look at future observatories, including the one that might uncover the secrets of this captivating system.

Activity 4 The TRAPPIST-1 planetary system

Allow about 30 minutes

See if you can find out anything more about the TRAPPIST-1 planetary system using the internet. Write a bullet-pointed summary of what is known.

Answer

There will be new studies of this system as time progresses, so you should be able to find out more than what is listed here – this is a start!

- The densities of the seven planets range from 3.4 g/cm^3 to 5.6 g/cm^3.
- All of the seven planets may have regions where liquid water could exist on their surface.

Activity 5 Life on another planet

Allow about 10 minutes

List all the things you can think of that are necessary for life to exist. Does the discovery of the TRAPPIST-1 system make you think life on another world is likely or unlikely?

Answer

We could devote a whole course to the definition of life, but we will stick to life as we know it on Earth: water, stable conditions amenable to the formation of complex carbon-based molecules like DNA, not too much harmful radiation, a source of energy.

The TRAPPIST-1 planets are orbiting a star which is very close to the Sun, at least 'close' in the context of the size of our Galaxy. Low-mass planets orbiting dim stars are intrinsically quite difficult to find and study. The fact that we are finding potentially habitable planets so close to us tends to suggest that the Galaxy might be full of such planets. Some of these could fulfil requirements like those above. So, there might be planets out there that we'd be able to walk around on.

5 This week's quiz

Well done – you have reached the end of Week 7 and can now take the weekly quiz to test your understanding.

Week 7 practice quiz

Open the quiz in a new tab or window (by holding down Ctrl [or Cmd on a Mac] when you click the link).

6 Summary of Week 7

This week, you've learned about the concept of transmission spectroscopy, and you've had the opportunity to try out being an exoplanet atmosphere detective. You've also learned about measurement uncertainty – one of the most important concepts in all scientific disciplines – and you've discussed some of the things that can affect it. You've been introduced to some of the most exciting and wonderful exoplanets we've discovered so far, and looked for the most up-to-date news on them.

You should now be able to:

- have a qualitative appreciation of how transmission spectroscopy tells us which atoms and molecules are present in exoplanet atmospheres
- appreciate why astronomers can get better measurements when an object is nearby
- recognise the importance of:
  - HD 189733 b, HD 209458 b and WASP-12 b
  - GJ 1214 b and GJ 1132 b
  - Kepler-1520 b
  - the TRAPPIST-1 system.

Next week, you'll look at potentially the most important exoplanet discovery there will ever be. You'll also learn how we expect to find out even more about these brave new worlds with future observatories.

You can now go to Week 8.

Week 8: Where do we go from here?

Introduction

This is the final week of your introduction to exoplanet science, and this week you'll be looking at the future of the field. There's a lot to be excited about, and much potential for groundbreaking discoveries over the next few years. We hope you've enjoyed this course and that you'll be keeping an eye on future developments!

Watch the following video with Carole Haswell.

Video content is not available in this format.

By the end of this week, you will be able to:

- explain why it is likely that nearby stars host exoplanets
- describe the 2016 planet search around Proxima Centauri
- explain the importance of the Kepler-444 planetary system
- summarise prospects for extraterrestrial life
- be familiar with Gaia, TESS, JWST, PLATO, Twinkle and ARIEL
- describe current and future possibilities for direct imaging of exoplanets.

1 Welcome to the neighbourhood

You learned in Week 6 that large exoplanet surveys such as Kepler have allowed statistical estimates to be made of how many stars have planets. Astronomers have recently discovered it's likely that stars have an average of one or more planets each. That means that there must be several planets around the stars nearest to the Sun.

Many of the exoplanets discussed in Week 7 are relatively close to Earth, residing in a region of space around 300 light years across called the 'Local Bubble'. This includes GJ 1214 b, HD 189733 b, HD 209458 b and, of course, the recently discovered TRAPPIST-1 planets. But a number of exoplanets have now been found even closer by. By the end the first decade of this century the closest confirmed detections of exoplanets were around stars 15 light years away. In 2015 the discovery of the first 'close' potentially rocky habitable planet was announced, orbiting the M dwarf star Wolf 1061, around 14 light years away. This 'super-Earth' was discovered using the radial velocity method and does not transit its star, so unfortunately we know relatively little about it.

In Week 6 you briefly reviewed our solar neighbourhood, out to a distance of about 15 light years. One current estimate is that there might be around 30 stars with Earth-sized planets in this region of space, as well as larger planets. The statistics suggest that eight or more of these Earth-sized planets will reside in the habitable zone of their star. Earth-sized planets are difficult to find though, so it's possible there are actually more – the estimates of numbers of small planets might be increased as astronomers identify new small planets on which to base the statistics.

While it's thrilling to know that there are planets around other stars neighbouring the Solar System – even possibly supporting life – the distances between stars is huge, so we are still a long way from being able to visit them. While people are beginning to explore ideas for technology that would allow us to visit these systems, it certainly doesn't exist yet. But if we *were* going to visit another planetary system, we'd pick the closest one possible. Before sending people to another star, we will undoubtedly send machines, just as we did with the exploration of the Moon. The Soviet Union's Luna 2 probe reached the Moon a decade before the NASA astronaut Neil Armstrong walked on the Moon's surface. Already, the Breakthrough Starshot project plans to send tiny laser-propelled 'nanocraft' to the nearest star.

2 The Pale Red Dot search: a planet around our closest neighbour?

As well as being the first choice destination for a visit, closer systems are much easier to study from a distance using telescopes. So this led to speculation: does our nearest star have planets?

In the following sections you will explore some of the stars nearest to us, learning about exoplanet discoveries and their potential for harbouring life.

2.1 Our closest stellar neighbour

The closest star to the Sun is an M dwarf – a small, cool, red star called Proxima Centauri, or Proxima for short (Figure 1). It is very dim – despite its proximity to us it appears one hundred times fainter than could be seen with the naked eye. It is part of a triple-star system with the binary stars Alpha Centauri A and B. In recent years astronomers suspected that they'd found planets orbiting Alpha Centauri B, although unfortunately further studies have questioned their existence.

Figure 1 (available here) The size of Proxima Centauri compared with Alpha Centauri A and B, the Sun, and the planets Jupiter and Saturn

But what about Proxima Centauri? It's a very favourable target for a planetary search. You've looked in previous weeks at the things that make it easier to detect a planet around a star, so now it's time for a quick refresher of them.

Activity 1 What makes a planet easy to spot?

Allow about 10 minutes

Can you remember what factors about a star make a planet easy to spot?

Is it easier to spot planets around a star that's (a) nearby or (b) further away?

Answer

(a) nearby

Is it easier to spot planets around (a) large, high-mass stars or (b) small, low-mass stars?

Answer

(b) smaller, low-mass stars are usually better because the planets create a greater orbital wobble or block relatively more of the star's light in transit. However, lower-mass stars are also fainter, so if they aren't near enough it can make things difficult.

If you want to find a small planet, what kind of star would you choose to observe?

Answer

Small, cool, nearby stars are best because there is enough light to get a precise measurement and the signal from the planet will be relatively large.

Because Proxima Centauri is small but close by, it is a good target for a radial velocity (RV) search. The transit method only works if the system is lined up perfectly, so the planet passes between us and the parent star. The RV method works for almost all orbital orientations, as you saw in Week 3. So, the Pale Red Dot project was born. Starting in January 2016, astronomers used the HARPS instrument mounted on the La Silla telescope in Chile to observe Proxima Centauri (Figure 2) and measure any tiny shifts in the positions of absorption lines in its spectrum (Figure 3).

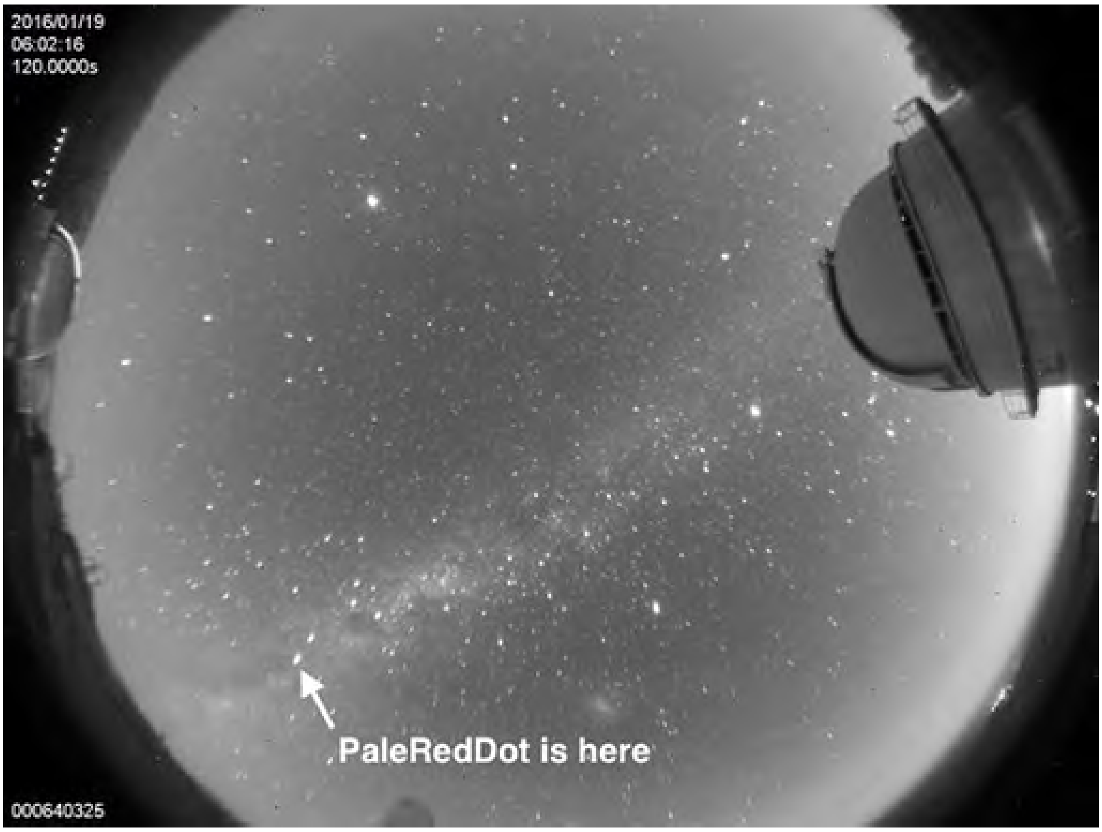


Figure 2 Proxima Centauri rising above La Silla

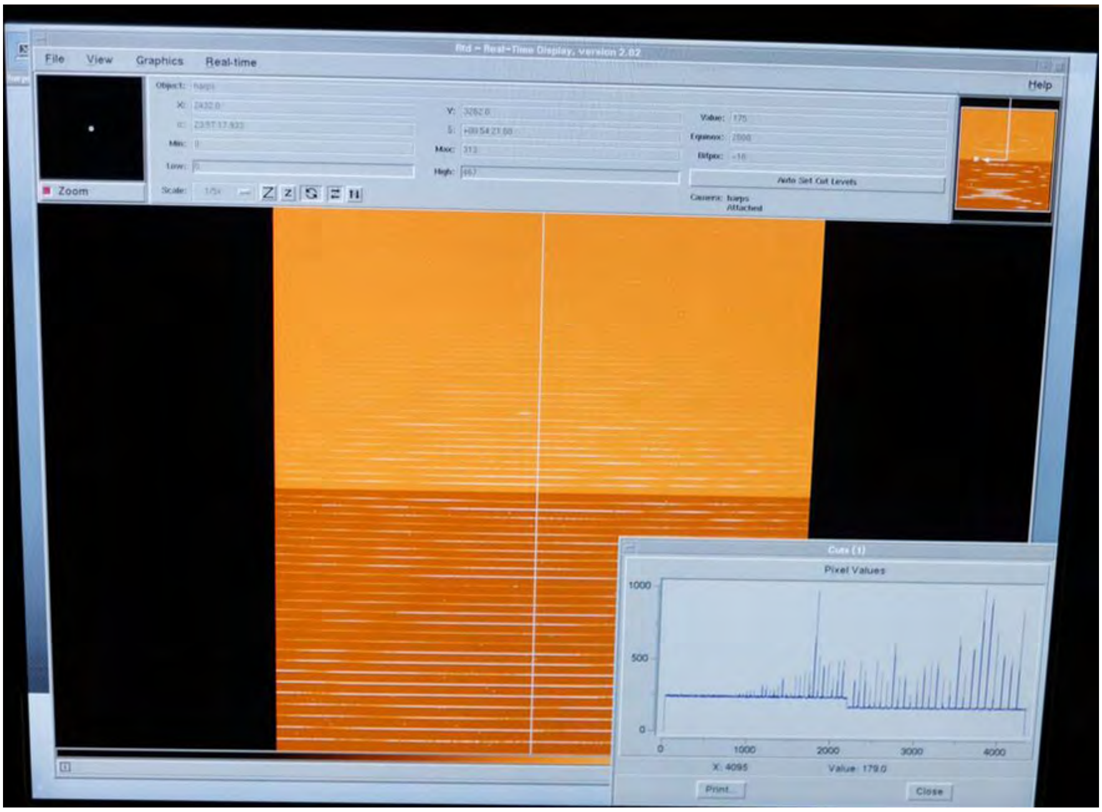


Figure 3 First spectrum from the Pale Red Dot project, which was broadcast live by the astronomers at the telescope

2.2 Our closest exoplanetary neighbour!

In August 2016, the Pale Red Dot team announced that they had indeed found a planet orbiting Proxima Centauri. The minimum mass of the planet, Proxima b, is 1.3 Earth masses, so it may well be that Proxima b is a terrestrial planet, like Earth.

Proxima b completes an orbit in about 11 days. This is much shorter than an Earth year because Proxima b is much closer to Proxima than Earth is to the Sun. In fact, the distance between Proxima b and its star is about 1/8th the distance between the Sun and Mercury. Despite this, because Proxima is much less luminous than the Sun, the planet has a temperature similar to Earth – just right for liquid water to exist on its surface. Such a planet has the potential to host life. This is just as you saw in Week 6 when you examined the locations of the habitable zone for stars like the Sun and M dwarf stars.

So, Proxima b is a potentially habitable planet orbiting the closest star to the Sun. This is very exciting news – maybe aliens are not that far away from us! The discovery attracted a lot of international news coverage:
A planet discovered close enough to Earth to be reached by future space missions could contain life.

2.3 Consequences of being so close to a star

Being so close to your star is not all good, even if it is a relatively cool M dwarf like Proxima Centauri. Proxima b would be a very different world from Earth despite being similar in size. As shown in Figure 4, the small, dim, red star would appear large in the planet's sky.

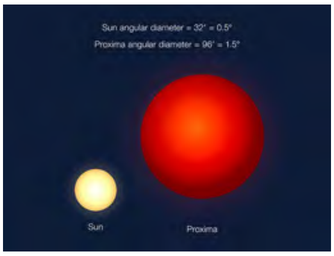


Figure 4 The M dwarf star Proxima Centauri as it would appear from its planet Proxima b compared with the size the Sun appears in our sky from Earth

As you learned in Week 6, being so close leads to tidal locking. The same part of Proxima b always points at its star. The Earth spins daily, so every part of our planet spends some time in sunlight, but there will be no cycle from day to night anywhere on Proxima b. On the dayside of Proxima b, the large disk of the dim red star will always beam down from exactly the same direction and temperatures will be high. On the nightside of Proxima b, it will be freezing and completely dark, except when Alpha Centauri A and B are in the sky (Figure 5). While Proxima b might have liquid water somewhere on its surface, perhaps in the boundary region between the two extremes, conditions there will be very different from the conditions on Earth.

Figure 5 Artist's impression of Proxima b's sky with its parent star Proxima Centauri remaining close to the horizon and the binary star Alpha Centauri AB to the upper right

You might imagine that small, dim M dwarfs like Proxima Centauri are peaceful stars, but are they really? The colours of starlight beyond violet in the electromagnetic spectrum – ultraviolet light – can be harmful to life. It is ultraviolet light that causes sunburn and overexposure can increase the chance of developing skin cancer. We are protected from the damaging radiation by our atmosphere. However, all stars release sudden explosions of energy called flares (Figure 6), which are often accompanied by jets of hot stellar material thrown out into space. Planets close to their stars might be gradually stripped of any atmosphere by such activity, leaving them exposed to this harmful kind of light.

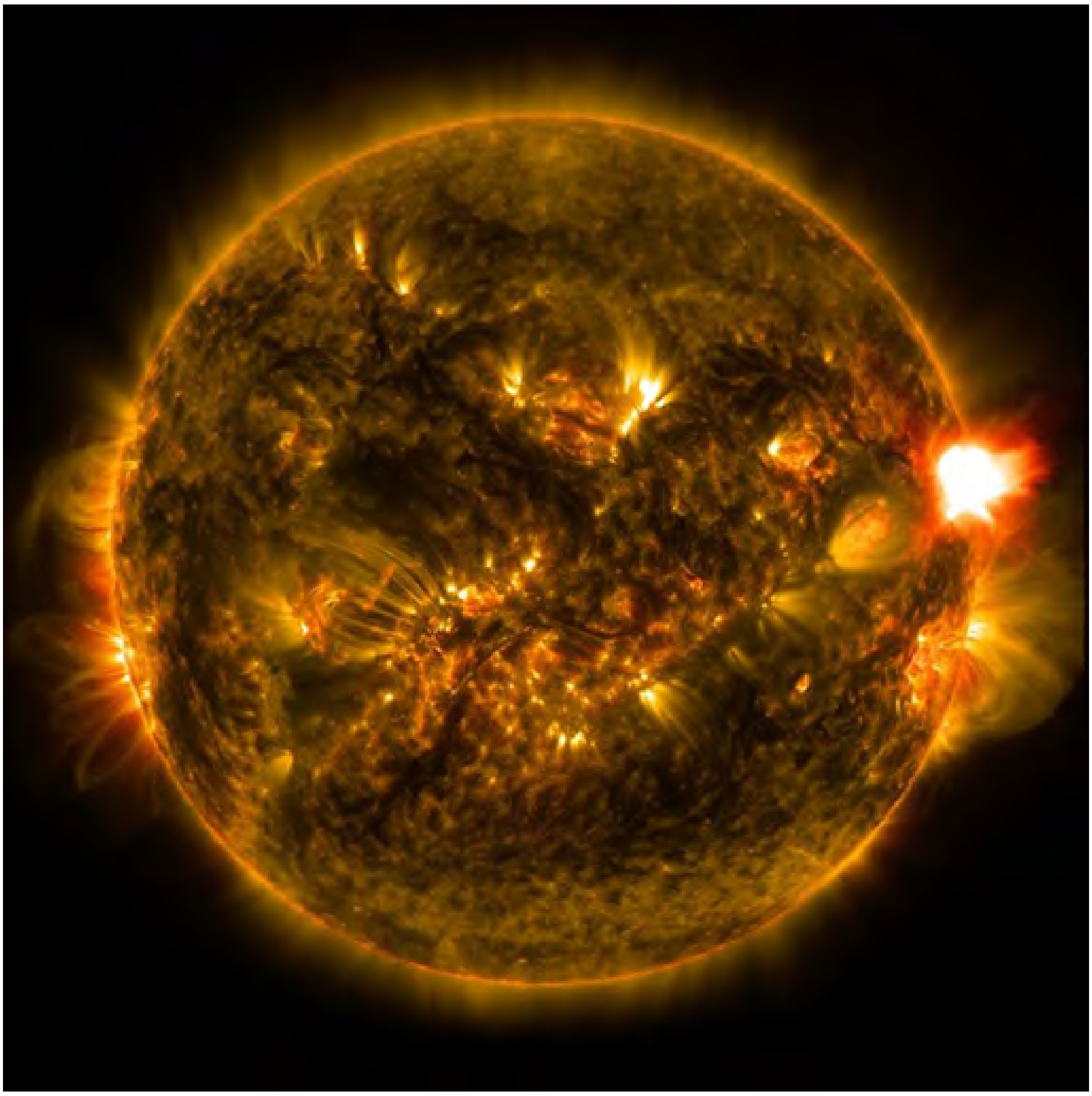


Figure 6 A flare emitted by the Sun is imaged by NASA's Solar Dynamic Observatory in ultraviolet light

Perhaps surprisingly, many M dwarfs including Proxima Centauri are very active stars. This is due to their internal structure being different from hotter stars like the Sun – the energy generated in their cores is transported to the surface entirely by convection currents, like water heated in a saucepan.

We might have hoped that Proxima b could retain or replenish its protective atmosphere in spite of such activity, but an observation in May 2016 and reported in 2018 seemed to dramatically reduce the possibility of Proxima b being home to life. Proxima Centauri emitted a 'superflare' so bright that the star became visible to the naked eye, ten times more powerful than any flares seen from Proxima Centauri before. Some bacteria on Earth can survive very high levels of radiation but if fully exposed this superflare would have been deadly even for them.

2.4 But what is it really like?

There is a lot of speculation about conditions on Proxima b. Strictly speaking, all we really know for certain is its orbital period, its minimum mass and how much starlight it receives.

As soon as the 2016 discovery of Proxima b was announced, astronomers started observations designed to search for transits. The probability of transit is increased by the closeness of the planet to its star, but it would still be very lucky indeed if the orbit happens to line up in this way. Because the star is so small, there is still only a 1.5 per cent chance that the orbit will be aligned such that we see transits. Returning to our hide-and-seek analogy from Week 5, the situation with Proxima b is like hiding behind a slender tree: your alignment needs to be exact.

It would have been exciting if Proxima b did transit. We would then be able to measure the size of this potentially habitable planet and hence its average density and likely composition. If a transit is discovered, all the telescopes we have will be trained on Proxima Centauri to measure the transit depth at all possible wavelengths. This will allow astronomers to discover whether Proxima b has an atmosphere and, if there is an atmosphere, what atoms and molecules it contains. At the time of writing (February 2019), it seems that the orbit of Proxima b is not favourably aligned for it to transit its host star: astronomers would probably have detected the transit by now.

However, there are other nearby stars.

2.5 Exploring the Galaxy's rocky planets

Whether or not Proxima b shows transits, there will be a lot of effort directed at measuring everything we can about Earth's nearest cousin. As you saw in the video in Section 2.2, we may be able to send small robotic spacecraft to Proxima b. Within 20 or 30 years we may see pictures from this planet, just as we now see images of the Martian landscape from space probes sent with cameras and radio transmitters.

Finding a potentially habitable planet in our own stellar neighbourhood gives us hope that we'll find plenty more close by. For the transiting examples, we will be able to measure their size and density, and learn about the gases present in their atmospheres. You will learn more about how rocky planets form and how they change over their lifetime. You will also look for evidence that a planet is not only habitable but inhabited.

2.6 Barnard's Star b

In November 2018, another thrilling discovery was announced – an exoplanet orbiting the nearest single star to the Sun, six light years away. This star is called Barnard's Star, named after the astronomer who first studied it. Like Proxima Centauri, Barnard's Star is an M dwarf, about a tenth the mass of the Sun. There is one big difference between the planet, Barnard's Star b, and Proxima b though – it has a much longer orbital period: 233 days compared with 11 days. Discovering a planet with such a long orbital period required the enormous task of very carefully combining many radial velocity measurements spanning 20 years from seven different instruments, and astronomers at The Open University were a key part of the team that did this.

This means that Barnard's Star b is also much further away from its dim parent star than Proxima b is, making it an icy world predicted to experience temperatures of −150 °C. This doesn't rule out the prospect of life completely though – a thick atmosphere creating a strong greenhouse effect could raise the surface temperature to create a more hospitable environment. Another scenario is that even if liquid water can't exist on the surface, it could exist beneath the surface. This is akin to Jupiter's moon, Europa, which is known to have similar icy surface temperatures but a sub-surface liquid water ocean – a tantalising potential habitat for life.

2.7 LHS 1140 system

LHS 1140 is an M dwarf star that is nearly ten times further away than Proxima Centauri, but this is still relatively a very close neighbour. What is significant about this nearby star is that it hosts two planets which transit, making it an ideal candidate for atmospheric studies in the near future, something that you'll learn more about later this week. This also means that their densities can be determined: these planets are marginally bigger than Earth and have densities similar or greater to Earth's so are almost certainly rocky. The first of these to be discovered in 2017, LHS 1140 b, is also the right distance from its star to have liquid water.

Another strong point in its favour is that LHS 1140 is a very inactive star, unlike many other M dwarfs like Proxima Centauri.

Figure 7 An artist's impression of the view of the M dwarf star LHS 1140 from orbit around one of its planets, LHS 1140 b

3 The history of rocky planet formation

In the following sections you will start to think about the chemical elements that make up planets and stars and then go on to look at the Kepler-444 planetary system that challenges our ideas about planet formation.

3.1 Stars, planets and chemical elements

Astronomers know that planets form along with their parent star from vast clouds of gas in space, so the age of the Earth is the same as the age of the Sun: 4.5 billion years (4.5×10^9 years). The Sun itself is middle-aged; it will spend another 4.5 billion years as a main sequence star, converting hydrogen into helium. Then, in the final stages of its life, the Sun, like most stars, will use further nuclear reactions to create heavier elements that didn’t even exist when the Universe was young. The whole Universe, including the Milky Way, is about 14 billion years old. This means there was almost time for another star like the Sun to complete its entire main sequence life before the Sun formed. More massive stars live their lives much more rapidly (on astronomical timescales!), the most massive taking as little as a few million years to leave the main sequence.

At the end of a star’s life it expels material into space, returning it to the Galaxy’s reservoir of gas, including the new elements it has created. This material then goes on to form subsequent generations of stars, as shown in Figure 8. This cycle underpins the formation of rocky planets and of life itself. Only material which has been processed by now-extinct stars contains the chemical elements needed to form rocky planets: chemicals such as iron, oxygen, silicon and magnesium. Similarly, only material which has been processed by now-extinct stars contains the chemical elements which are needed for life: carbon, nitrogen and oxygen.

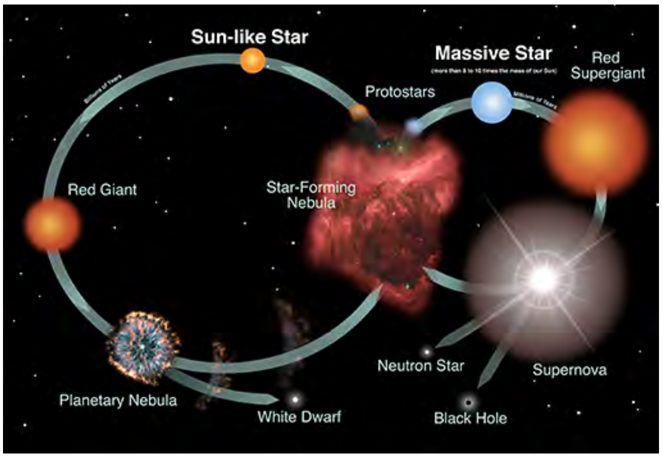


Figure 8 The lifecycle of stars and the cycle of chemical enrichment of the material in the Galaxy

Until recently, astronomers didn’t know if there were many rocky planets in our Galaxy which are older than Earth. It could have taken billions of years for the Galaxy to accumulate enough iron, oxygen, silicon and magnesium in its gas for rocky planets to form.

3.2 The Kepler-444 planetary system

In 2015, astronomers found a system of five transiting planets orbiting the star Kepler-444. Finding five new planets orbiting the same star is exciting, but what is most intriguing about this planetary system is the age of the star: it has been deduced to be 11.2 billion years old. This means Kepler-444 formed when the Universe was young. The planets orbiting this ancient star are small, similar in size to the terrestrial planets in our own Solar System. Kepler-444 probably hosts a system of five rocky planets!

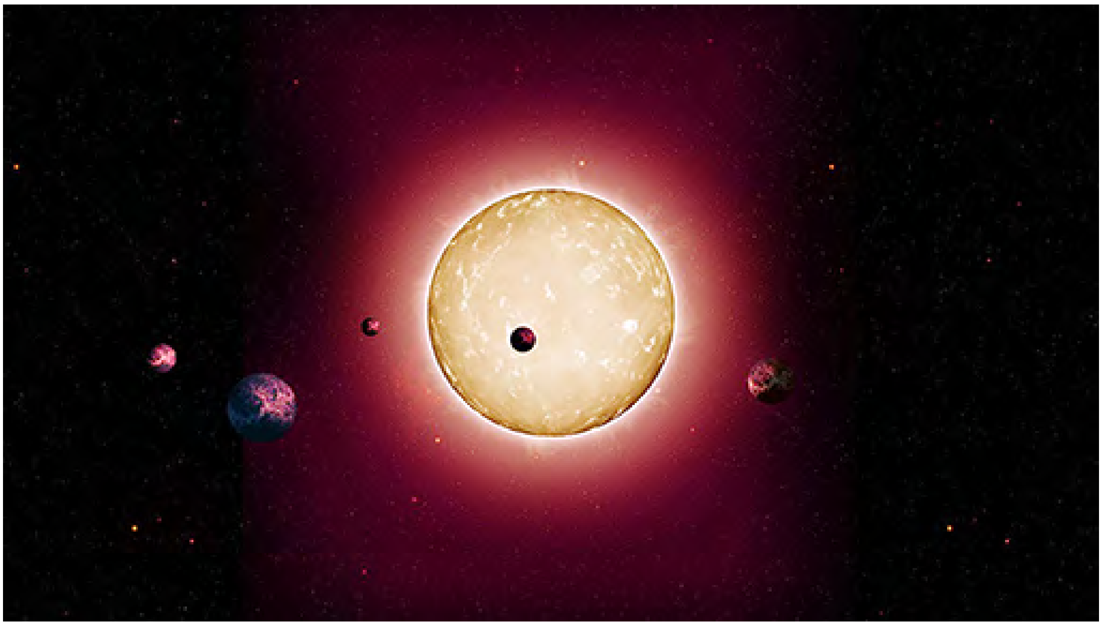


Figure 9 Kepler-444 and its planets

To find terrestrial-sized planets orbiting such an ancient star suggests that rocky planet formation began early in the Universe's history. How might this be possible? Well, researchers suggest that rocky planet formation requires less chemical enrichment than previously thought, less than is needed for gas giants. Habitats similar to the early Earth may have been present in the Universe for much of its 14-billion-year history! This presents the possibility of ancient life in the Galaxy.

4 Prospects for extraterrestrial life

As mentioned in Week 6, we still don't really know how likely it is for life to spontaneously evolve on a planet, even if conditions are apparently favourable. The only way that we can really make an informed estimate is to look for evidence of life on another planet. This evidence may be present in transmission spectra. So, if a potentially habitable planet transits its star, like the planets in the TRAPPIST system, then we may be able to detect signs of life.

4.1 Biosignatures

Signs of life that we can detect in a planet's atmosphere are called 'biosignatures'. These are gases that would be unlikely to occur without the presence of life. Earth's main biosignature is a very important gas for all of us: oxygen.

An atmosphere with as much oxygen as Earth's – 20 per cent of the total – simply shouldn't exist under normal circumstances. This is because oxygen is an extremely reactive gas. That means that it readily combines with other chemicals to form something completely different. So, generally, oxygen doesn't hang around for long.

We experience oxygen's tendency to react with other chemicals every day. When you light a fire, you are adding enough heat to prompt the chemicals in the fuel to combine with the oxygen in the air. After a while, rust forms on iron products left uncoated – this is caused by oxygen in the air reacting with the iron.

Activity 2 Reactions with oxygen

Allow about 10 minutes

For this activity you'll need an apple and a sharp knife. Always take care when using sharp knives!

Cut the apple in half and leave it exposed to the air for a few minutes. You should start to see the apple change colour and turn brown fairly quickly. This is another example of oxygen in the air reacting with other chemicals – in this case, chemicals in the apple. If you like, leave the apple for a bit longer and return to it later: the brown colour will have increased as the chemical reaction has continued – it will look pretty unappetising!

It's possible to prevent apples from going brown by coating them in lemon juice. Citric acid, which is present in all citrus fruit, prevents the reaction with oxygen from happening.

Photosynthesis and oxygen

Given that oxygen so readily reacts with other chemicals, it would be expected to eventually disappear from our atmosphere. But it isn't disappearing. There has been around the same amount of oxygen in our atmosphere for millions of years. The reason is that oxygen is being continuously resupplied to the atmosphere by plants. Photosynthesis is a chemical process that occurs in the cells of plants – they collect light from the Sun and combine it with carbon dioxide gas in the air to form sugars, their energy source. A by-product of photosynthesis is oxygen.

Ozone

The oxygen we breathe comprises an oxygen molecule in the form of two oxygen atoms stuck together. Another gas present in Earth's atmosphere is ozone. This is a gas comprising three atoms of oxygen stuck together, and it can only exist in large quantities if there's a lot of oxygen present. Earth has a layer of ozone gas beginning around 10 km above its surface; it's very useful to us as it absorbs harmful ultraviolet light from the Sun. The ozone layer is a bit like the Earth's natural sunscreen.

If there's enough oxygen and ozone in a planet's atmosphere, it might be possible to detect these gases in transmission spectra. Therefore, if one of the TRAPPIST planets has an atmosphere exactly like the Earth's, we would be able to detect the ozone in its atmosphere, using a space telescope that is due to launch in 2021. You''l learn more about this later.

4.2 Life on strange worlds

Of course, planets like the TRAPPIST planets and Proxima Centauri b orbit stars that are very different from the Sun. To receive enough starlight to be in the habitable zone, planets need to be much closer to cooler stars. You've already met some of the consequences of this for Proxima b.

Tidal locking means that one side permanently faces the star and experiences permanent day, whilst the other side experiences permanent night. We don't know how well life would be able to cope with this sort of environment. The temperature distribution on this kind of planet would be very different from Earth, even if the planet received the same amount of light overall.

It is thought that one very hot super Earth, a planet called 55 Cancri e, may have a dayside surface that is molten lava, due to the extreme temperatures (Figure 10). In Week 7 you met the strange planet Kepler-1520 b, with the possibility of the rocky surface facing the star being turned directly to vapour in a process called 'sublimation'.

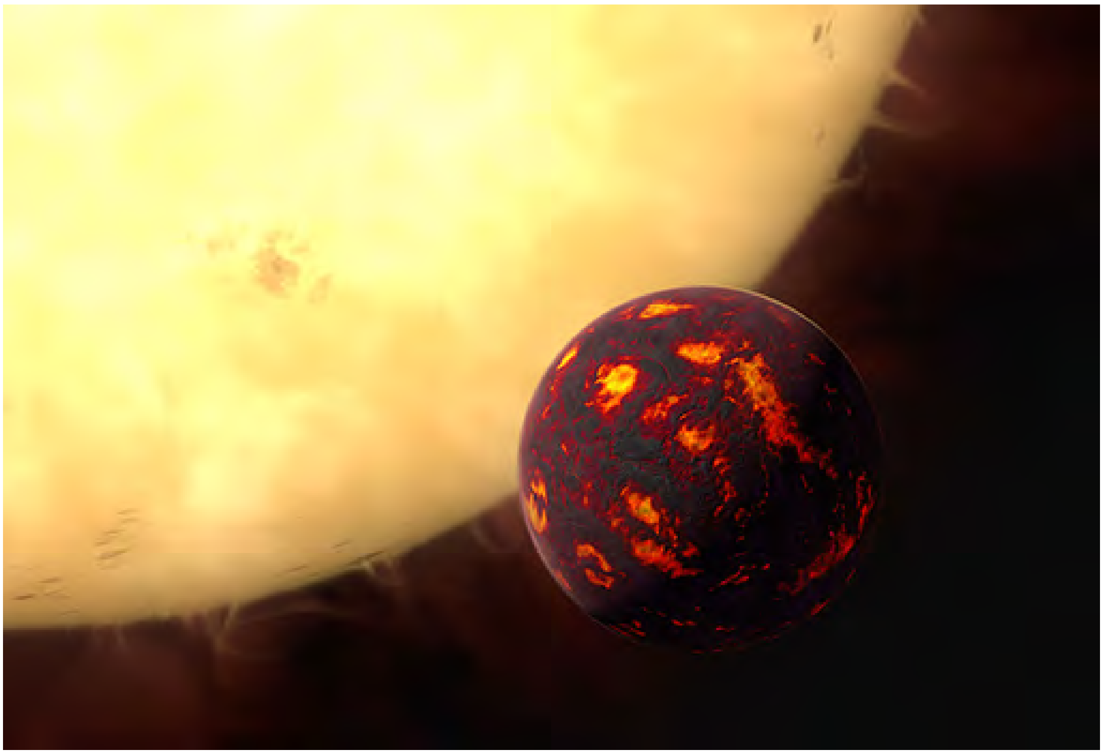


Figure 10 55 Cancri e artist's impression

There is still hope for some close-in planets though. The Earth spins on its axis, but another reason temperatures across our planet don't vary that much is because the atmosphere and the oceans are fluids which can move around the Earth. If a tidally locked planet has a thick enough atmosphere, strong winds could distribute heat around both hemispheres.

It's not just tidal locking that could be problematic for cool stars. As you've already seen with Proxima b, any aliens would also be very vulnerable to stellar flares which might physically strip away the planet's protective atmosphere.

So, life on a planet orbiting close by a cool star could be in for a rough ride, and if we want to find alien life that resembles life on Earth we might be better off looking for Earth twins rather than Earth cousins. These can be rather tricky to find, as you discovered in Week 6, but in the not-too-distant future new space telescopes will be performing this exciting work.

Figure 11 Could this be Earth's twin? (artist's impression)

5 The future of exoplanet exploration

The field of exoplanet research has gone from being non-existent to thriving in just 20 years, and it is showing no signs of slowing down. Several new and imminent projects are designed to discover and study new and exciting planets – some of which may turn out to be eagerly pawaited Earth twins.

5.1 Planet finders: Gaia, TESS and PLATO

These latest missions can be split into two categories: planet finders, and characterisation observatories. One planet-finding mission, TESS, launched in March 2018, is already starting to discover new planets. Gaia is also operational, and has been collecting data on over a billion stars since 2014. Another mission, PLATO, is due to launch in 2026.

The Gaia mission

Gaia is not designed just to look for exoplanets. Instead, its task is to make the most accurate 3D star catalogue so far. This is a pretty ambitious task – and it isn't just mapping out the precise positions of over a billion stars, it is also revisiting them many times during its mission to find out if they have moved, and by how much. It's making an average of 40 million observations a day!

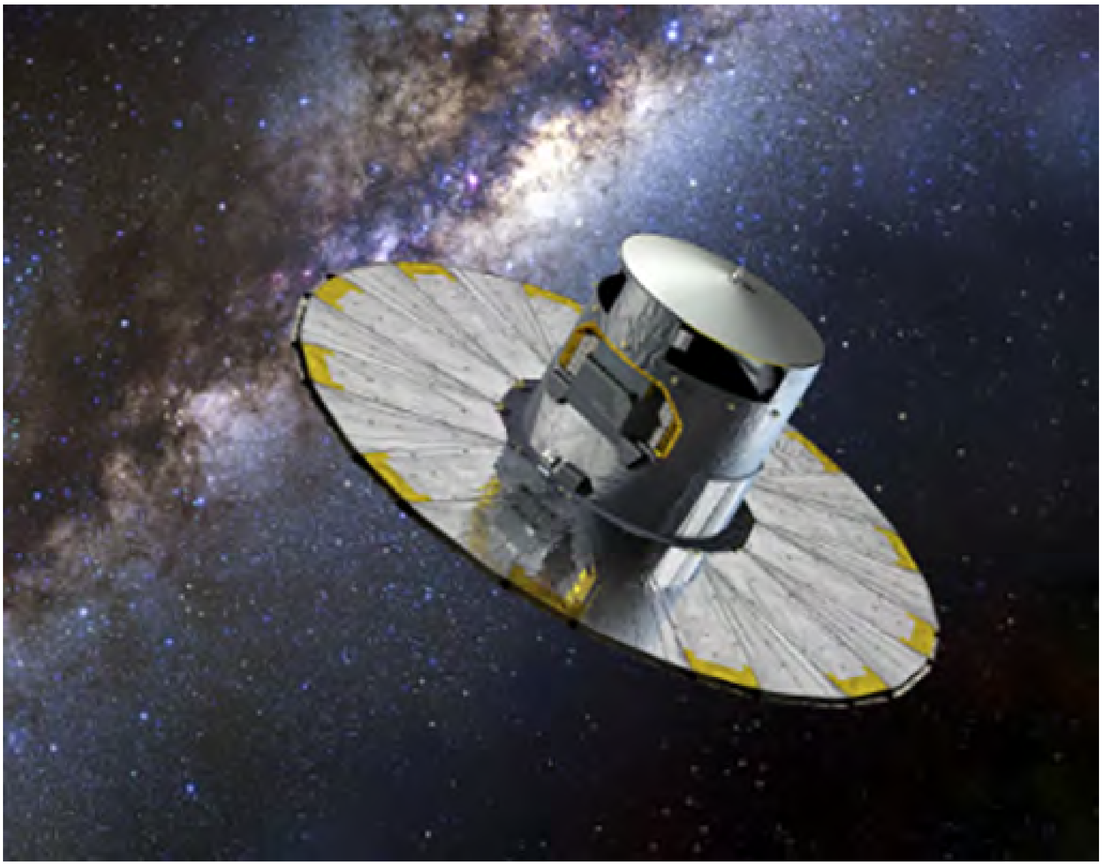


Figure 12 Artist's impression of the Gaia spacecraft

You learned in Week 3 about how we can identify the presence of planets from measuring wobbling stars using the radial velocity (RV) technique. Sometimes, if the planet is massive enough and the orbit is wide enough, it may be possible to see the tiny star movements directly – a technique called 'astrometry'. Gaia can make astonishingly precise measurements of star positions, equivalent to measuring the width of a human hair 1000 km away! With this capability it is expected to detect tens of thousands of new Jupiter-like planets. See the European Space Agency's webpage about astrometry.

While Gaia will certainly add to the planet haul, it's probably not going to help us in our search for an Earth twin. It's going to be much easier for Gaia to find larger planets that make stars wobble more. For smaller worlds, we need to turn to TESS, and the future mission PLATO.

Activity 3 Exoplanet.eu website

Allow about 5 minutes

Revisit the Exoplanet.eu website. Are there any planets that have already been found using the astrometry technique? If so, how many? (Reminder: the website is http://exoplanet.eu/; to get to the catalogue click the 'All Catalogs' link, select 'Show All entries', then use the 'Detection' drop-down menu.)

Answer

At least one planet has already been detected using astrometry. By the time you do this activity, there may be more. You can find the amount by changing the 'Detection' option to show 'Astrometry'.

You may have noticed that some of the objects listed don't seem to follow the exoplanet naming conventions you learned about in Week 3. In particular, upper-case rather than lower-case letters are used. These objects are so massive that they may in fact be failed stars – brown dwarfs – rather than gas giant planets. The boundary between such objects is a bit fuzzy, so the labelling convention for binary star companions has been used.

The Transiting Exoplanet Survey Satellite – TESS

TESS is a NASA mission that launched in March 2018. It is a small space telescope dedicated to searching for transiting planets around nearby, bright stars.

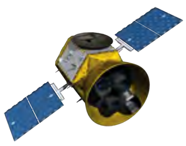


Figure 13 Artist's rendering of the TESS spacecraft

Activity 4 Planets orbiting nearby stars

Allow about 5 minutes

Why are planets orbiting bright, nearby stars particularly important?

Answer

You learned in Week 7 that it's much easier to make good measurements when the star emits plenty of light, and the nearer the star is the brighter it will appear. Collecting a lot of light allows astronomers to make more detailed measurements and means the measurement uncertainties are relatively small.

Finding planets around bright, nearby stars will allow follow-up observations from large ground-based telescopes that weren't possible for many of the Kepler planets. Kepler has helped astronomers make huge strides in working out the numbers of planets that are out there, but TESS will discover planets that can be studied in remarkable detail.

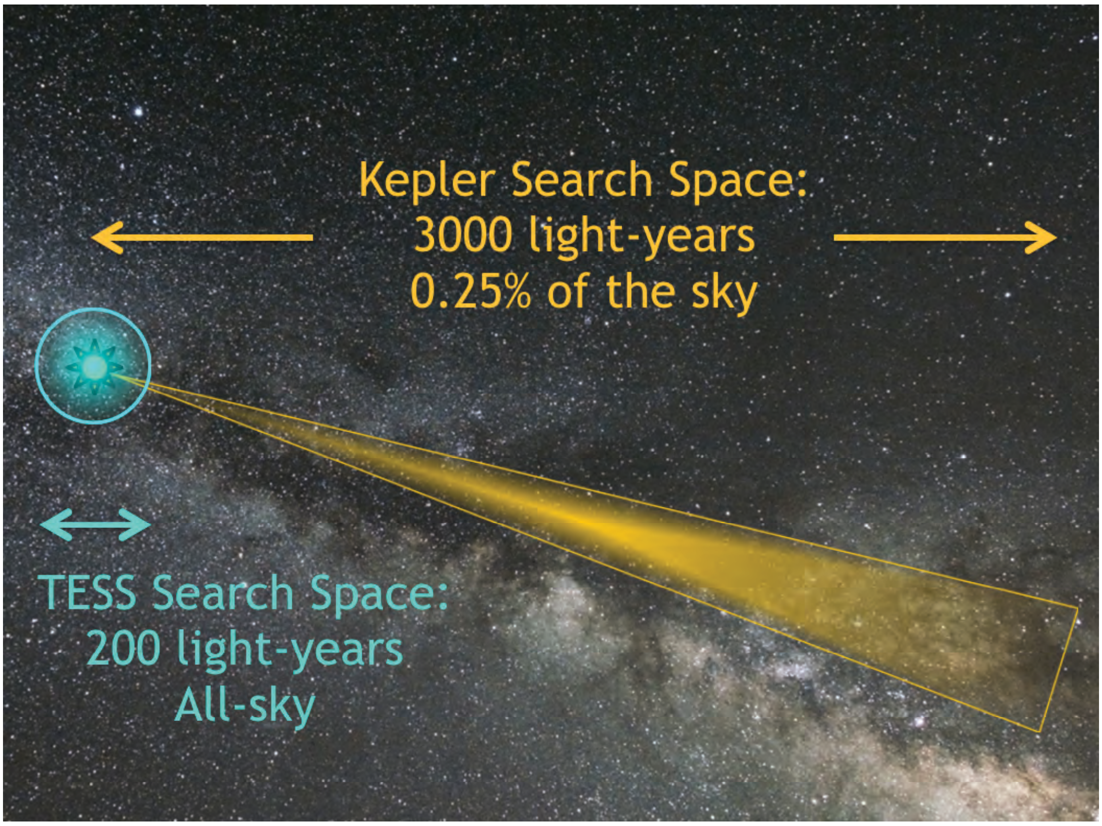


Figure 14 TESS will search a much greater area of sky than Kepler did but will concentrate on stars that are closer to Earth

TESS aims to study 200 000 of the brightest, closest stars, covering an area of the sky 400 times larger than that covered by the Kepler mission, as shown in Figure 14. The expectation is that TESS will find thousands of transiting exoplanet candidates. But what kind of planets will these be?

TESS is capable of finding planets as small as Earth, especially around smaller stars, but it's unlikely to find Earth twins. This is because it has to keep changing which bit of sky it's looking at to make sure it covers the whole of the sky. It will therefore not spend very long looking at any particular patch, so it will only be able to detect planets with relatively short periods. A true Earth twin orbiting a Sun-like star would have a period of approximately a year, which would take several years of observation to detect – we need at least three transits to be confident we have discovered an orbiting planet.

Activity 5 TESS planets

Allow about 5 minutes

TESS is likely to find lots of planets with relatively short orbital periods, close to their parent stars. How do you think these planets are likely to compare with the planets in the Solar System?

Answer

Most TESS planets are likely to be orbiting close to their stars, so they will be very hot – much hotter than the planets in the Solar System.

TESS has already had three planets confirmed from its first three months of observations, with hundreds more candidates being followed up using ground-based observatories. One of these, LHS 3844 b, is only a little larger than Earth, but has an orbital period of just 11 hours – a 'hot Earth'! A big question is whether such a planet so close to its star could retain any kind of atmosphere. Being just 50 light years away it will be an ideal subject for transmission spectroscopy to find out.

5.2 PLAnetary Transits and Oscillations of stars – the PLATO mission

PLATO is a European Space Agency (ESA) mission that is due to launch in 2026. Like TESS, it's a space telescope designed to search for transiting exoplanets, but the detail of what it's going to be looking for is different.

In Week 4 you watched a video about SuperWASP, a collection of ground-based telescopes looking for transiting exoplanets. SuperWASP has been very successful at detecting hot Jupiters. PLATO is designed to be a bit like a space-based version of SuperWASP, having 26 separate cameras mounted on the spacecraft. Because it is space-based, it can make precise measurements of the brightness of stars, unaffected by the Earth's atmosphere.

Activity 5 The transit depth equation

Allow about 5 minutes

The radius of the Earth is about 1/100th of the radius of the Sun. Work out the depth of the transit of an Earth-like planet across a Sun-like star.

Hint: the transit depth equation was last mentioned in Week 7.

Answer

The transit depth is given by

So, if the size ratio R_p/R_{star} is 1/100, the transit depth will be $(1/100)^2$ or 0.0001, or 1/100th of 1 per cent. That's roughly equivalent to trying to detect a tiny fly crawling across a car headlight several miles away!

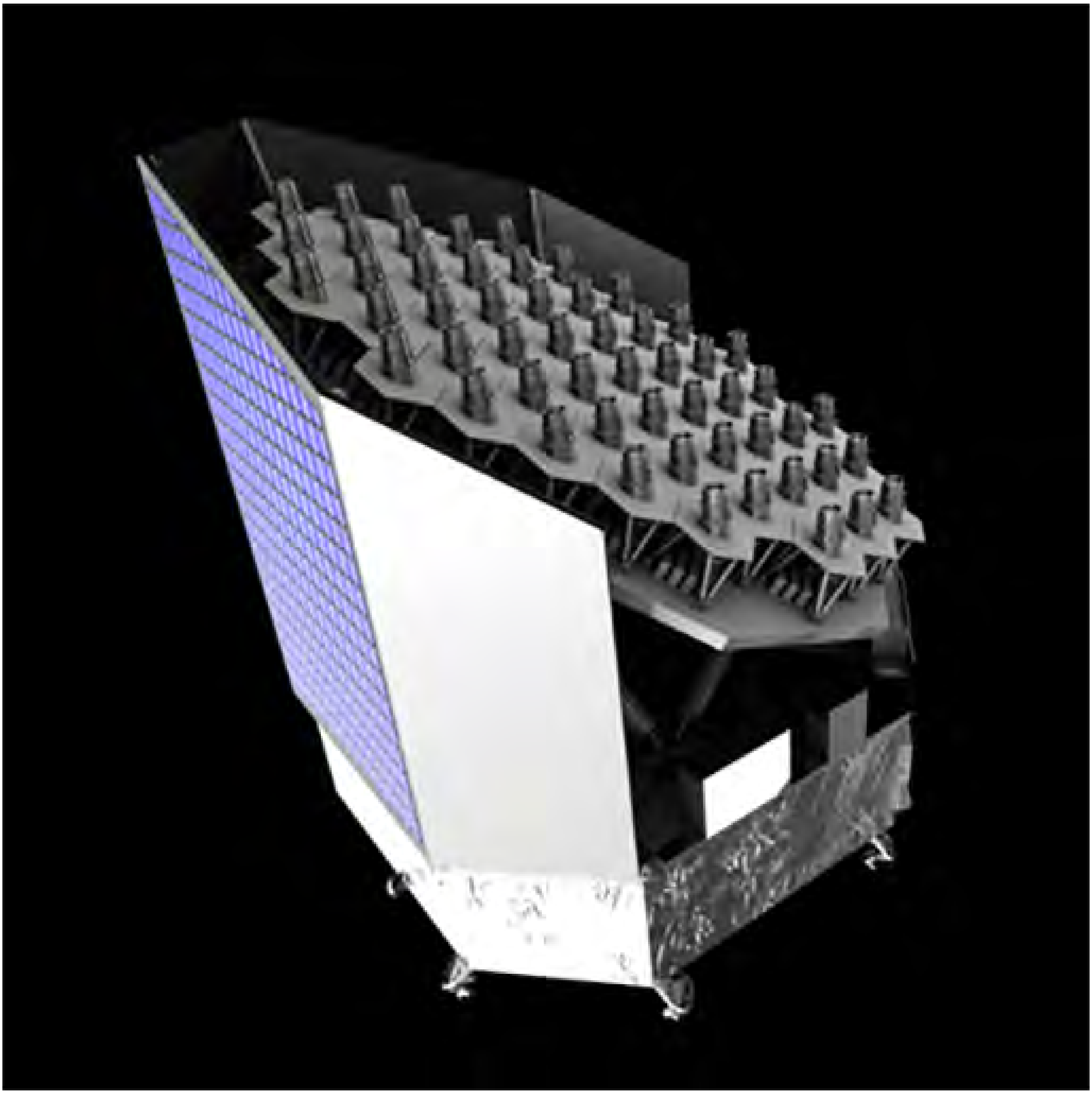


Figure 15 Artist's rendering of the PLATO spacecraft, nearly four metres in length

The advantage of the multi-camera setup is that PLATO will be able to study a relatively large area of sky at any given time, and during the mission it will look at around 1 million stars. One of PLATO's key goals is to find Earth-sized planets in the habitable zones of Sun-like stars, which involves observing planets with periods of around one year. It should find lots of small transiting planets, just like Kepler has. The big advantage is that the PLATO planets will be orbiting bright, nearby stars.

Therefore, in tandem with follow-up investigations from large current and future ground-based observatories, and from a new space telescope to be launched in the next few years, PLATO will help to address some pretty big questions. How do planetary systems form? How common are worlds like ours? And even, what conditions are needed for the emergence of life?

Apart from finding planets, PLATO will also be doing important work in helping us to gain a better understanding of the stars themselves. One of the things that makes spotting transits and radial velocity wobbles harder is that stars themselves undergo changes that can mimic signals caused by small planets.

Our Sun, and most other stars, have darker regions on their surfaces that come and go with time. These are called 'starspots' (or 'sunspots' in the case of the Sun). They can move slowly over the star's surface, and they appear and disappear over a few weeks or months. Starspots can cover different parts and a different fraction of the star at different times. Our Sun has an 11-year cycle, in which it goes from its most spotty phase, which we call Solar Maximum, to its least spotty phase, or Solar Minimum.

Variation in these dark patches can change a star's brightness over time, which can interfere with other measurements like transits. By studying stars in more detail with PLATO, astronomers will be able to understand these processes and other properties of stars better.

Watch this video, taken by a camera on NASA's Solar Dynamics Observatory, which shows a cluster of sunspots moving over the surface of the Sun and changing shape.

View at: youtube:U0Lt3SgiEQ8

Video 1 Sunspot cluster evolving over two weeks (please note this video has no audio)

Activity 6 PLATO

Allow about 5 minutes

Why is it so important that PLATO is able to detect planets with periods of around one year?

Answer

PLATO being able to detect planets with periods of around a year means that it is possible to detect Earth twins – Earth-sized planets in the habitable zones of Sun-like stars.

To be able to detect dips in brightness of one hundredth of one per cent, separated by a year, PLATO's work to understand the small intrinsic variations in starlight will be vital. Like many worthwhile projects, the basic idea is simple and straightforward. The challenge is getting all the details right.

5.3 Studying new worlds: JWST, Twinkle and ARIEL

Of course, the ultimate goal is to be able to find out what all of these planets are like. In Week 7 you learned about transmission spectroscopy and how we've been able to learn about the atmospheres of some transiting planets. Over the next few years, the opportunity to do this sort of work will increase with the launch of the new international observatory called the James Webb Space Telescope (JWST). There are also two proposed spacecraft that would be dedicated to transmission spectroscopy that may also be launched within the next decade.

The James Webb Space Telescope

The eagerly awaited 2018 launch of JWST has unfortunately had to be delayed and is currently scheduled for March 2021. Seen on some level as the successor to the successful Hubble Space Telescope, it will actually be capable of very different science. JWST's 6.5 metre gold-coated mirror is nearly three times the diameter of Hubble's, making it a much more sensitive telescope, but the key difference is that JWST will observe almost exclusively in the infrared. This makes it especially suitable for spotting gases in planetary atmospheres.

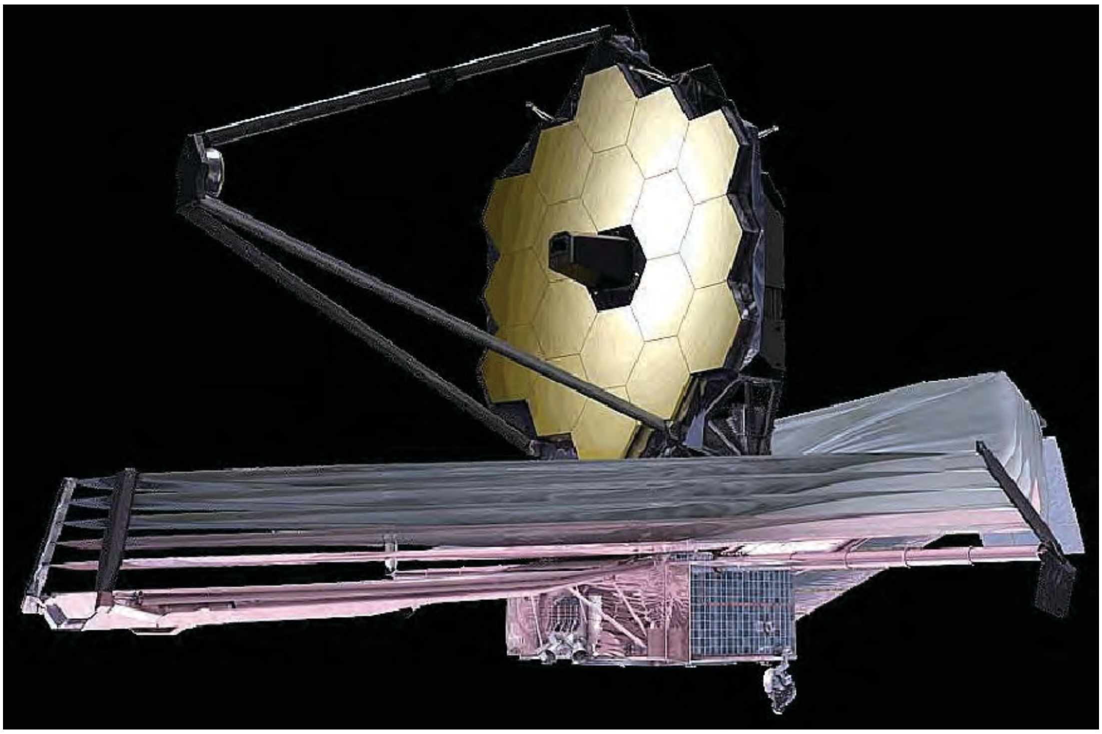


Figure 16 Artist's rendering of the James Webb Space Telescope, roughly the size of a tennis court

JWST has an ambitious design. On launch, it will travel to a region of space on the other side of the Earth from the Sun. This means JWST will orbit the Sun in Earth's shadow, which will keep JWST cool. Because warm things emit infrared radiation, as you learned in Week 7, infrared telescopes need to be kept very cold so they don't interfere with their own measurements. The telescope has to be folded up small for launch, so when it gets to its new home it will have to unfold itself over a period of several days.

The following video is fairly long, but it shows just how complicated space telescopes like JWST can be. It will take JWST 15 days to fully unfold. Its large composite mirror has to fold, and importantly its heat shield – the bit that looks like layers of tin foil – has to deploy to make sure the spacecraft can maintain a cool enough temperature.

View at: youtube:bTxLAGchWnA

Video 2 JWST deployment (please note this video has no spoken audio)

JWST will be able to obtain transmission spectra of exoplanets spanning a wide chunk of the infrared region. Importantly, because of its large mirror and impressive sensitivity, it even has the potential to do this for small planets like those in the TRAPPIST-1 system. By observing these planets several times over, it could detect the presence of the biosignature gas ozone if it's present in large enough quantities like the Earth's atmosphere. JWST could therefore provide us with our first hint of another inhabited world.

Activity 7 JWST

Allow about 5 minutes

Name two things that help JWST to keep itself cool enough to make measurements.

Answer

JWST orbits the Sun, but it will permanently remain in Earth's shadow, which helps to keep it cooler. The heat shield also helps the spacecraft to stay at an appropriate temperature.

Twinkle: off-the-shelf science in the UK

The Twinkle Mission is on a very different scale to JWST. It is being developed on a small budget in the UK with the aim of launching in 2022, and unlike most specialist space telescopes it will make use of technology that is already available. It will be a small telescope, about a quarter of the diameter of the Hubble Space Telescope, in orbit around the Earth, and it will be able to look at transiting exoplanets using both visible and infrared light.

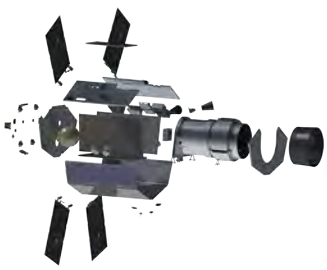


Figure 17 Exploded view of the Twinkle spacecraft

It may seem like a minnow next to the shark that is JWST, but Twinkle has one very big advantage for exoplanet scientists. JWST is a multi-purpose telescope and it will certainly not be devoting all, or even most, of its time to looking at exoplanets. There are lots of other branches of astronomy eager to make use of it. A small telescope like Twinkle, on the other hand, would be dedicated to transmission spectroscopy of exoplanets.

Having a dedicated telescope increases the number of exoplanets that can be studied. Why is this important?

At some point, you've probably met and interacted with a dog – maybe a Labrador or a Golden Retriever. You probably wouldn't want either of those dogs sitting on your lap, nor would you be likely to carry one in a handbag, but you would perhaps feel fine doing so for a small terrier or a chihuahua. If you want to own, or just play with, a particular dog it's obviously a good idea to get to know the individual, but it helps to know about the typical behaviour of the breed to put the dog's personality in context.

Exoplanets, in this respect, are not that different to dogs. At the moment, we've studied a few individuals of various types, but what we don't know is whether or not the things we're seeing are typical of the type. We also don't really know exactly where the boundaries lie between different 'breeds' of exoplanet. A mission like Twinkle would help us to learn these things.

Another advantage is the potential to conduct repeated observations of planets many times over the lifetime of the mission to see changes in their atmospheres and cloud cover. This could tell us what the weather is like on these distant worlds!

ARIEL: The Atmospheric Remote-Sensing Infrared Exoplanet Large-survey

The latest in our series of transmission spectroscopy missions is ARIEL. It is an exciting time for the ARIEL team, a consortium of more than 50 institutes from 12 European countries: the mission was recently selected by the European Space Agency (ESA) to launch in 2028 against competition from two other candidate space missions.

ARIEL is also a visible-to-infrared small space telescope, about half the diameter of the Hubble Space Telescope. Unlike Twinkle, which will orbit the Earth, ARIEL will be following JWST into Earth's shadow.

ARIEL is designed to look at up to a thousand transiting exoplanets during a four-year mission, and so will provide a large-scale survey of the chemistry of exoplanet atmospheres. Like Twinkle, it will help us to put previous discoveries in context, helping to build a broader picture of different types of exoplanets and how planetary systems form. Since it won't be launched until 2028 it will have the opportunity to carry on from missions like JWST, and follow up on targets from PLATO.

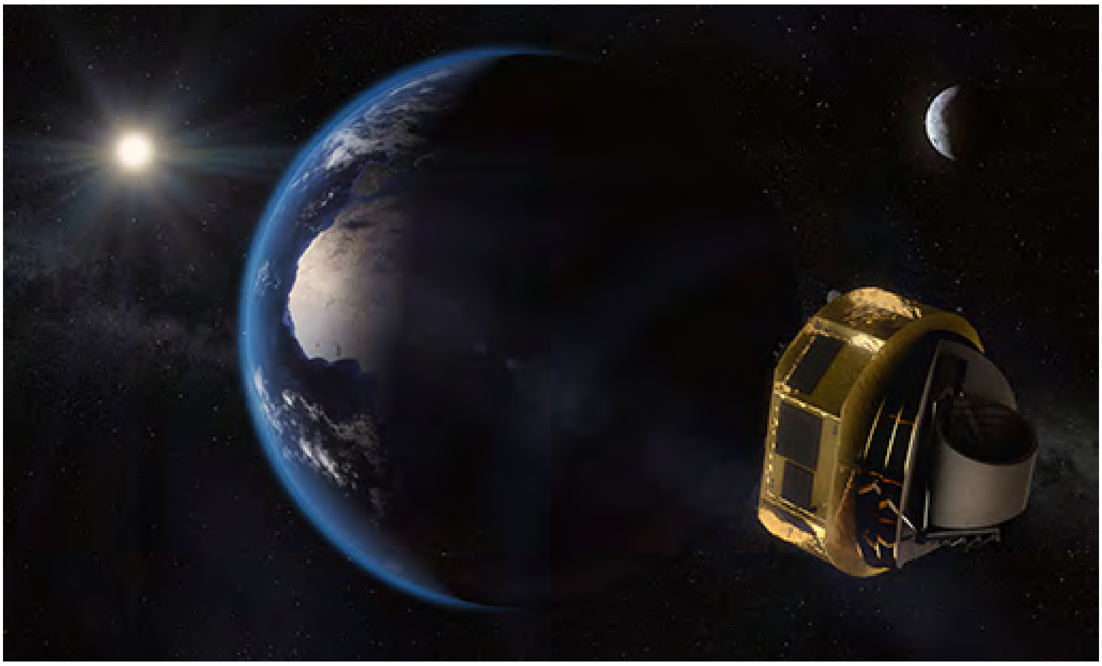


Figure 18 Artist's impression of the ARIEL spacecraft in position shielded from the Sun by Earth

Activity 8 Twinkle and ARIEL missions

Allow about 5 minutes

Even though they are smaller telescopes than JWST, Twinkle and ARIEL can contribute major advances in our knowledge of exoplanets. What is special about missions like Twinkle and ARIEL?

Answer

Twinkle and ARIEL are purpose-built survey spacecraft, so they will study a lot of exoplanets, whereas multi-purpose observatory JWST will only study a few objects. Twinkle and ARIEL provide crucial context for exoplanet observations.

The problem with transmission spectroscopy and related methods is that they rely on the fortuitous alignment of planet and star. So, only a small fraction of exoplanets can be characterised in this way.

5.4 Seeing exoplanets directly

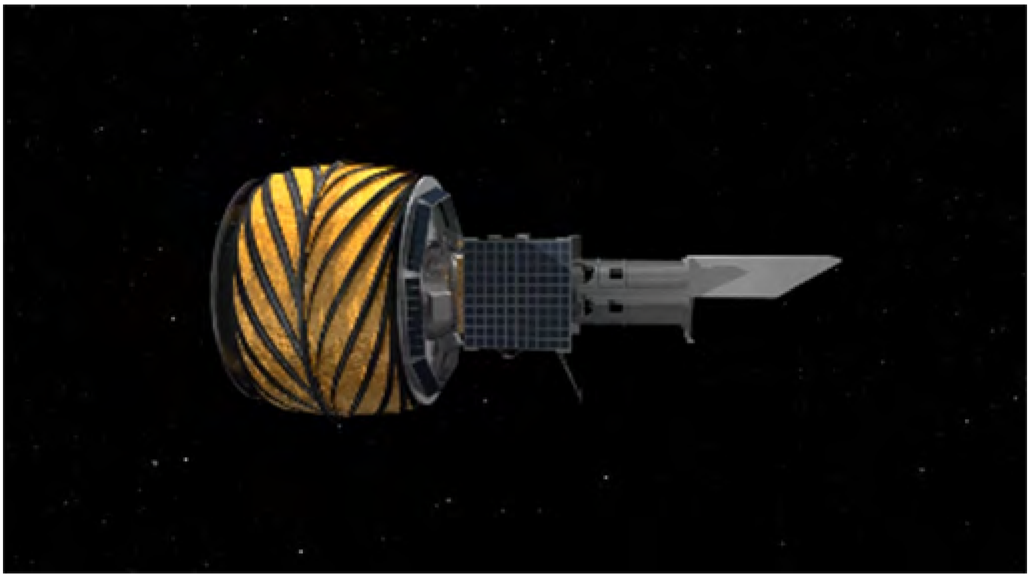
All the techniques you've seen throughout the weeks so far rely on ingenious ways of analysing the light from just a single point source on the sky – the combined light of a star and its planets.

What hope is there of actually seeing an exoplanet directly? Remember that the bright starlight overwhelms the weak reflected light of the planet, sometimes by as much as a factor of a billion! The challenge of directly imaging an Earth twin has been likened to spotting a firefly in the glare of a searchlight when the firefly and searchlight are thousands of kilometres away. This would certainly require observing from above the Earth's turbulent atmosphere.

Current ideas that are being developed of how to do this include blocking out the light from the star within the telescope system itself, or using a distant 'starshade' to create a dark shadow so that only the reflected light from the exoplanet enters the telescope. The following video shows quite beautifully how this could work.

Video content is not available in this format.

Video 3 A flower-shaped 'starshade' designed by a team at NASA. The starshade would move in tandem with a space telescope, precisely positioning itself at a great distance to block the light from different stars. (Please note this video has no audio.)



In spite of the immense challenge, a few much larger planets in special circumstances have already been imaged directly. The first was Fomalhaut b.

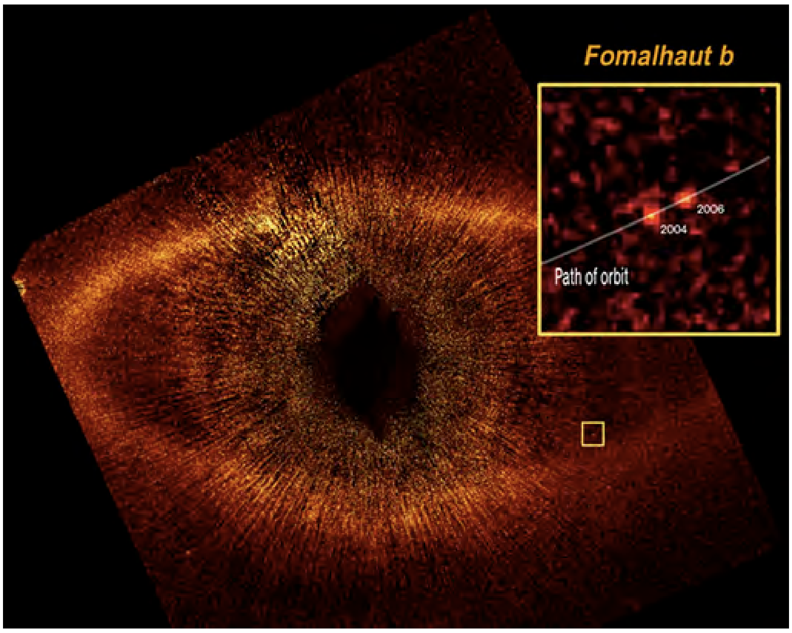


Figure 19 Direct image of Fomalhaut b using the Hubble Space Telescope. The light from its parent star in the centre is blocked out. The bright ring is a vast belt of dusty and icy

debris and the other light is scattered starlight.

Imaging Fomalhaut b was feasible for a couple of key reasons. One is that it is very far from its star allowing the starlight to be successfully blocked out. In fact, Fomalhaut b has an orbital period of 2000 years. The second reason is that it is unusually bright in the visible part of the electromagnetic spectrum. Astronomers believe this could be due to a dust shroud, or a ring system like Saturn's but much larger and thicker, reflecting the light from the star.

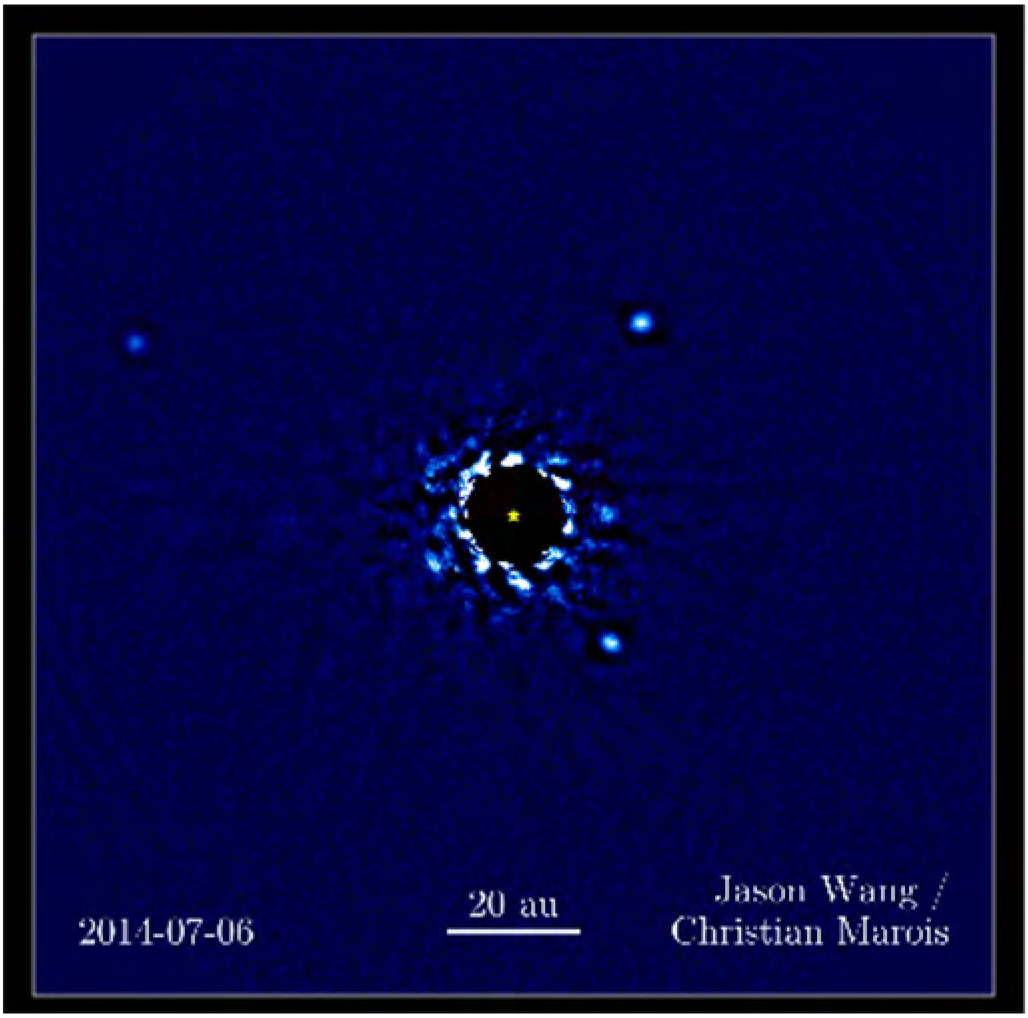
Fomalhaut b probably remains the least massive directly imaged exoplanet, but there have been other remarkable observations.

One example is a system of four planets orbiting the star HR 8799. Again, the planets are very large and are far from their star, with orbital periods ranging from decades to centuries. This is a young system which means that the planets have retained heat from their formation. This allows them to be seen in infrared light, because the star is relatively less bright at these wavelengths than in visible light.

How wonderful to be able to see directly the orbit of exoplanets some 130 light years away.

Video content is not available in this format.

Video 4 The HR 8799 system in motion. Seven images taken over seven years using the ground-based Keck and Gemini Observatories in Hawaii have been combined to create this video. (Please note this video has no audio.)


2014-07-06
20 au
Jason Wang /
Christian Marois

6 This week's quiz

Well done – you have reached the end of Week 8. It's now time to complete the Week 8 badge quiz. It is similar to previous quizzes but instead of 5 questions there are 15.

Week 8 compulsory badge quiz

Remember, this quiz counts towards your badge. If you're not successful in passing it you can have another go in 24 hours.

Open the quiz in a new tab or window (by holding down Ctrl [or Cmd on a Mac] when you click the link).

7 Summary of Week 8

Over the last eight weeks, you have had an introduction to the field of exoplanets. In the last 20 years we've come a long way: we've gone from discovering a single exoplanet to knowing of several thousands. For some of these planets, we know their size, mass and density, and we have even been able to identify the presence of particular gases and clouds in their atmospheres. Many of these planets are far more exotic than we ever imagined they would be.

As technology improves, we are starting to be able to detect progressively smaller and more Earth-like planets. With space telescopes like JWST, we could even detect the atmospheres of Earth-like worlds. This could provide us with the first indication of alien life. We may even be able to directly image such worlds.

You should now be able to:

- explain why it is likely that nearby stars host exoplanets
- describe the 2016 planet search around Proxima Centauri
- explain the importance of the Kepler-444 planetary system
- summarise prospects for extraterrestrial life
- be familiar with Gaia, TESS, JWST, PLATO, Twinkle and ARIEL
- describe current and future possibilities for direct imaging of exoplanets.

Over the next few years, the field of exoplanet science is only going to get more exciting. Some of the things we have speculated about may have happened by the time you study this course. Did you spot any?

We hope you have enjoyed this course and that you will continue to follow new developments in the field. To keep in touch with exoplanet science, there are various websites you may find useful.

https://exoplanets.nasa.gov/
https://palereddot.org/
http://sci.esa.int/plato/
http://sci.esa.int/gaia/
http://tess.gsfc.nasa.gov/
http://www.jwst.nasa.gov/
http://www.twinkle-spacemission.co.uk/

Of course there's lots more about exoplanets and space exploration in a variety of Open University modules. Whether you stay with The OU or not, we hope you continue to enjoy learning about the amazing Universe we live in.

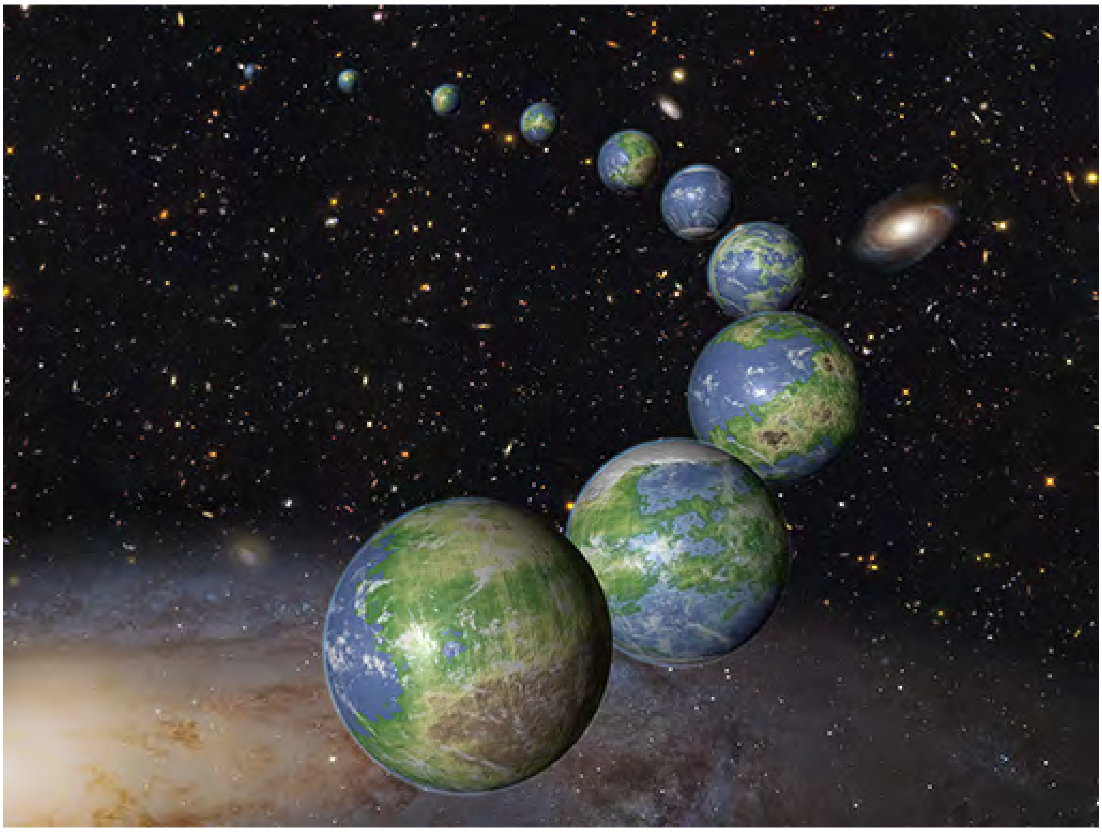


Figure 20 Innumerable Earth-like planets, not yet born, over the following trillion years in the evolving Universe. (An artist's impression.)

Where next?

If you've enjoyed this course you can find more free resources and courses on OpenLearn . You might be particularly interested in the free OpenLearn courses:

- *Moons of our Solar System*
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Tell us what you think

Now you've come to the end of the course, we would appreciate a few minutes of your time to complete this short end-of-course survey (you may have already completed this survey at the end of Week 4). We'd like to find out a bit about your experience of studying the course and what you plan to do next. We will use this information to provide better online experiences for all our learners and to share our findings with others. Participation will be completely confidential and we will not pass on your details to others.

Acknowledgements

This free course was written by Carole Haswell, Flora Rees and Joanna Barstow, with contributions from Amanda Smith. It was first published in May 2019.

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Week 1

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Video 1: What is a Planet: ScienceatNASA

Video 2: The Universe in 3D: courtesy of lenny27G

Video 3: Guide to our Galaxy: European Space Agency, ESA

Video 4: TSO Photography

Week 2

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Week 3

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Week 4

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Week 5

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Video 1: Ethan Kruse

Week 6

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Figure 2: Carole Haswell

Figure 3: IOP Publishing

Figure 4: taken from: https://userscontent2.emaze.com

Figure 5: NASA/Kepler Mission/Dana Berry

Figure 6: taken from: www.weather-climate.org.uk

Figure 7: taken from:
http://ichef.bbci.co.uk/news/660/media/images/48092000/jpg/_48092623_glacier_painting0510145.jpg

Figure 8: University of Rochester

Figure 9: NASA Ames/SETI Institute/JPL-Caltech

Figure 10: Harvard-Smithsonian Center for Astrophysics

Figures 11: Dana Berry

Figure 12: ESO/L.Calcada; https:/creativecommons.org/licenses/by/4.0/

Week 7

Figure 1: Nigel Sharp (NOAO), FTS, NSO, KPNO, AURA, NSF

Figure 2: taken from: http://www.phy.olemiss.edu/~luca/astr101/Lectures/L12.html

Figure 3: NASA/IPAC/Caltech

Figure 4: taken from: http://www.weather-climate.org.uk

Figure 5: taken from: http://www.phy.olemiss.edu/~luca/astr101/Lectures/L12.html

Figure 6: Elyar Sedaghati; taken from http://www.sc.eso.org/~esedagha/research.html

Figure 7: European Space Agency (ESA)

Figure 9: NASA, ESA, and G. Bacon (STScI)

Figure 18: NASA, ESA, M. Kornmesser

Figure 19: NASA/ESA/G. Bacon

Figure 20: taken from http://www.nature.com

Figure 21: courtesy Space Telescope Science Institute

Figures 22 and 25: NASA/JPL-Caltech

Figure 23: ESO/M. Gillon et al.; https://creativecommons.org/licenses/by/4.0/

Figure 24: ESO/N. Bartmann/spaceengine.org;https://creativecommons.org/licenses/by/4.0/

Week 8

Figure 1: P.Kervella (CNRS/U.de.Chile/Oberservatoire de Paris/LESIA), NASA/ESA and The Hubble Heritage Team(STScI/AURA) NASA SDO

Figures 2, 3: Pale Red Dot

Figure 4: ESO/G.Coleman;https://creativecommons.org/licenses/by/4.0/

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Figure 8, 13, 14 and 16: NASA; http://tess.gsfc.nasa.gov/documents/TESS-Litho.pdf

Figure 9: Illustration by Tiago Campante/Peter Devine.

Figure 10: ESA/Hubble, M. Kornmesser; https://creativecommons.org/licenses/by/3.0/

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Figures 12, 15 and 18: European Space Agency, ESA

Figure 17: SSTL

Figure 19: Paul Kalas/NASA/ESA

Figure 20: (c) NASA/STScI

Video 1: (c) NASA/Solar Dynamic Observatory

Video 2: James Webb Space Telescope (JWST) video; NASA/ESA/CSA

Video 3: NASA/JPL/Caltech

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