Exoplanets

Discover New Worlds

This guide will take you step-by-step, through the procedures, websites and tools necessary for you to be able to detect exoplanets yourself.

Each section of the guide is designed to be largely independent from the others, so you may make use of only the parts of the guide which are of interest to you.

Extended Project suggestions are provided towards the end of the guide for those considering pursuing an EPQ or HPQ, and links to the broader physics, maths and computer science curricula are also explored.

Contents

Practical activity **Quick calculation** **Computer-based activity**

The importance of detecting exoplanets

Just a few hundred years ago, it was widely believed that the Earth was the centre of the entire universe. Our home was thought to be fixed in place, with the Sun, planets and stars orbiting around it. The concept of exoplanets orbiting other stars was not just deemed an outlandish thought at the time, but one that could have landed you in jail, or worse!

Our knowledge of the workings of the universe has progressed considerably since then. Advances in astronomical instruments now allow us to prove definitively that these previously held beliefs are false. The universe is far more vast than any conjectures imagined and there is a chance that in this universe we may not be alone.

Yondu, a character from Guardians of the Galaxy, is said to originate from Alpha Centauri, the star system clostest to our own Sun.

The idea of extraterrestrial life existing elsewhere in our Solar System, our galaxy, or the wider universe is one that has fascinated humans in recent history. Modern blockbusters are a testament to this, with Sci-Fi and comic-based films such as Guardians of the Galaxy enjoying huge success in recent years.

However, before we can start planning what we might say to these potential galactic neighbours, we first need to check whether they are home. This involves searching for evidence of the exoplanets and when we find them trying to determine whether any of these other worlds may have the potential to hold life.

The detection and characterisation of exoplanets is not only important in discovering whether we are alone in the universe, but it may also be necessary for the survival of the human race. The pressures of climate change on our planet continue to rise and the Earth has only a limited supply of resources available to us. We also remain susceptible to a potential devastating mass extinction event, similar to those that led to the demise of the dinosaurs.

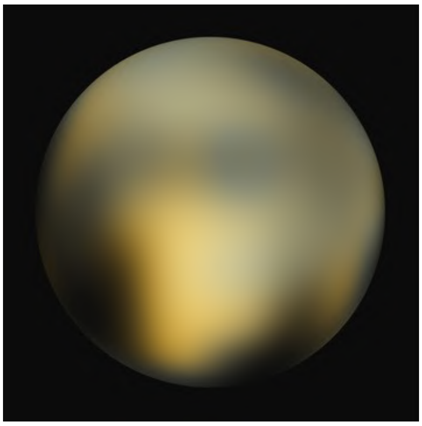
Therefore, it maybe appropriate for the future survival of our species to consider colonisation of other planets. However, given the immense distances that separate us from these other worlds, it is essential that we are able to confirm the existence and habitability of these planets before travelling to them (once technology permits such journeys!). So, despite exoplanet research being a relatively recent venture, it could prove to be some of the most exciting and important work science has performed to date!

The challenges involved in detecting exoplanets

The first exoplanet ever discovered orbiting a main-sequence star (like our Sun) was announced in 1995 and since then thousands more have been discovered - you can search through a catalogue containing all of these discoveries here http://exoplanet.eu/catalog/ or here http://exoplanets.org, with more info found on http://simbad.u-strasbg.fr/. However, despite these seemingly large numbers, detecting exoplanets is far from easy!

On a clear night, even in large cities, it may be possible to see Venus, Mars, Mercury, Jupiter and Saturn with the naked eye (depending on whether they lie above the horizon). These planets are visible as bright dots in the night sky, much like distant stars. However, planets don't emit visible light themselves, but instead reflect the Sun's light back towards us. See the 'atmospheres' section later in the guide for discussions about other types of light (e.g. infra-red) planets may emit. Since planets do not produce their own visible light, as well as the fact that they are much smaller than stars, makes them very hard to detect.

The other Solar System planets Neptune, Uranus and Pluto also reflect some of the Sun's light back towards us, but as they are much further away from us and far smaller than Jupiter and Saturn, they are not visible with the naked eye. As can be seen from the fuzziness of the Hubble Space Telescope picture to the right, rather sophisticated telescopes are required in order to directly image the minor planet Pluto.



Pluto - imaged by the HST in 2010.

It is exceedingly difficult to image planets orbiting other stars this way - the nearest star to us is over 5,000 times further away from the Earth than Pluto is! Therefore, we require another approach to detect exoplanets.

Discussion - Cosmic distances

You've just found out that some planets in our Solar System are visible with the naked eye from the Earth. This truly is incredible given the vast distances involved and the fact that planets emit no *visible* light themselves!

The distances between ourselves and other planets and stars might seem impossibly large. It is therefore useful to shrink everything down to a more manageable scale - https://astrosociety.org/edu/family/materials/toiletpaper.pdf does this very well. The 'toilet paper' scale model of the Solar System provides a very accessible way to picture these distances. Note - this model is designed to represent the distances between the planets only, not their relative sizes. This is because Jupiter, the largest planet in our solar system, would still only be the size of a grain of salt at this scale! The table below summarises the distances of each planet from the Sun using two different scales.

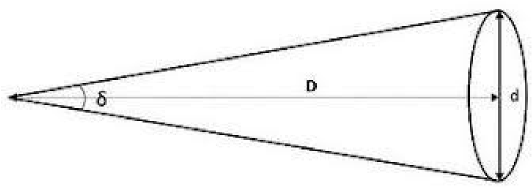
Planet	Distance from Sun (km)	Squares of Toilet Paper Out to Planet's Orbit (short version)	Squares of Toilet Paper Out to Planet's Orbit (long version)
Mercury	57,910,000 km	1.0	2.0
Venus	108,200,000 km	1.8	3.7
Earth	149,600,000 km	2.5	5.1
Mars	227,940,000 km	3.8	7.7
Ceres	414,436,363 km	7.0	14.0
Jupiter	778,330,000 km	13.2	26.4
Saturn	1,429,400,000 km	24.2	48.4
Uranus	2,870,990,000 km	48.6	97.3
Neptune	4,504,000,000 km	76.3	152.5
Pluto	5,913,520,000 km	100.0	200.0

In order to reach our nearest star, Proxima Centauri, you would require approximately 1,352,000 sheets of toilet paper if using the larger of the two scale models! This would mean your roll of toilet paper would have to be almost 100 miles long!

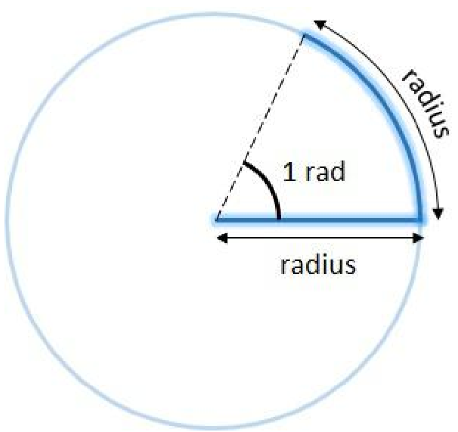
Direct imaging and angular resolution

Telescopes, cameras and your eyes each have an 'angular resolution' which describes their ability to distinguish two points clearly from one another. Our eyes, on average, have an angular resolution of around 0.02°. This means our eyes can identify two points clearly from one another when they are just a tiny fraction of a degree apart.

The *angular* resolution of a telescope, a camera, or your eyes is fixed. However, the *spatial* distance the angular resolution corresponds to varies depending on how far away the objects are from the observer. For very small angles, the angle between two points can be approximated by $\delta \approx \frac{d}{D}$, where d is the distance between the two points, and D is the distance between the points and the observer (see the diagram to the right). As our eyes' angular resolution is fixed, we struggle to distinguish small details of an object the further away we are from it. This is because if we double D, then the smallest spatial distance we can resolve, d, must also double i.e. the ratio of d to D is fixed. Try reading this guide from 10m away and you'll struggle a lot more than if it were on the table in front of you!



Angular resolution 'δ' for two points distance 'd' apart, and a distance 'D' away from an observer.



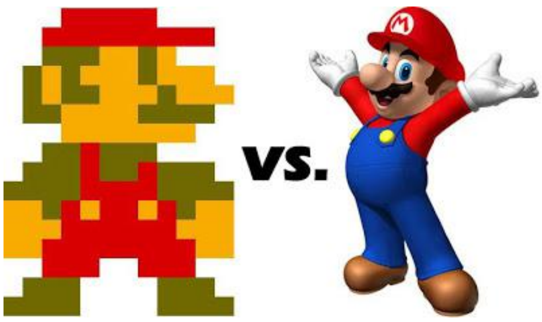
Radians measure angles, just like degrees. There are 360 degrees in a full rotation, but only 2π (around 6.3) radians.

In the above formula it is important to ensure we use the correct units. d and D must both be in the same units e.g. both in metres, or both in km. The angle δ must be given in 'radians'. Radians are simply another unit to measure angles in, just like degrees. One radian though is much larger than one degree. Degrees are defined so that one full rotation contains 360 degrees. Radians on the other hand are defined so that one full rotation contains only 2π (approximately 6.3) radians. One radian corresponds to the angle created by a 'slice of pizza' whose crust is the same length as the radius of the pizza (see diagram to the left). This means that one radian is equal to about 57.3°. If you are performing calculations and you need to convert between degrees and radians you can use the following: 1 rad $= \frac{360}{2\pi}$ degrees; 1 degree $= \frac{2\pi}{360}$ rad. Online, you may also see the angular resolution of a telescope given in 'arcminutes' or 'arcseconds'. These are simply related to degrees by thinking about the hours, minutes and seconds of a clock: 1 arcminute $= \frac{1}{60}$ degree; 1 arcsecond $= \frac{1}{60}$ arcminute.

Directly imaging Mario

Having seen the maths involved in determining the angular resolution of an instrument, you can now calculate the angular resolution of your phone camera, or any camera you might have access to. To do this, you can take photos of 'modern-day-Mario' at increasing distances until the quality of your image is reduced to that of 'classic-Mario', standing just 16 pixels tall!

✂ Print out an image of modern-day-Mario, shown to the right. The image of Mario below is designed to be 4cm tall when the guide is printed on A4 paper. Now, take photos of your printout from different distances away e.g. every metre from 1m to 10m away, or further if you are using a good quality camera. Ensure you focus the camera on your printout for each photo taken and record your distances clearly.



Upload your photos to a computer, maintaining their original quality (do not reduce the file size in the upload). Open your 'middle distance' (e.g. 5m) photo within Paint, or a similar application. In Paint, the dimensions of the whole image are given at the bottom of the screen e.g 3456 $\times$ 4608px, while the dimensions of your image of Mario can be found by drawing a 'Select' box around Mario e.g. 26 $\times$ 35px.

Search the different photos you have taken and find your image in which Mario is (very close to) 16 pixels tall. In this image, these 16 pixels represent the 4cm height of the real-life print out, therefore each pixel represents 0.25cm. To find the angular resolution of your camera you must now divide 0.25cm (your minimum resolvable separation, d) by the distance you were away from the printout, D, when you took the picture e.g. 8m (remember to make sure the units are the same). Using these numbers as an example, an angular resolution of approximately 0.00031rad (0.018°) is obtained. When rounded to one significant figure, this value happens to be the same as the resolution of the human eye mentioned earlier (0.02°).

Modern day telescopes have angular resolutions much better than our eyes or a phone camera. The Hubble Space Telescope has an angular resolution of 0.05 arcseconds ($\approx$ 0.00001°), which would allow it to obtain the same 16 pixel image of Mario from over 10km away! Unfortunately, even this incredibly impressive angular resolution still isn't sufficient to image even large, Jupiter-type planets orbiting our nearest stars.

Discussion - Resolution needed to directly image closest exoplanets

The closest star to us that is thought to host a planet is actually our nearest star, Proxima Centauri. Details about this planet can be found in the exoplanet catalogues mentioned earlier. Searching these databases tells us:

- Distance to Proxima Centauri = 4.22 lightyears
- Mass of the exoplanet, Proxima Cen b = 0.004 M_{Jup}

Where the mass of the planet is given in units of Jupiter masses - in this case, the mass of the planet is a small fraction of that of Jupiter. Unfortunately the radius of the planet is not known, but as the Earth's mass is similar to that of Proxima Cen b, you may assume they have similar radii for the purpose of your calculation. The Earth's radius is approximately 6,400km. The only other information required for the calculation is to know how many metres there are in a lightyear - 1 lightyear is approximately 9,500,000,000,000,000 (9.5×10^{15}) metres i.e. 9.5 trillion kilometres!

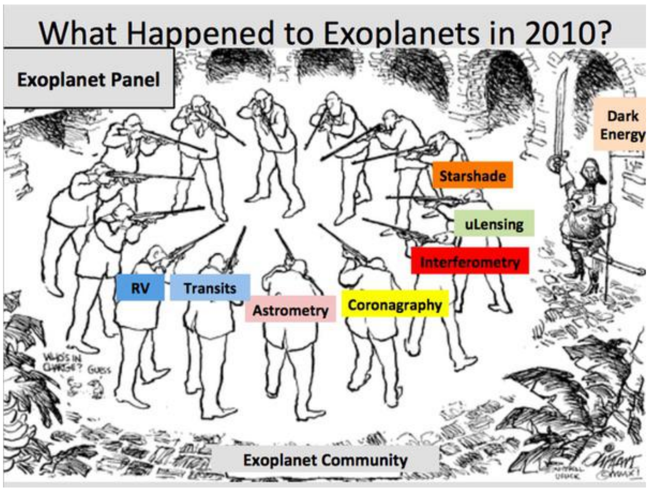
To resolve the planet, consider trying to resolve two points on opposite sides of the planet - these points will be separated from one another by the planet's diameter, so $d \approx$ 12,800km. The distance to the star, D, is equal to 4.22 × 9.5 trillion km $\approx 4 \times 10^{13}$ km. Therefore:

$$\begin{aligned}\delta &= \frac{\text{diameter of planet, } d}{\text{distance to Proxima Centauri, } D} \\ &= \frac{12,800}{4 \times 10^{13}} \\ &= 3.2 \times 10^{-10} \text{ rad} \\ &= 1.8 \times 10^{-8} \text{ degrees} \\ &= 0.00007 \text{ arcseconds}\end{aligned}$$

This is almost a thousand times more precise than the resolution of Hubble! This illustrates the difficulties involved in directly imaging exoplanets, and the bias towards detection of very large planets over smaller ones.

Methods of detection

Due to the vast distances involved, limited technology and the fact that stars far outshine the reflected light of their planets, direct imaging is not possible in all but the rarest instances. Several other methods exist though which offer improved detection with various levels of success.



Scientists have thought of so many methods of detection that the infighting has led to a notable loss of funding.

You may have heard of the General Theory of Relativity, devised by Einstein over a hundred years ago. This theory states that gravity is a result of the curvature of space-time caused by the presence of massive objects - think of a bowling ball on a trampoline. Things that have mass, such as stars, planets and ourselves, all feel the effects of gravity - this was known before Einstein. However, Einstein proved that light feels these effects too (this explains why Black Holes are black!). When light travels by massive objects its path is bent slightly. This means that the light of a distant star can be bent by the gravitational field of another star or planet that crosses our line of sight - this is called 'Gravitational microlensing' and it has the effect of magnifying the image of the distant star. Planets are of course always found orbiting stars which are far more massive than themselves and bend the distant star's light much more than the planet does. It is hard, but important to be able to separate these two effects. One great advantage of microlensing over other detection techniques is that it is well suited to detect small planets that orbit at large distances from the host star.

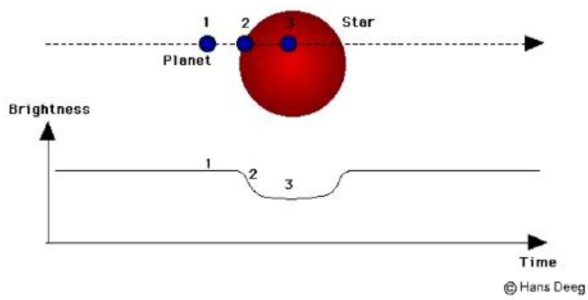
'Reflection/emission' builds upon the idea of direct imaging and looks for subtle changes of light from the host star due to planets orbiting very close to their host star as they catch more light compared to the same planet orbiting further away. 'Astrometry' meanwhile approaches the idea of direct imaging in a different way – instead of looking for planets directly, the star's movement is very closely monitored. Any regular 'wobble' in the star's position might be caused by the gravitational tug of a planetary companion.

'Pulsar timing analysis' and 'eclipsing binary minima timing' can help in detecting planets in the cases where they are found orbiting either a pulsar or one star that is locked in a binary orbit with another star. However, most of these situations are rather uncommon. Despite this, the first widely accepted exoplanet discovery (1992) was found using pulsar timing analysis (`https://www.space.com/35253-exoplanet-discovery-anniversary-25-years.html`)! For the rest of this guide, the Transit Method and Radial Velocity Technique will be primarily pursued since these two have seen the widest success to date. Astrometry is also explored further towards the end of the guide.

Transit Method

When observing stars, we can detect how much light we receive from them every second – this is called their flux. If a planet were to pass between the star and our telescope when we are looking at it, we might hope to see a small black dot making its way across the image of the star. However, we cannot resolve the star with sufficient detail, so instead what we observe is a reduction in the amount of light we receive from the star during the time that the planet is in front of it. This fall in intensity is our evidence that we may have detected a planet.

We can find out how much of the stellar disk the planet covers by using the formula for the area of a circle. We can use the area of a circle rather than the area of a 3D sphere because when we look at planets or stars from far away they do look like very small circles, much like in the figure to the right. The area of a circle is given by $A = \pi r^2$, where 'r' is the radius of the circle. Using this formula, and the following information, calculate what percentage of the Sun's light the Earth and Jupiter would block out in a transit when viewed from very far away.



Transit signature showing the reduction in flux observed when a planet passes in front of a star.

- Sun's radius ≈ 700,000km
- Jupiter's radius ≈ 70,000km
- Earth's radius ≈ 6,400km

You should calculate that a large planet like Jupiter will block out much more of the Sun's light than an Earth-like planet, over 100 times more in this case! This means it is much easier to detect large planets via the transit technique than small planets. Why haven't we had to worry about the distance between the star and the planet in this case?

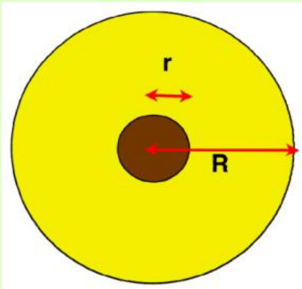
Use the transit simulator http://astro.unl.edu/classaction/animations/extrasolarplanets/transitsimulator.html to picture both Jupiter and the Earth passing in front of the Sun. Do the reductions in flux match your calculations in each case? Have a play around with the different parameters to see what effect each has on the shape of the light curve generated. Note - ensure 'Flash' is enabled in your browser for the simulations to run.

Solved - Transit Method

To find the fraction of starlight blocked by the planet from our point of view we must find the fraction of the star's area that we see which is covered by the planet. This is calculated using:

$$\text{fractional change in flux, } \Delta f = \frac{\pi r^2}{\pi R^2}$$

Where 'r' is the radius of the planet and 'R' is the radius of the star (taken to be the Sun in this example). Note - we have assumed that the entire planet passes in front of the star. We could also have a 'grazing' incidence, where only a fraction of the planet covers the edge of the star - in this instance we would observe a smaller reduction in flux. The factors of π cancel on the top and bottom of the equation meaning we can calculate the percentage reduction in flux for the two examples as:



$$\text{Jupiter: } (\frac{70,000}{700,000})^2 \times 100\% = 1\% \text{ reduction in flux expected}$$

$$\text{Earth: } (\frac{6,400}{700,000})^2 \times 100\% = 0.008\% \text{ reduction in flux expected}$$

Why haven't we had to worry about the distance between the star and planet in this case? Picture this: when you hold out your hand at arm's length, you can completely block out the Sun from your point of view. This isn't because your hand is larger than the Sun, but rather because you hand is much, much closer to you than the Sun is. In the case of exoplanets orbiting other stars, the opposite is true – the distance to the star-exoplanet system is far greater than the orbital distance between the star and the exoplanet. This fact allows us to approximate the star and exoplanet as being the same distance away, and so we don't have to account for any depth effects. The apparent size of an exoplanet to us barely changes as it orbits its host star.

Solved - Transit Method

Simulating Jupiter is relatively simple given that the parameters are given in terms of Jupiter radii and masses. Using the transit simulator mentioned earlier http://astro.unl.edu/classaction/animations/extrasolarplanets/transitsimulator.html set both the planet's mass and radius equal to '1', set the stellar mass equal to '1 M_{sun}' and ensure the orbital inclination is set to $90°$. You should see the normalised flux drops from '1' to '0.990' at the bottom of the transit, a fall of 1%, agreeing with the calculation. Ensure 'theoretical curve' and 'simulated measurements' are both ticked in order to appreciate how astronomers results are often a far from perfect match to the theory.

The Earth's radius is approximately 0.09 Jupiter radii. The mass of a planet does not affect the shape of transit curves so we do not need to worry about the mass of the Earth in this instance. Changing only the radius to approximately 10% of Jupiter's almost eliminates the signal we had observed. To see the depth of the signal clearly it is necessary to plot only the theoretical light curve. This sees a reduction from '1' to approximately '0.99992', which again agrees with the previous calculation of 0.008%. Note that the 'eclipse depth' is given to the bottom right of the plot in each case, stating the precise depth of the transit generated by the simulation.

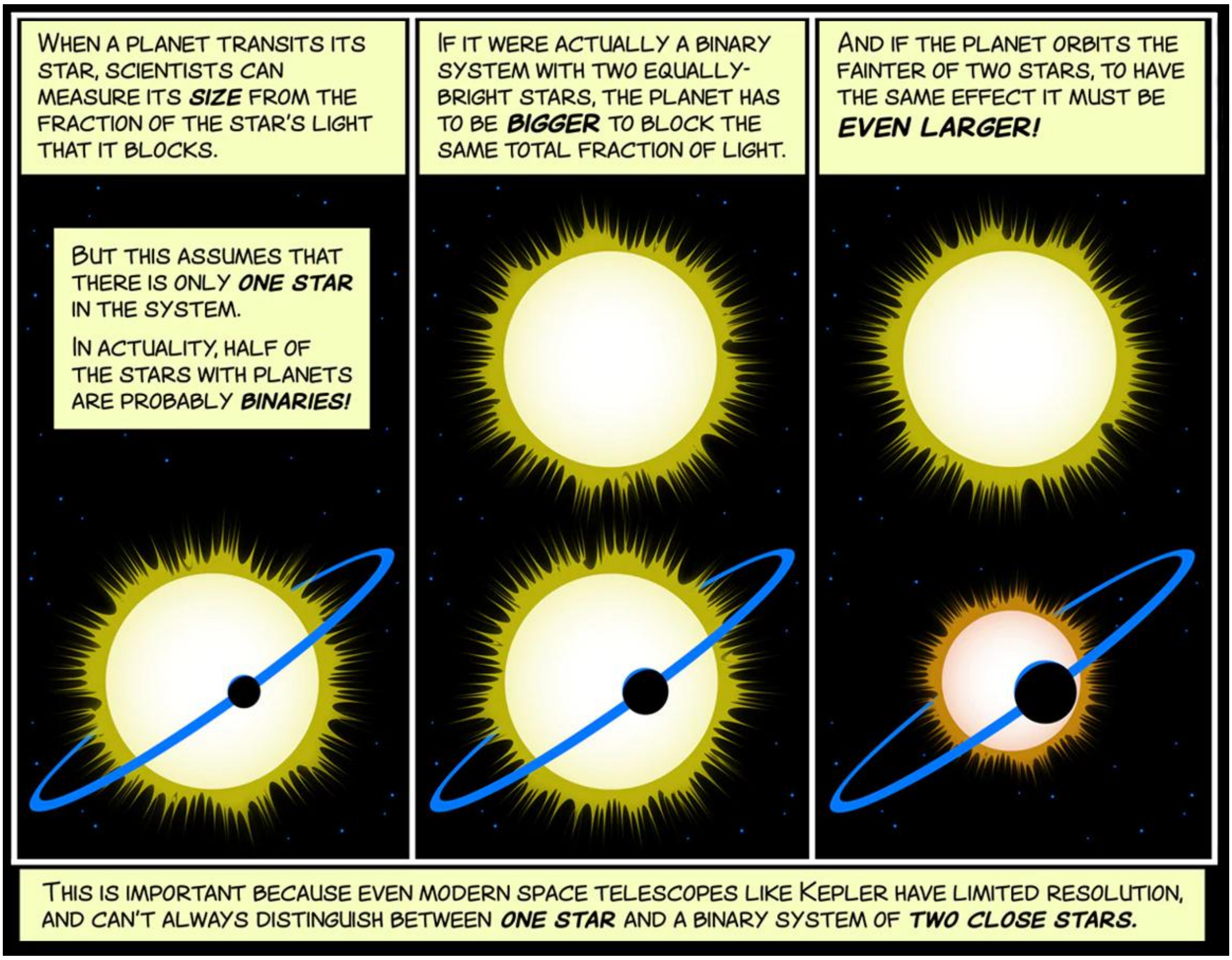
Discussion points:

- Why are the 'edges' of the transit signal sloped and not vertical? An exoplanet does not suddenly 'jump' from being out of our line of sight to in front of a star. Instead, the planet gradually passes over the star, covering just a small part of it at first and therefore blocking just a small amount of light. As more of the planet crosses the face of the star a larger fraction of the light is blocked. It might take a few hours for an exoplanet to simply cross the edge of a star, so we observe a gradual reduction in light over this time, hence the 'sloped edges' of the transit signal.
- In the simulation, set the parameters corresponding to a planet the same size of Jupiter orbiting a star like our Sun at a distance of 1AU. For what range of inclinations would the orbit be visible to us? The planet only passes in front of the star for inclinations between $\approx 89.75°$ to $90.25°$. This corresponds to an extremely narrow range of inclinations (only $\approx 0.3\%$ of all possible orbits) and highlights that we preferentially detect large planets that orbit close to their host star with the transit method.

Transit Method continued

One interesting point that hasn't been accounted for in our calculations is that stars often aren't found alone, like our Sun. In fact, most of the time stars are found in binaries - two stars orbiting their common centre of mass. It was initially believed that planets would not be able to form around these systems due to the varying gravitational forces a binary system creates. However, we now know that is not the case and that planets can and do exist that orbit either one or both of these stars (called S-type and P-type orbits respectively).

In these scenarios our calculations for the planet's radius could be incorrect. The cartoon below illustrates this point well.



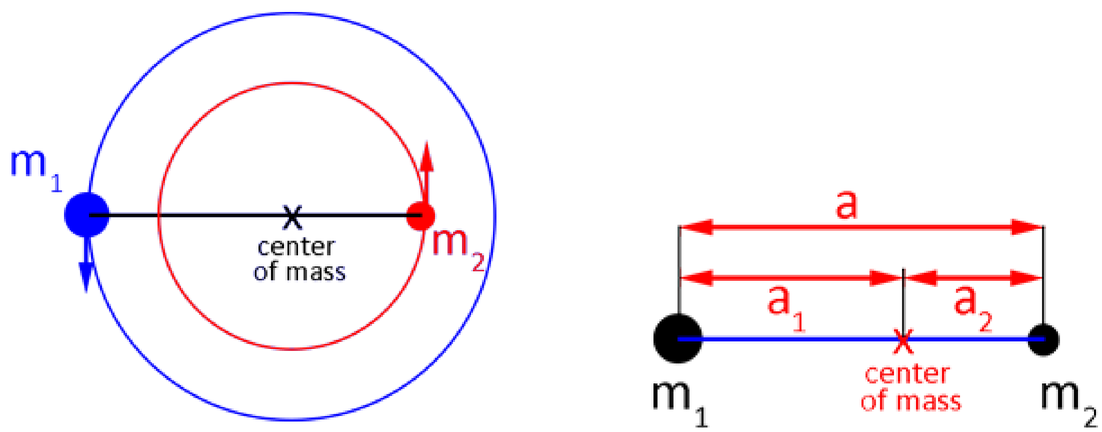
This cartoon explains why the reported sizes of some exoplanets may need to be revised in cases where there is a second star in the system. Credit: NASA/JPL-Caltech.

Radial Velocity Method

You might picture our Solar System with the Sun in the middle, completely stationary, while all the planets move around it. However, this isn't true – in reality, the planets and the Sun orbit their common centre of mass. This is most easily pictured by considering just one planet orbiting a star.

In this situation, the centre of mass will lie somewhere between the centre of the star and the centre of the planet. As the star is always more massive that the planet, the centre of mass will always lie closer to the centre of the star (this point often lies inside the star itself but displaced slightly from its centre). This means that the circular or elliptical path the star follows will be shorter than that of the planet and so the star will move slower too. The important thing to note though, is that the star does move.

The diagram below shows a simplified version of such a star-planet system. You can see that the centre of mass lies closer to m_2 in the diagram, therefore m_2 must be the more massive of the two objects in this situation i.e. m_2 is the star. You can also see that the circular path the star (m_2) follows is smaller than that of the planet (m_1). The star and planet always remain opposite sides of the centre of mass, like in the diagram, and so the time taken for the planet to complete its orbit is the same as that of the star. As the star is travelling a shorter distance in the same amount of time its speed must be slower, but it does move! Note - the distances in the diagram below are exaggerated and the sizes of the star and planet are not to scale. In reality, the star would likely be many times larger than the planet and the centre of mass would lie well within the star's radius.



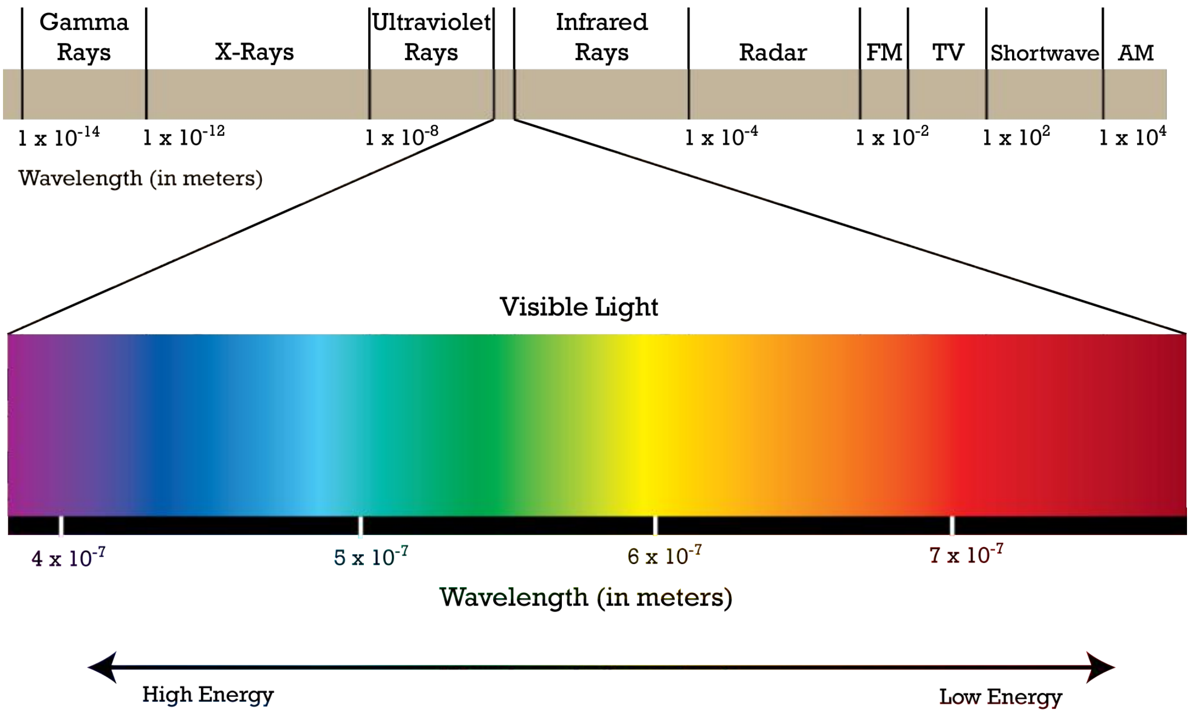
A diagram showing a two-body system (e.g. star-planet) with circular orbits. The star is represented by the more massive m_2, while the planet is represented by the less massive m_1. The diagram should be used to answer the questions on the following pages.

Radial Velocity Method continued

When viewed from the Earth, the movement of the star caused by the planet along our line of sight results in small changes to the spectrum of light we detect from it - this is called 'Doppler shift'.

The 'spectrum' of light simply describes light of different wavelengths and frequencies. 'Light' in this instance doesn't solely refer to *visible* light but encompasses the entire 'electromagnetic (EM) spectrum', from high energy Gamma and X-rays, all the way down to low energy Radio and Microwaves. The diagram below shows the entire EM spectrum and stars will likely emit some of their radiation at over a large range of these different wavelengths!

The high inner temperature of stars produces a 'continuum' spectrum of light i.e. light is emitted over a continuous range of wavelengths rather than only at very specific, isolated ones. However, the cooler outer regions of a star (still many thousands of degrees!) do absorb some specific wavelengths of light before they reach us. The specific wavelengths of light that are absorbed vary depending on the elements present in the outer regions of the star e.g. Helium will absorb different wavelengths of light to Iron. This absorption can lead to a reduction in the amount of light we receive from the star at these specific wavelengths. As we know which elements absorb each unique wavelength of light, we can tell a lot about the composition of star by looking for where these dips in intensity occur in the spectrum. An example of these absorption lines is shown on the next page - they are the dark lines in the otherwise continuum emission.

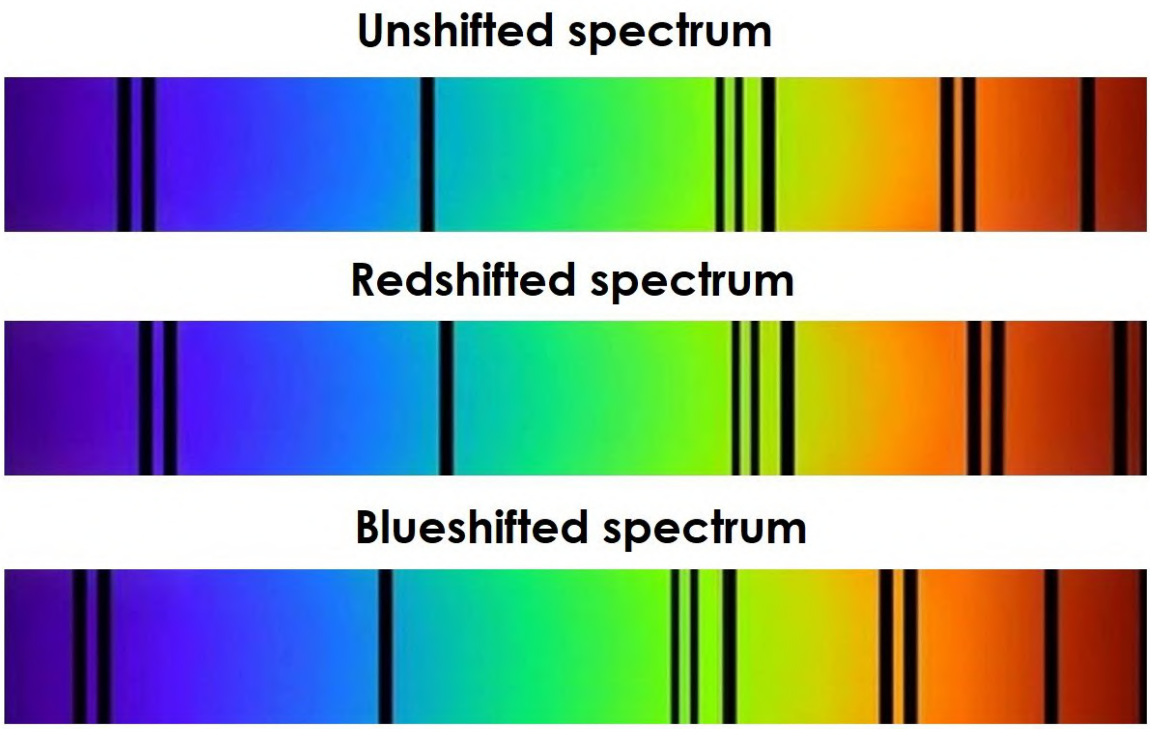


Radial Velocity Method continued

If a star is moving towards or away from us then the spectrum of light we observe from it will be 'Doppler shifted'. If the star is moving towards us then we detect the spectrum of light it emits to be shifted slightly towards higher frequencies/shorter wavelengths ('blue-shifted'). Conversely, if the star is moving away from us, we detect the spectrum to be shifted towards lower frequencies/longer wavelengths ('red-shifted'). It is useful to think about an ambulance driving towards you and away from you. When the ambulance is moving towards you its siren sounds higher pitched. This is because the siren's sound is shifted towards higher frequencies. Conversely, when the ambulance is moving away from you the pitch of the sound is lower as the siren's sound is shifted towards lower frequencies.

We can't tell how much a star's spectrum is shifted from the continuum emission it produces as this changes for each star. However, the absorption lines will always occur at specific wavelengths and so we can measure how far these lines have shifted from their 'rest' positions (the wavelengths where we would expect to find them if the star was not moving away/towards us). The images below highlight the spectra an astronomer might observe for a given star that is either not moving, moving away from us or moving towards us.

If the observed spectrum of a star shifts regularly between the two extremes, red-shift and blue-shift, this implies that the star is orbiting some centre of mass that may be the result of a planetary companion! Explore the following simulations to better understand Doppler shift:
http://astro.unl.edu/classaction/animations/light/radialvelocitydemo.html
http://astro.unl.edu/classaction/animations/light/dopplershift.html



Discussion - Doppler Shift

Which radiation within the electromagnetic spectrum is the most energetic? Gamma rays - these are very energetic, with extremely high frequencies and very short wavelengths. They are produced by the hottest and most energetic objects in the universe, such as neutron stars, pulsars, supernova explosions and the regions around black holes.

Which light is more energetic, blue or red? Blue light is more energetic than red light as it has a higher frequency. The energy of light, or any electromagnetic radiation, is 'directly proportional' to its frequency i.e. if you double the frequency of the light, its energy will double to!

Imagine a star in the night sky. Which direction must the star be moving relative to us for the light to be red-shifted? What about blue-shifted? Can we ever receive non-Doppler shifted light from a moving star? Red-shift = star moving away; blue-shift = star moving towards us; an observer will receive light that is not Doppler shifted at all from a star moving at a right angle to their line of sight.

If Betelgeuse is a red star and Rigel is a blue star, does this mean Betelgeuse is definitely moving away from us while Rigel is moving towards us? The colour of a star does not tell you if it is moving. A star's colour is determined (largely) by its surface temperature - hotter stars appear bluer, while cooler stars are redder. To find evidence of Doppler shift, you have to look at the shift in wavelength of the lines of a star's absorption spectrum.

Radial Velocity Method continued

To picture how slow a star might move and to appreciate the difficulties in detecting their movement, now imagine the Earth was the only planet orbiting the Sun, at the same distance and speed that it currently does. With respect to the diagram a few pages back, m_2 represents the mass of the Sun and m_1 the mass of the Earth. The centre of mass is defined such that $m_1 a_1 = m_2 a_2$. Using the fact that the total separation of the Sun and the Earth, a, is equal to the sum of a_1 and a_2, it is possible to rearrange the above equation into the following form:

$$a_2 = (\frac{m_1}{m_1 + m_2}) \times a$$

Given that the mass of the Earth (m_1) is approximately 6×10^{24} kg, the mass of the Sun (m_2) is 2×10^{30} kg and their separation is equal to 1 Astronomical Unit (AU) $= 1.5 \times 10^{11}$ m, find out the distance of the centre of the Sun from the centre of mass of the whole system.

Having calculated the size of a_2, you can now find out the speed with which the Sun moves around the centre of mass, assuming a circular orbit. This speed is calculated using the formulae shown below:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

$$\text{Circumference}, C = 2\pi r$$

Where the second equation is the formula used to calculate the circumference of a circle of radius 'r'. In this example, the distance travelled by the Sun is equal to the circumference of a circle of radius a_2. The time taken for the Sun to travel this distance is equal to one year – this is because the Earth and Sun must always remain opposite sides of the centre of mass, so if the time taken for the Earth to complete one orbit is 365 days, the time taken for the Sun to complete one orbit must be the same. Using these facts, it is possible to combine the two equations above so that you may work out how fast the Sun moves around the centre of mass:

$$\text{speed, } v_2 = \frac{\text{distance travelled by Sun in one orbit}}{\text{time taken to complete one orbit}} = \frac{2\pi a_2}{P}$$

Where v_2 is the speed of the Sun and P is the orbital period. Using the value of a_2 calculated earlier (given in metres) and using P is equal to one year (given in seconds), calculate the orbital speed of the Sun.

Solved - Radial Velocity Method

Plugging in the numbers into the centre of mass equation gives a_2 = 450,000m = 450km. This may seem quite far when compared to distances we are used to on Earth, but it is tiny when compared to the radius of the Sun = 700,000km!

To find the speed of the orbit we must first find out how many seconds are in 1 hour:

1 minute = 60 seconds
1 hour = 60 minutes = 60 × 60s = 3,600 seconds
1 day = 24 hours = 24 × 3,600s = 86,400 seconds
1 year = 365 days = 365 × 86,400s = 31,536,000 seconds

We can now calculate the orbital speed of the star in units of metres per second:

$$v_2 = \left(\frac{2\pi \times 450,000}{31,536,000}\right) = 0.1\text{ms}^{-1}$$

This is equivalent to approximately 0.2mph or 0.4km/h - far slower than the average walking speed of approximately 3mph! Attaining this level of precision is not possible using current technology – HARPS, one of the most advanced instruments used in radial velocity measurements, has a precision of approximately 1m/s.

The small speed calculated is the result of the Earth's mass being much, much smaller than that of the Sun. If the Earth's mass were larger, then a_2 would be larger and so v_2 would be larger. This means it is far easier to detect massive planets (like Jupiter) in these scenarios.

What other factor will reduce the radial velocity measurements taken on Earth? The orbital inclination. We only measure the component of the star's speed along our line of sight. If the orbit is at a right angle to our line of sight, then we detect no radial velocity for the star at all! If the orbit was inclined at some angle between 0 and 90 degrees, then our measured radial velocity would be less than the true radial velocity. As it is not possible for us to measure this angle, we can only calculate the minimum possible radial velocity and therefore estimate only the minimum possible planetary mass.

Radial Velocity Method continued

As with the Transit Method section earlier, you might now check your calculated results against those of a simulation: http://astro.unl.edu/classaction/animations/extrasolarplanets/radialvelocitysimulator.html.

For our example we will set the stellar mass to be 1 solar mass and the semi-major axis to be 1AU. We will also assume the orbit of the Earth is perfectly circular and so we can set the eccentricity equal to zero. The mass of the Earth is approximately equal to 0.003 times the mass of Jupiter and we will set the 'orbital inclination' equal to $90°$. You should see that the radial velocity curve looks like a smooth 'sine' wave, very different to the transit curve seen earlier. This is due to the continuous motion of the star creating a continuous signal, whereas the transit signal is only a short-lived blocking of the light from the star. The maximum value of the radial velocity should agree with the speed of the Sun calculated on the previous page.

Play around with the parameter values like before and see what effect each has on the shape of the radial velocity curve. Open both the radial velocity and Doppler shift simulations simultaneously and compare the two to one another. Remember, astronomers detect only the Doppler shifted spectrum of the star light and then convert this information into a speed using the ratio below:

$$\frac{\text{radial velocity of star}}{\text{speed of light}} = \frac{\text{change in wavelength}}{\text{original rest wavelngth}}$$

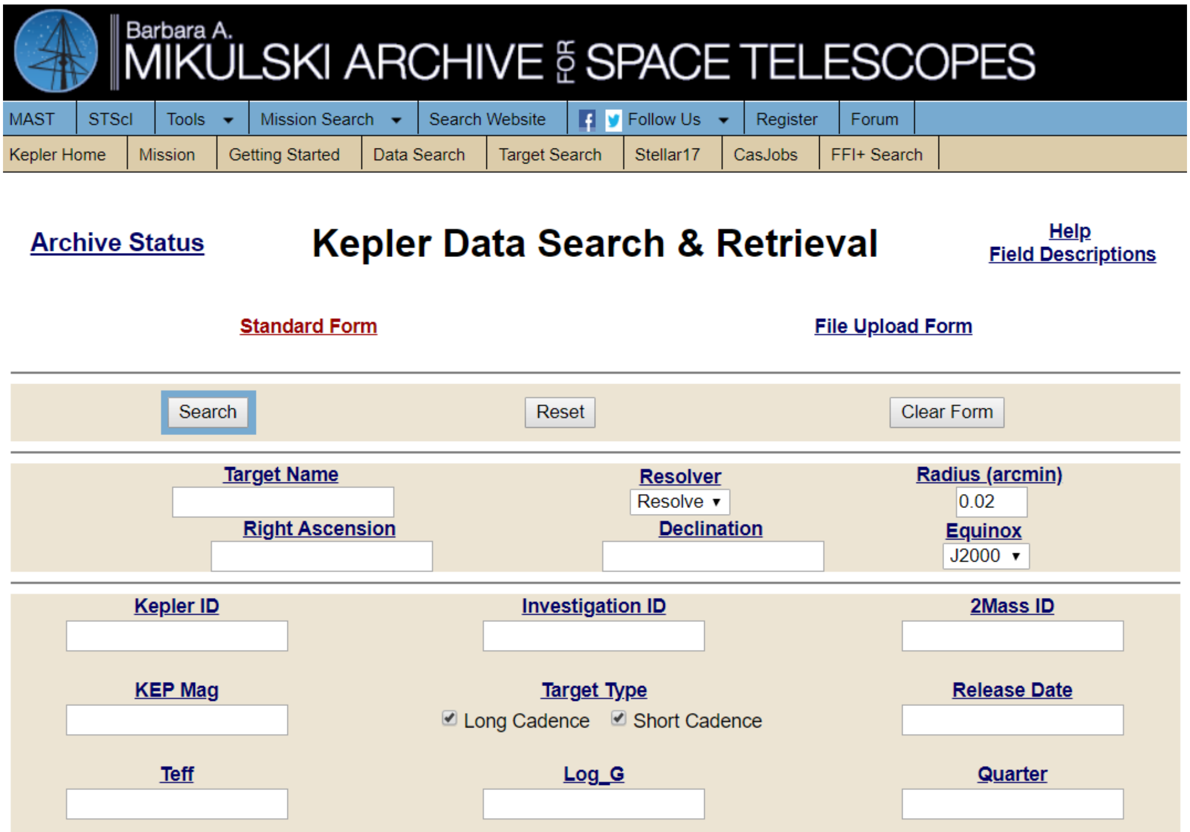
Note that if we double the radial velocity of the star, the change in wavelength we detect doubles too. This ratio holds true so long as the speed of the star is much less than the speed of light. 'Hypervelocity stars' do exist though with speeds of several million miles per hour, but even they are still significantly slower than the speed of light (3×10^8 ms^{-1}, 670,000,000mph!). These ultra-fast stars are thought to originate from our galactic centre - initially part of a binary star system, these stars were kicked out when the super massive black hole at the centre of the galaxy devoured their stellar companion! These stars now travel with enough speed that they can escape the gravitational attraction on the Milky Way altogether and end up drifting through intergalactic space alone.

You should now have a good idea of the physics behind making transit and radial velocity measurements. Briefly recap the work you have already completed to refresh these ideas if necessary. Now you will move on from the theory regarding exoplanet detection to making real-life measurements. Worked examples are given initially for known exoplanets, but once you have the necessary knowledge in place you can apply this to help discover previously unobserved planets!

Obtaining Transit data - Step 1

To search for transits, we can look at data collected using the Kepler Space Telescope. The Kepler mission has collected 'photometry' data on over a hundred thousand stars since it first began. The data collected tells us about how the brightness of each star has changed over the course of time we have observed them, and its analysis has resulted in the detection of almost 2,500 exoplanets! The following instructions will guide you through the steps required to find the Kepler data online, view the light curves and understand their meaning.

Click, or copy and paste the following URL into your browser:
https://archive.stsci.edu/kepler/data_search/search.php
You should see a webpage that looks like the one below.



Obtaining Transit data - Step 2

Stars usually don't have the most imaginative or attractive names. The brightest stars in the night sky might have unique names as they were discovered centuries ago, when the total number of astronomical objects recorded was in the thousands. Now though, scientists have identified over a billion astronomical objects, and so they have had to resort to naming these objects with a series of seemingly random letters and numbers.

Most of these stars even have many different names just to add to the confusion, but fortunately resources do exist where you can search any one of these names and it will return the correct stellar information alongside a list of the other names the star goes by. Simbad (http://simbad.u-strasbg.fr/simbad/) is a good resource for accessing this information.

In the 'target name' box on the Kepler website, you need to search one of these names. For this example, we are going to look at a star called "BD+472846". Enter the target name in the relevant box (without the quotation marks) and click the 'search' button just above it. You will be presented with a page that looks like the one below. You may also search this star name in the 'basic search' box in Simbad to find the other names the star goes by – there are 10 of them!

Mission Search / Missions / Contacts / STScI / MAST

Columns Help / Archive Status

Kepler Data Search Results

Edit Query

Object name BD+472846 resolved by SIMBADCFA (via SANTA cache) to **BD+47 2846** (Star)
RA: 19 28 59.35 **Dec:** 47 58 10.23 **(J2000)**

number of rows returned = 67

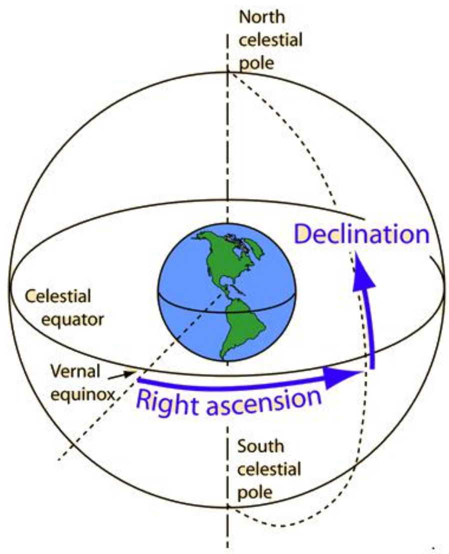
Table info

Plot marked Light Curves | Submit marked data for retrieval from STDADS
Mark all | Unmark all

Mark	Kepler ID	Investigation ID	Dataset Name	Quarter	RA (J2000)	Dec (J2000)	Target Type	Archive Class	Ref	Actual Start Time	Actual End Time	Release Date	R Mag
	10666592	EX_STKS	KPLR010666592-2009131105131	0	19 28 59.347	+47 58 10.27	LC	CLC	9	2009-05-02 00:54:56	2009-05-11 17:51:31	2009-12-31 00:00:00	10.490
	10666592	STKS	KPLR010666592-2009131110544	0	19 28 59.347	+47 58 10.27	SC	CSC	14	2009-05-02 00:40:43	2009-05-11 18:05:44	2010-10-15 00:00:00	10.490
	10666592	EX_STKS	KPLR010666592-2009166043257	1	19 28 59.347	+47 58 10.27	LC	CLC	7	2009-05-13 00:15:49	2009-06-15 11:32:57	2010-11-23 13:08:12	10.490
	10666592	EX_STKS	KPLR010666592-2009166044711	1	19 28 59.347	+47 58 10.27	SC	CSC	15	2009-05-13 00:01:36	2009-06-15 11:47:11	2010-11-05 18:41:19	10.490
	10666592	EX_STKS	KPLR010666592-2009201121230	2	19 28 59.347	+47 58 10.27	SC	CSC	13	2009-06-20 00:10:56	2009-07-20 19:12:30	2011-02-02 06:00:00	10.490
	10666592	EX_STKS	KPLR010666592-2009231120729	2	19 28 59.347	+47 58 10.27	SC	CSC	13	2009-07-20 19:42:54	2009-08-19 19:07:29	2011-02-02 06:00:00	10.490
	10666592	EX_STKS	KPLR010666592-2009259160929	2	19 28 59.347	+47 58 10.27	LC	CLC	6	2009-06-20 00:25:09	2009-09-16 23:09:29	2011-02-02 06:00:00	10.490
	10666592	EX_STKS	KPLR010666592-2009259162342	2	19 28 59.347	+47 58 10.27	SC	CSC	13	2009-08-20 20:38:32	2009-09-16 23:23:42	2011-02-02 06:00:00	10.490
	10666592	EX_STKS	KPLR010666592-2009291181958	3	19 28 59.347	+47 58 10.27	SC	CSC	10	2009-09-18 17:05:45	2009-10-19 01:19:58	2011-09-23 09:00:00	10.490
	10666592	EX_STKS	KPLR010666592-2009322144938	3	19 28 59.347	+47 58 10.27	SC	CSC	10	2009-10-19 21:56:47	2009-11-18 22:49:38	2011-09-23 09:00:00	10.490

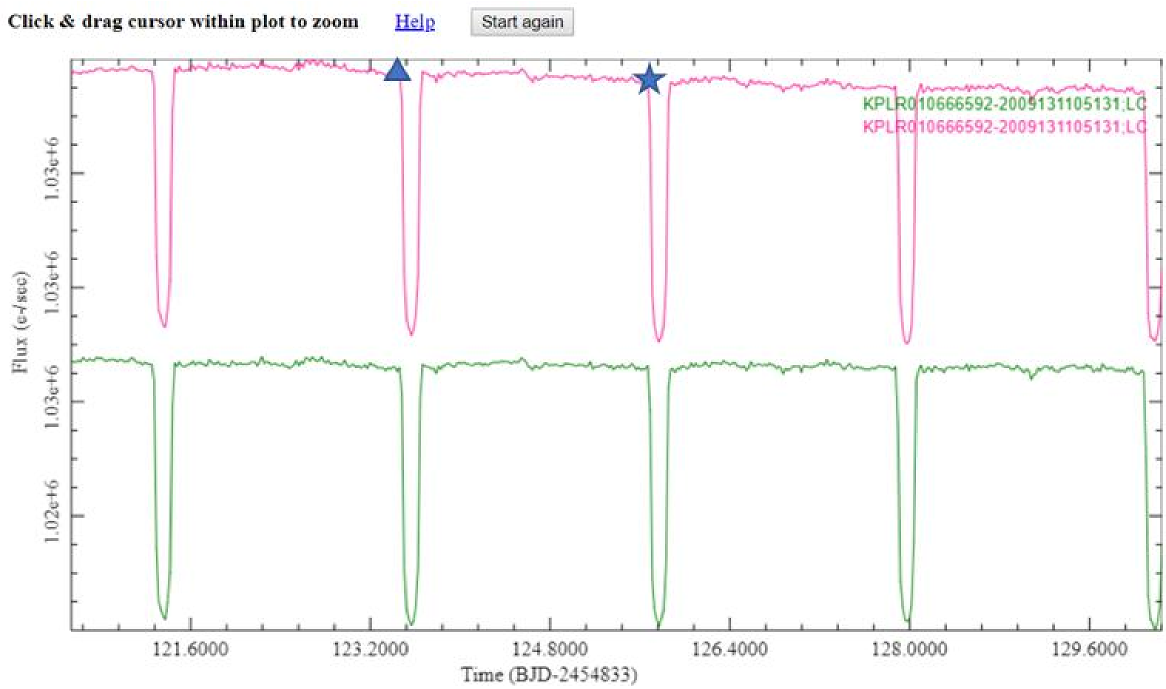
Obtaining Transit data - Step 3

Each row in the table corresponds to a different dataset, each of which holds different recorded light intensities for the star BD+472846. The columns tell us various other information about the star. Much of this information is the same for each row as all the datasets involve the same star. Perhaps the most interesting information is the 'RA' and 'Dec' coordinates (similar to Longitude and Latitude). These coordinates are fixed in relation to the stars rather than the Earth and allow other astronomers to easily find a given star if they wish to observe it again.



To view a graph showing how the recorded light intensity from the star varies with time you now need to click in one of the boxes on the left of the table. For this example, select the first dataset listed. Once a tick has appeared in the box you may now click the 'Plot marked Light Curves' button to the top left of the table.

You should now be able to view the plot shown below. You might notice that the two curves plotted (pink and green) look very similar. They look similar because they are created from the same recorded data. The green curve ('Sap Flux') is the result of the less processed data, while the pink curve ('PDCsap Flux') is created from the data after it has undergone further analysis to help reduce some of the background. We'll focus on the pink curve for now, though you can switch between the two using the tick boxes located below the plot.



Discussion - Binary stars

Earlier you saw that approximately half of all stars in our galaxy are thought to exist in binary systems. Similarly to a planet orbiting a star, these stars can create transit signatures when one passes in front of the other. Can you think of ways in which we might be able to distinguish an exoplanet transit from that of a binary star system?

- The depth of the transit i.e. size of the signal, should be much larger for a transiting binary. This is because stars are far larger than planets and so they can block out more of each others light. If both stars are the same size and temperature as one another and they are perfectly aligned with our line of sight then we could expect to see a 50% drop in the observed flux every time one star passes in front of the other. So rather a large change compared to say a 0.5% decrease in the case of an exoplanet transit.
- If the stars aren't completely identical (which is likely) then the dips in flux should be of different depths depending on which star is passing in front of the other. If the brighter of the two stars is hidden then we can expect a larger dip in flux, while if the dimmer star is covered we should observe a smaller fall. These alternating transit depths are evidence we may have observed a binary star system as opposed to an exoplanet transit.
- The shape of the dip in flux. As planets are much smaller than the stars they orbit they will often spend most of their time in transit with their full area covering the light of the star. As the area covered by the planet remains constant for the time the planet is in front of the star, we would expect the dip in flux to be constant too i.e. we expect a 'flat bottomed' dip in flux. Binary stars meanwhile will not usually have this feature due to their similarity in size. In these cases we would expect to see a dip in flux resembling the shape of the letter 'V' instead.

Obtaining Transit data - Step 4

We can tell a lot about this planet's orbit simply through looking at the plot. By comparing the shape of the curve to that of the one shown in the 'Transit Method' section earlier, we can see that the planet must be passing in front of the star each time the light curve drops in flux. In the example shown, we can see that the planet passes in front of the star 4 (and a bit) times over the duration of observation. If we were to measure the time between two of these transits, this would tell us the 'orbital period' of the planet.

If you look now at the x-axis of the plot you can see that the graph does tell us the times at which each observation occurred, however the unit of time may seem a little strange. In this plot, time has been measured in 'Julian Days' (minus 2,454,833 days), which is a measure of the number of days that have passed since the start of the Julian calendar, all the way back in 4,713BC! The important thing to note though is that one Julian day is just the same as one 'normal' day, so the time elapsed between 121.6 and 129.6 Julian days on the plot is simply 8 days. We can now work out the time between two of the 'dips' in the graph and work out the orbital period of the planet.

Move the mouse over the plot and you can see the 'Time' and 'Flux' shown in bold below it change. These values correspond to the time and flux at the point where your mouse is currently located. First, position your mouse over the star symbol shown imposed on the plot above and make a record of the time shown, then do the same for the triangle's position. The star's and triangle's positions were chosen so that they both lie at the same point in the transit window (the start). Now, take the time recorded at the triangle's position away from that recorded at the star's position – this is the orbital period of the planet! In this case, you should have obtained a period of approximately 2.2 days. This is much shorter than the orbital period of the Earth, which is approximately 365 days (1 year)!

This period can now be checked against previous measurements using the websites mentioned earlier: `http://exoplanet.eu/catalog/` and `http://simbad.u-strasbg.fr/simbad/`. Try searching BD+472846 in the exoplanet.eu website – you will return no results. This is because the planet is not named after this variation of the star name. Look instead on the Simbad website for alternative names and you will see one named 'HAT-P-7'. Search this name on the more user-friendly exoplanet.eu website and you will see a record for one known exoplanet – 'HAT-P-7 b'. Most exoplanets follow a similar naming protocol, with subsequently discovered planets named 'HAT-P-7 c' and so on. The period is clearly stated as 2.2047... days for the known planet, the same as the period discovered in this guide! Therefore, in this case we have confirmed the published measurement.

Discussion - Obtaining Transit data Step 4

What does the planet's short orbital period mean?

The planet is likely very close to its host star – see 'Semi-Major axis' and 'Calculated Temperature' on the Exoplanet.eu website. These show that the planet lies much closer to the star than the Earth is to the Sun (1AU) and that it is much hotter than the temperature of the Earth (∼290K) because of this.

Compare this value to our own Solar System. Which of these planets has the shortest orbital period? What is this period?

Mercury has has the shortest period of the planets in our Solar System, orbiting the Sun every 88 days. The planet with the longest orbital period is Neptune which has a period of 165 years! The planets in our Solar System furthest away from the Sun have the longest orbital periods.

Do you think it is important to look at other datasets? Why?

Yes. Observations at different times should still give the same results – same period. If not, then something may be wrong with the data. Also, you may miss transit signatures altogether when the transit period is greater than the observation window if you look at only one dataset.

Obtaining Transit data - Step 5

Earlier, in the Transit Method section, you worked out the percentage reduction in light caused by the Earth and Jupiter passing in front of the Sun. This method can be used in reverse to calculate the planet's radius when the reduction in flux is known instead. This does require us to know the star's radius, but, if we don't, we can simply assume the star is 'average', much like our Sun, and say the star's radius is equal to the Sun's (r = 700,000km).

For the star BD+472846, the fractional reduction in flux can be found by recording the value of the flux just before the planet crosses the star (max flux) and the minimum flux recorded when the planet covers as much of the star as possible (min flux). The fractional reduction in flux is then given by:

$$\Delta f = \frac{\text{max} f - \text{min} f}{\text{max} f}$$

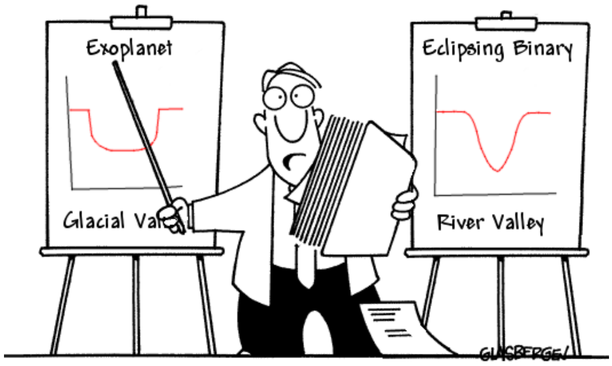
Using the values for the star BD+472846, we obtain a value of approximately 0.007 (or 0.7%). We could now use the Sun's radius for our calculation, but it is worth checking to see if the star's radius is known. Fortunately, this information can be easily found by clicking on the name 'HAT-P-7 b' on the Exoplanet.eu page described in the previous step. Here, the star's radius is listed as being equal to twice the Sun's radius i.e. 1,400,000km. The fractional reduction in flux, Δf, caused by a planet of radius r passing in front of a star of radius R is given by the following, which can be rearranged for r:

$$\begin{aligned} \Delta f &= \frac{\pi r^2}{\pi R^2} \\ r &= \sqrt{R^2 \times \Delta f} \\ &= \sqrt{1,400,000^2 \times 0.007} \\ &= 117,000\text{km} = 1.7 R_J \end{aligned}$$

So, the radius of the planet is found to be 117,000km, or 1.7 times larger than that of Jupiter. This agrees quite well with the value given on the Exoplanet.eu page of $1.4 R_J$. Comparing the size of this planet to those in our solar system indicates the planet likely most closely resembles Jupiter – a gas giant as opposed to a rocky planet like the Earth. Look at the other information on the Exoplanet.eu website to gain a better picture of what the star-planet system might look like in general.

Obtaining Transit data - Step 6

You have now seen how to navigate the Kepler website, look at light curves and deduce planets' orbital periods from them. However, most stars' light curves will not show any evidence of a planet orbiting them. This may be because some stars don't have any planetary companions, or it may be because the orbit of most planets are not aligned with our line of sight. However, even in these cases, the light curve often isn't a simple flat line. In fact, the flux may still change periodically in time, but this is not due to a planet transiting the star. Instead, these variations are caused by the star rotating, just like the Earth rotates about its axis each day.



Teaching Exoplanet astronomy to a geography student.

Remain aware that eclipsing binary stars have similar light curves to transiting exoplanets.

Stars are not uniform balls of burning gas. The surface of the star at one point may vary in temperature by thousands of degrees compared to other points on its surface. This is true for sunspots - cooler, darker regions on the surface of our Sun which appear and disappear with changes in the Sun's magnetic field. When the Sun rotates causing these sunspots to face us, the light intensity we receive from the Sun falls ever so slightly. Similar cool spots occur on other stars and we observe changes in brightness resulting from these. It is important to be able to distinguish periodically varying light curves that are the result of stellar rotation from those caused by transits.

Check out the NASA webpage - `https://sdo.gsfc.nasa.gov/` - for real time images of the Sun and short videos illustrating how active and changing the surface of the Sun really is.

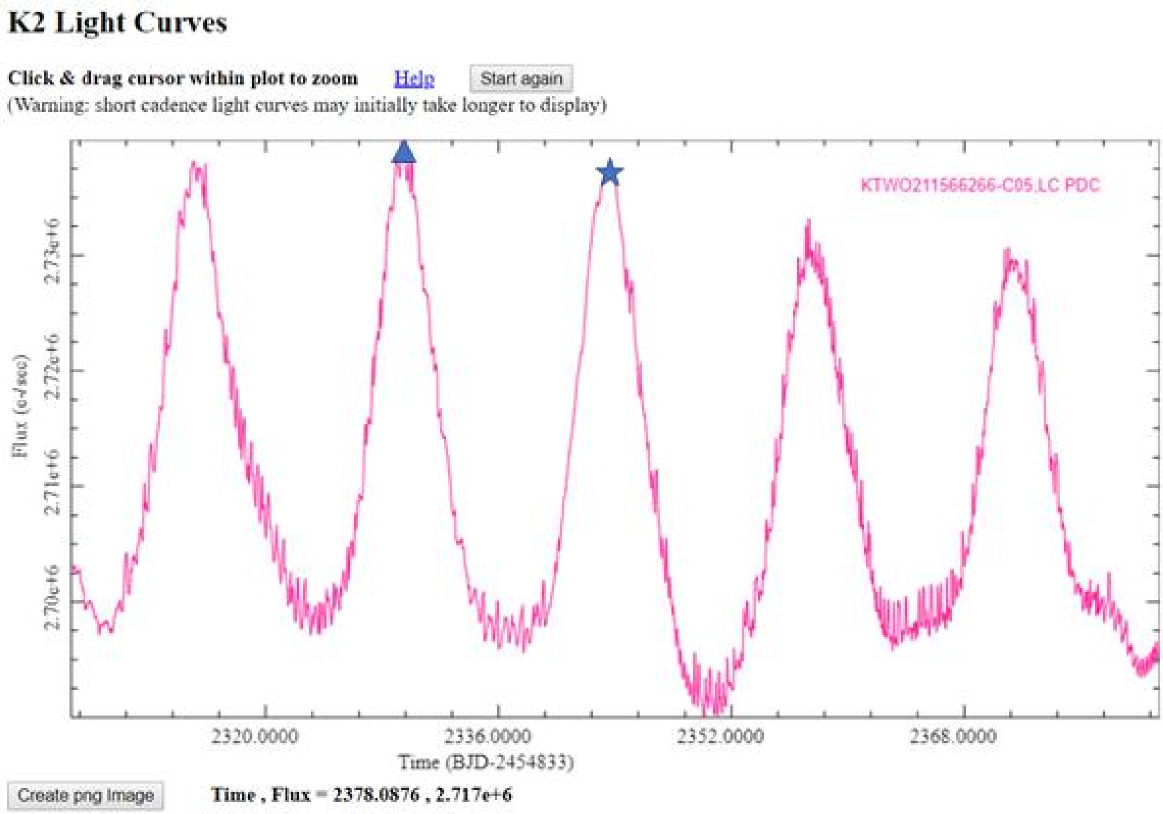
Copy and paste the following URL into your browser:
`https://archive.stsci.edu/k2/data_search/search.php`. You might notice that the only difference between this URL and the one entered in Step 1 is that 'kepler' has been replaced by 'k2'. The websites are also identical, but with 'Kepler' replaced by 'K2' throughout. K2 is simply the second stage of the Kepler mission. Both websites can be used in the same way, but some targets can only be found on the Kepler version of the website, while others can only be found on the K2 version. Now enter the target name "HIP40910" in the relevant box and click search. On the next page you will see only one dataset exists for this star. This is common for most K2 targets, with the second stage of the mission studying more stars but for shorter periods of time. Click the 'Mark' tick box next to the dataset and then click 'Plot marked Light Curves'.

Obtaining Transit data - Step 7

Like the first star examined, this light curve (shown below) also shows clear periodicity, however the shape of this light curve is more rounded than the other, with no prolonged flat periods in the flux. There is no set formula dictating the shape of these rotation light curves as they can vary wildly depending on the number, location and size of the sunspots, as well as the angle the star's rotation axis makes with our line of sight. Sunspots can even shrink or grow and appear or disappear during the period of observation!

The factors described above will result in more complex looking light curves; however, they do allow easier identification of transits as the size and shape of the planet does not change, meaning the amplitude of the signal we observe should not change either in these instances. This uniformity of transit light curves is one of their most distinguishing features.

We can use the same approach as before to find the rotation period of the star this time, rather than an orbital period. Record the times given at the positions indicated by the star and triangle and take their difference. This time we find a period of around 14 days, approximately half that of the Sun.



Obtaining Transit data - Exercises

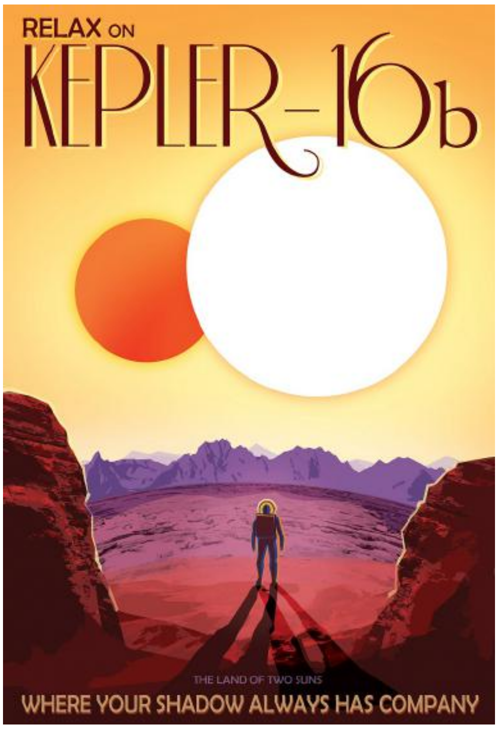
It is useful to work through a few stars to become familiar with using the website and making measurements by eye. Though you may think a computer would be better suited to the job, they can sometimes struggle to see some signals that may be 'obvious' to humans. Examine the data for the stars listed below, making a note regarding whether you believe the light curves to show evidence of transits or stellar rotation and calculate the periods in each case where possible. Check the values you obtain against any existing measurements. Note – it is possible to zoom in on parts of the plot by clicking and dragging the mouse over the desired area. If multiple datasets exist for a star, try examining a few different light curves if you are struggling to find a clear signal in one of them.

Kepler targets:

- BD+462629
- Kepler-63
- Kepler-16

K2 targets:

- HD31966
- HIP41130
- HD103720
- GJ876
- HD8648



Like Luke Skywalker's home planet, Kepler-16b orbits a pair of binary stars. Credit: NASA's Exoplanet Travel Bureau.

Solved - Obtaining Transit data Exercises

Kepler targets:

- BD+462629 - Very strong signal for a transit with period ≈1.8 days. A secondary, smaller dip in flux exists between the larger dips - this corresponds to the planet passing behind the star. Before passing behind the star we observe the light from the star and the reflected light from the planet. When the planet passes behind the star we observe only the star's light, resulting in a small reduction in recorded flux. A possible rotation period exists of ≈20 days. This is most easily seen by selecting a dataset with a large observation time and zooming in on the top part of the curve only.
- Kepler-63 - There appears to be a very nice convolution of a transit and rotation signature. The orbital period of the planet looks to be ≈9.4 days, while the rotation period of the star is ≈5.4 days.
- Kepler-16 - Kepler's first discovery of a planet that orbits two stars! The eclipsing binary signature is extremely strong in the data - a periodic repetition of a large dip followed by a smaller dip corresponding to each star passing in front of the other. The eclipsing stars have an orbital period of approximately 41 days (record the time between two dips of the same depth to find the time taken to complete a full orbit). The planet orbiting these stars is hard to see in the data as it has a long orbital period and a transit depth similar to that of the smaller binary transit. The orbital period of the planet is equal to approximately 229 days - try to find this now if you haven't already. Remember, it will not be visible in most datasets.

K2 targets:

- HD31966 - Evidence of a rotation period ≈40 days, most easily seen by zooming in. There exists possible evidence of a transit at the end of the observation window. As only one transit dip exists, the orbital period must be greater than time between start of observation window and time of transit i.e. >60 days.
- HIP41130 - Evidence of a rotation period ≈18 days. Quite noisy and looks like there are two features caused by sunspots that overlap to make up the shape of the curve. No evidence of a transit.
- HD103720 - Clear evidence of rotation period ≈18 days. No evidence of a transit.
- GJ876 - Evidence of stellar rotation, unfortunately the observation window seems to be slightly smaller than the rotation period. We can estimate the stellar rotation period to be ≈70 days. No evidence of transit.
- HD8648 - Quite noisy, but evidence of rotation period ≈26 days. No evidence of transit.

Obtaining Radial Velocity data - Systemic

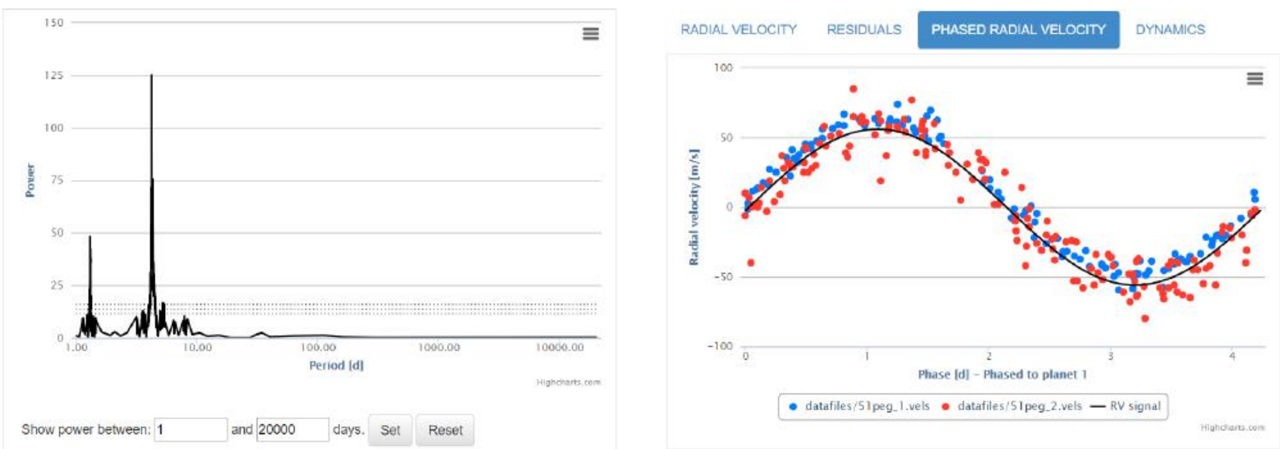
You can now rediscover the first exoplanet ever detected orbiting a main sequence star. First, navigate to: http://www.stefanom.org/systemic-online/. Systemic is a very user-friendly tool designed for finding periods in radial velocity data. The short tutorial guide (http://www.stefanom.org/51-pegged/) leads you carefully through the steps required to rediscover 51 Peg b, the first exoplanet found to be orbiting a main sequence star like our Sun.

You will see the radial velocity data presented on the website looks different to that of Kepler - it is presented only as a scatter plot, with no lines joining the points. This is because RV observations are often taken months apart, so it is impossible to see periods of a few days by eye in this case. Smart computer analysis is therefore needed to find periods in radial velocity data.

Following the steps in the Systemic guide will allow you to create 'periodograms' and 'phased radial velocity curves' for the data. Periodograms help us to find periods in data by trying to fit it with curves of different periods and then telling us how good a fit each period provides. We can then take our most likely period and cut our entire observation window (which could be many years) into 'strips' the same width as our period. Plotting these 'strips' on top of one another generates the phased radial velocity. This new plot makes it easy to see by eye whether the period stated really does exist in the data.

It is worth examining a couple of other stars while you are on the website. Why not see if any of the stars you examined in the previous section also have RV data? Do your results agree or differ?

One drawback of Systemic Live is that you are limited to looking at only the stars that are preloaded into the application, as well as its use of only one basic type of periodogram. The 'NASA Exoplanet Archive' is an alternative resource which enables you to load your own data and is introduced on the following page, while 'Agatha' allows more sophisticated analysis of a variety of data, though you do need to download and prepare the data yourself in this instance. The steps involved in using Agatha are explored later too.



Periodogram and phased radial velocity curve for the system 51 Peg.

Discussion - Periodograms

Transits

When examining the light curves recorded by Kepler it was often quite obvious when periods, both orbital and rotation, were present in the data. This is because Kepler made observations of an object every 30 minutes. This regular sampling generates reasonably smooth, continuous data sets, making it relatively easier to find periods without having to use computer analysis.

Radial Velocity

Radial velocity measurements on the other hand are often randomly sampled, with the time between measurements varying greatly. The frequency and total number of observations is also very different to transit observations. Often, you may find only 10 recorded radial velocity measurements for a star, which may have been spread out over the course of 5 years! In these instances it is challenging to find periods in the data 'by-eye'. Periodograms are essential in these situations, but they are also useful to obtain quantitative measurements of periods in transit data too.

What are periodograms and how do they work?

Periodograms analyse time-series data by attempting to fit theoretical curves to the data with different periods. For each iteration the computer will select a period in the range it has been told to search. It will then generate a theoretical curve with this period and try to align this with the real data points. If the two align well i.e. the theoretical curve matches the observations closely, then the period will be assigned a high 'power' (a high likelihood that the period does actually exist in the data). Conversely, if the theoretical curve and the data points have poor agreement then that period will be assigned a low power.

The above process is repeated for a large number of periods over the desired range, with each period earning an assigned power. This data can then be plotted in a periodogram, such as the one shown on the previous page. In this case there is a very strong signal (peak in the periodogram) between 1 and 10 days, strong evidence that a planet may be orbiting the star. Remember, periodograms can be used to find periods in both radial velocity and transit data.

In some cases, you might observe multiple peaks in a periodogram, such as the smaller one to the left of the large peak in the plot on the previous page. This could be evidence of another planet, or it may be an artificial artefact of the primary planet. In the case of 51 Peg this smaller signal turns out to be nothing more than an artificial peak. This is confirmed by adding the planet, 51 Peg b, into Systemic. The periodogram plot then changes to show the 'leftover' periodogram that results from taking into account 51 Peg b. The smaller peak has now disappeared, with another artificial peak appearing at 1 day - this results from the Earth's rotation about its own axis. All periods found to be very close to 1 day should be met with a degree of scepticism!

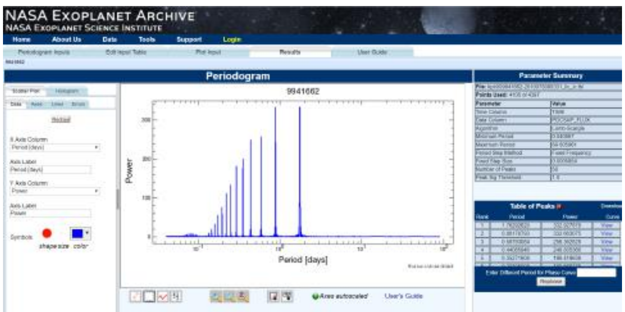
Obtaining Radial Velocity data - NASA Exoplanet Archive

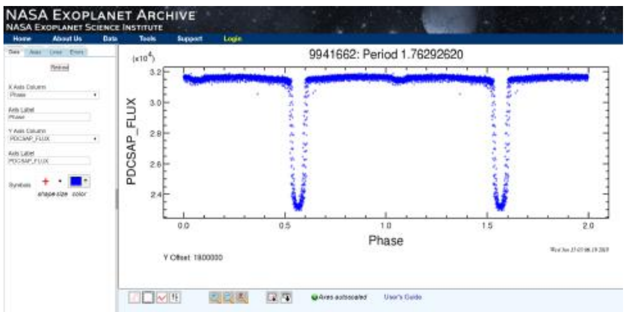
The NASA Exoplanet Archive (https://exoplanetarchive.ipac.caltech.edu/) offers a similar set of tools as Systemic. At first glance they may seem slightly less user friendly, but NASA's tool has the benefit of holding data for both confirmed and candidate exoplanets collected using any method of detection! This means you can create periodograms for transit data too! Note that it is still important to make 'by-eye' measurements when possible as the computer can still get it wrong. In fact, Planet Hunters (https://www.planethunters.org/) was created with this sole purpose in mind!

On the NASA website, click on whether you would like to look at confirmed or candidate exoplanets. To plot periodograms for transit data, hover over the 'i' button next to the host star's name and select the 'Time Series and Periodogram' button. Note that this option is not available for all targets. You should now be able to analyse the data to create periodograms and phase curves, just like in Systemic. If multiple datasets are available for a specific target it is best to deselect all of these and choose to analyse just one dataset at a time. This process can be repeated to ensure the same period is present in all the data gathered.

To plot RV data, click on the host star's name (to the left of the 'i' button) you wish to examine. This will take you to an 'overview' page containing all available information about the planet in question. Near the bottom of this page is a table labelled 'Literature Time Series'. Here, you can click on the links in the 'Time Series Viewer' column to plot the data gathered from various experiments. You can now analyse this data, and create periodograms and phase curves for it.

Play around with this website too, again re-examining targets you have looked at previously, as well as new targets. The table containing the list of all the planets can be structured in any way you wish e.g. you can choose to look only at single planet systems discovered by Kepler. These stars can then be arranged from brightest to dimmest, hopefully allowing you to select transits that will have the clearest signals.





Periodogram and phased transit curve for the star BD+422629 examined earlier. Note that the star is only searchable by the name KOI-13 in the NASA database. Only one dataset has been used in creating these plots.

Obtaining RV data - Agatha Step 1

Kepler has done an excellent job of providing an initial reconnaissance of transiting exoplanets across about 1/50th of the sky since its initial launch back in 2009. Data from its successor mission TESS – the Transiting Exoplanet Survey Satellite is keenly anticipated. Obtaining radial velocity data on the other hand has been the aim of multiple players over the past decades. To make life easier, we have put some of this data into http://herts.ac.uk/h2h/data

This may look slightly messy at first, but fortunately you can ignore most of what is here. The few folders you are interested in are labelled:

- HARPN/
- HARPS/
- KECK/
- SOPHIE/

These names refer to the different instruments that have collected the data. 'HARPS' is the High Accuracy Radial Velocity Planet Searcher, a high precision spectrograph which is able to detect the small changes in a star's spectrum caused by its movement discussed earlier. HARPS is installed on a telescope in Chile, so to gain full sky measurements, a copy of HARPS was installed on a similar telescope located in the Canary Islands. This was given the names HARPS-N, which has been condensed to HARPN for brevity, where the 'N' refers to it being located in the Northern hemisphere.

KECK is an observatory located near the summit of Mauna Kea, Hawaii. It too houses a spectrometer capable of detecting the movement of stars to high precision. Finally, SOPHIE provides the acronym to the Spectrographe pour l'Observation des Phénomènes des Intérieurs stellaires et des Exoplanètes, another high-resolution spectrograph, this time located in south-eastern France.

The following steps will guide you through how to analyse this radial velocity data to find the periods hidden within it.

Obtaining RV data - Agatha Step 2

Open the UH webpage stated above if you haven't already and scroll down until you find the folder labelled HARPS. Alternatively, you can simply add 'HARPS/' immediately after the URL given above. You will see a list of files like those shown below. Scroll down until you find the one labelled 'HD103720.rv'. This file contains radial velocity data for the star HD103720. Clicking on this file (or downloading it and opening it within a text editor) will reveal 3 columns of numbers. The first shows the Julian date at which each measurement was taken, while the second column shows the radial velocity measured at each of these times (given in units of metres per second). The final column states the error associated with the radial velocity.

Unfortunately, the data doesn't present itself nicely in a graph like the Systemic or Kepler data did, so we are going to have to do a bit more of the work ourselves. First, we must save the data locally onto our own computer. This can be done quite easily by selecting all the data (Ctrl + A), copying it (Ctrl + C) and then pasting it (Ctrl + V) into a text editor such as Notepad. Next, save the file in a convenient location. It will probably be best to make a folder for this data so that you can save future work here too. Finally, save the document as a '.txt' document.

Index of /~hraj/Dwarfs/kepler_/HARPS

Name	Last modified	Size	Description
Parent Directory		-	
BD+111933.rv	2018-04-17 14:21	1.0K	
BD+111933_ccf.rv	2018-04-17 14:21	2.7K	
GJ176.rv	2018-04-17 14:21	6.3K	
GJ176_ccf.rv	2018-04-17 14:21	17K	
HD4256.rv	2018-04-17 14:21	304	
HD4256_ccf.rv	2018-04-17 14:21	804	
HD4313.rv	2018-04-17 14:21	684	
HD4313_ccf.rv	2018-04-17 14:21	1.8K	
HD25825.rv	2018-04-17 14:21	456	
HD25825_ccf.rv	2018-04-17 14:21	1.2K	
HD73667.rv	2018-04-17 14:21	228	
HD73667_ccf.rv	2018-04-17 14:21	603	
HD90125.rv	2018-04-17 14:21	152	
HD90125_ccf.rv	2018-04-17 14:21	201	
HD100777.rv	2018-04-17 14:21	2.7K	
HD100777_ccf.rv	2018-04-17 14:21	7.3K	
HD102195.rv	2018-04-17 14:21	1.8K	
HD102195_ccf.rv	2018-04-17 14:21	4.7K	
HD103720.rv	2018-04-17 14:21	5.8K	

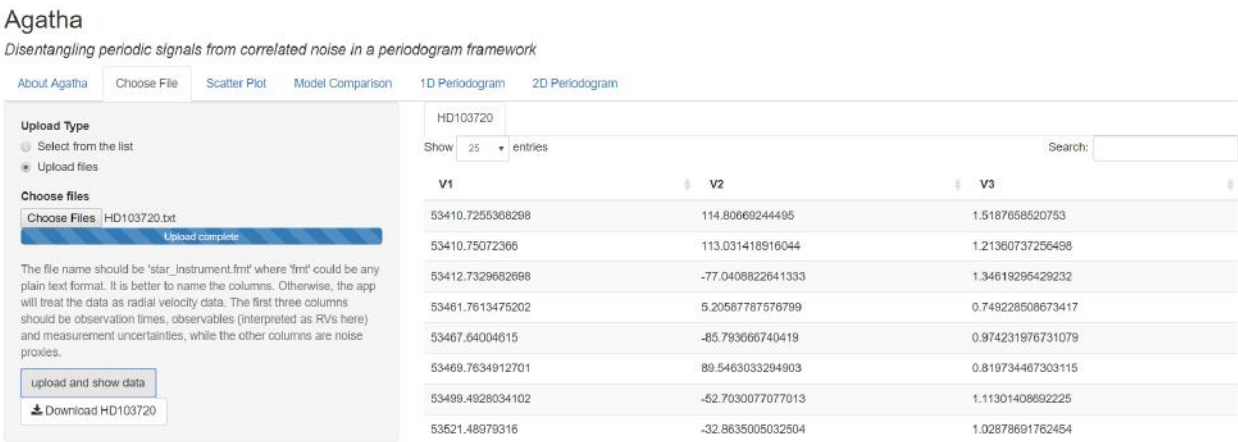
53410.72553682979	114.8066924449504	1.518765852075302
53410.75072365999	113.0314189160435	1.2136073725649836
53412.73296826985	-77.04088226413333	1.3461929542923208
53461.761347520165	5.205877875767985	0.7492285086734172
53467.64004614996	-85.79366674041898	0.9742319767310793
53469.76349127013	89.54630332949033	0.8197344673031154
53499.49280341016	-52.70300770770132	1.1130140869222507
53521.48979316	-32.86350050325043	1.0287869176245357
53542.55464679981	104.58535309808018	2.290906516630819
53764.875570360105	48.77037252615593	1.4250957834141735
53765.77998154983	109.71889482667528	1.7252897692384306
54166.75875554979	72.5017866122413	1.5263030659590349
54168.742727320176	-63.74800024387189	1.4859896669090777
54170.746496079955	93.47044667016979	1.2534185742453616
54172.76433230005	-23.627362822234907	1.3357000008562314
54174.72623493988	31.38799138161174	1.3975620962289965
54229.65211449005	74.9110933275549	2.670180239706397
54231.66476876987	-6.263046744749678	2.00746282981128
54232.559019309934	-76.81819994727113	1.7671400107275872
54234.59806569014	98.52434774194714	3.12840525271935
54254.49324866012	-3.51530478825077	2.3301662469969475
54259.55077240011	-48.0930055024882	1.9746499586345145
54568.64726882009	-0.25950045094065644	1.4882978337103208
54569.640519539826	-70.81284911262698	1.1592659609525817
54570.648594529834	-18.50652765999679	1.637206987397882
55325.57197439019	-50.75384818095425	2.184641336089483
55577.838643880095	30.53590077255373	1.8542465104554504
55580.784534330014	-54.936330450130036	1.9487798016039315
55586.82940752013	16.617174156091554	1.3491706156931116
55587.84269755008	120.22670021223034	1.4704268618254246
55616.7034949502	-9.792628856762088	1.067942408395259
55637.7141490099	70.61426634734272	1.9703118760695482
55657.70428735996	-20.589998595444953	1.5688126803750486
55658.726448430214	-76.60926586991589	2.4696038923961092
55659.60601921985	-19.012809765508045	2.769691750279812
55660.66265525017	91.32158453264032	1.480607114621555 8
55662.6288203001	-45.50376697822834	1.1944713863317844
55663.65709572006	-71.64496659359831	1.676876396755767

Obtaining RV data - Agatha Step 3

Now the data is saved locally we can load it into Agatha, http://agatha.herts.ac.uk/, an analysis tool created by the UH specifically designed to find periods in data contaminated by lots of noise. Agatha comes with lots of statistical tools that you don't need to use right now, so we'll stick to the basics.

Click the 'Choose File' button near the top of the page, then select 'Upload files'. This will allow you to click the second 'Choose Files' button and find the copy of the radial velocity data that you saved earlier. Load it and then click 'upload and show data'. The three columns of data you now see are the same as those in your text file. To recap – the first column (V1) shows the time, the second (V2) shows the radial velocity, and the third (V3) is the error on the radial velocity. For our purposes we are only interested in the first two columns, V1 and V2.

Clicking 'Scatter Plot' at the top of the page and then 'show scatter plot' will provide you with a graphical representation of your data, similar to those initially shown in Systemic. On the x-axis is the time (V1) and the y-axis shows the radial velocity (V2). You can see no curve joining the points as no analysis has taken place yet, so we don't know what that curve should look like.



Obtaining RV data - Agatha Step 4

We now want to skip to the '1D Periodogram' button at the top of the page. Earlier you learnt that periodograms help us to find periods in data by trialing many different possible periods for the data and telling us how good a fit each period provides. Many different types of periodogram exist, which all use slightly different mathematical methods to determine how well each period fits the data. We have the option to select multiple types of periodogram from the drop down menu shown.

Agatha is based on the 'Bayes Factor Periodogram' (BFP) and this periodogram often provides the best results. However, it is worth including a couple of other types of periodogram to see if there is agreement between them – if all chosen periodograms indicate the same 'best fit' period, then this provides greater weight to the result. In this example the BFP has been chosen along with the GLST and LS periodograms. The LS periodogram is the one used in Systemic and the NASA Exoplanet Archive. The two boxes below – 'Number of MA components' and 'Noise proxies' – have been left untouched, set to zero, as these are not of use to us at this time.

The 'Period range in base-10 log scale' offers a neater, more condensed way of plotting our x-axis. The period range included in the above example extends from $10^{\mathbf{0.2}}$ days (≈1.6 days) up to $10^{\mathbf{3}}$ days (1,000 days). Only periods within this defined range are searched for and plotted. This means that the data could possibly have a period in it that is longer than 1,000 days or shorter than 1.6 days and we would not be able to tell as we haven't asked Agatha to look for these periods. We can extend this period range if we wish using the sliding bar, however this means the analysis takes longer to run. It is important to find a balance between searching for a wide range of periods and not waiting hours for the analysis to complete!

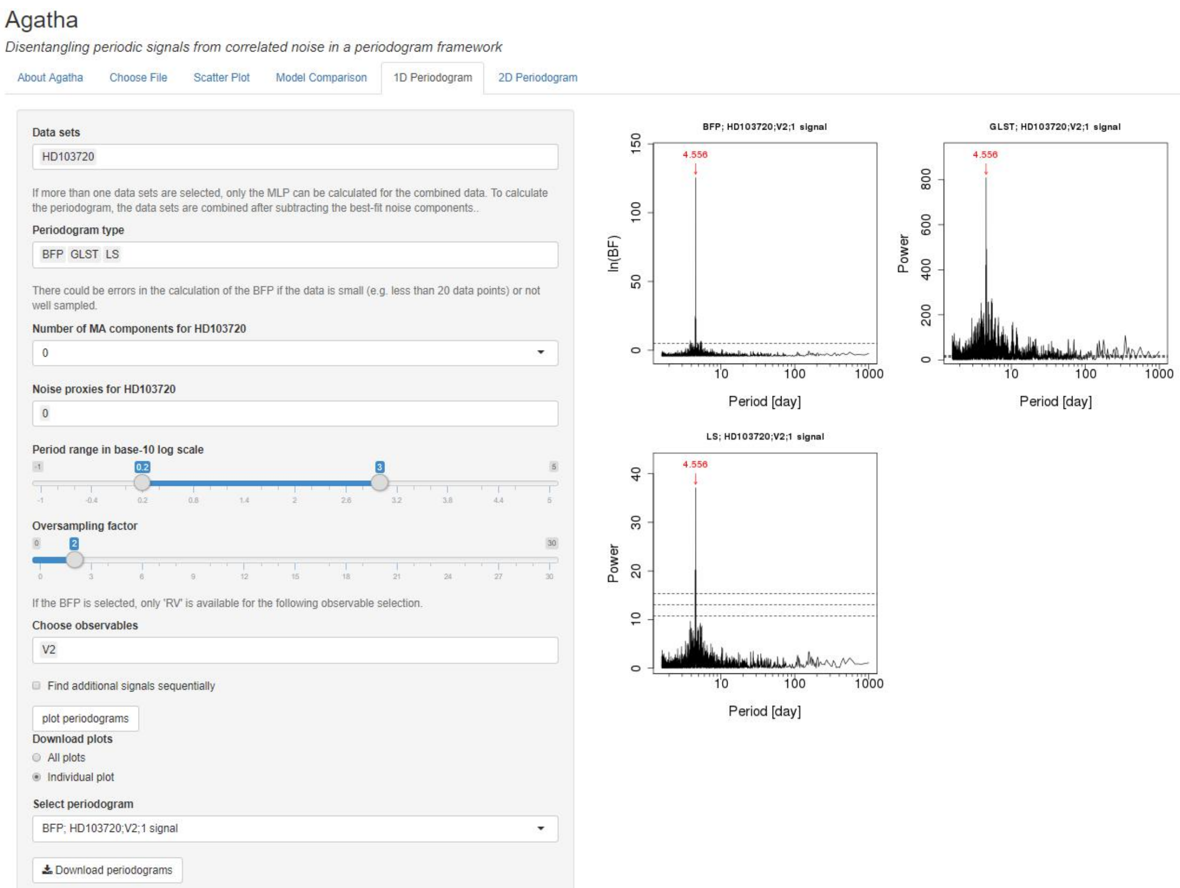
The second sliding bar allows us to include an 'oversampling factor'. This factor allows us to compensate somewhat for having limited data points. Returning to the 'Choose File' tab at the top of the page and scrolling down you should see a line saying, 'Showing 1 to 25 of 78 entries'. This means that we have 78 data points. This is very few compared to Kepler which could have recorded the flux every 30 minutes for 3 months at a time. By 'oversampling' our data, we effectively count each data point more than once, increasing their significance. This can allow us to achieve improved resolution and reduced noise. In this example the oversampling factor has been set to '2', but this can be increased when dealing with datasets with even fewer points e.g. less than 20.

Finally, we choose to plot the 'observable' V2 which is the radial velocity as this is the observable that we are hoping to find a period in.

Obtaining RV data - Agatha Step 5

Now, with the settings set to those described above, you can click 'plot periodograms' and you should (after a couple of minutes) see the 3 periodograms shown. We can see large peaks at a period of 4.556 days in all 3 periodograms, strong evidence that there is a signal in our data with this period. Therefore, it is likely that this star is orbited by a planet with an orbital period of approximately 4.6 days.

If there appear to be multiple peaks in the periodogram (possibly caused by multiple planets) we can choose to run the analysis again, this time searching for multiple signals, though for time's sake, it is often worth limiting this to a maximum of 3 signals. These periodograms can be downloaded and saved to your computer using the button provided if you wish. Similarly, the scatter plot discussed earlier can be downloaded and saved locally too.



Obtaining Radial Velocity data - Exercises

You can now try working your way through the following examples, just as you did in the transit method. Note that the KECK data has additional columns which you don't need to worry about. The first three columns are in the same order as those in the worked example.

KECK:

- GL876
- HD103459

HARPS:

- HD100777

Remember, after analysing data to find evidence of planetary orbits or stellar rotation, it is important to check your findings against those of others. Many stars have already undergone thorough analysis, so you may find that your results corroborate those of previous findings. Alternatively, you may believe you have found evidence for planets that have not been detected before. Finally, other sources may claim to have found planets that you have not found evidence for - this may happen if other studies have had access to different data or more sophisticated analysis tools. Rest assured though that the tools described in this guide do enable you to obtain results that very closely match the precision and accuracy of published work.

In addition to exoplanet.eu, exoplanet.org and the NASA Exoplanet Archive, another great source for finding papers regarding specific stars and planets is the Astrophysics Data System (`http://adsabs.harvard.edu/abstract_service.html`). This website allows you to search for papers that include a target name and specific key words. This is particularly useful when trying to check stellar rotation periods but can also be used to find exoplanet measurements. The target name can be entered in the top right box, while key words such as 'rotation period' can be entered in the bottom one. Sending that query will return a list of papers ranked in the order that they matched your search criteria.

Solved - Obtaining Radial Velocity data Exercises

KECK:

- GL876 - Sometimes called GJ876 instead. Very strong, sharp peak in periodograms at 61.12 days. Good evidence of a planet orbiting the star with this period. Calculated using the same settings as in the worked example.
- HD103459 - It is possible to see a pattern in the RV data by eye this time. Rather than looking like a smooth sine wave, with the maximum positive RV equalling the maximum negative, this RV, this data represents a highly eccentric orbit (oval shape as opposed to circular). When the object is close the star it is moving very quickly and so the star must be too, while the opposite is true when the separation between the two is large. To find this long period signal the period range must be extended up to 100,000 days (10^5 days). When searching for one period we find a peak at 1,780 days. When searching for 3 signals we find peaks at 1,661 days, 29.46 days and 94.07 days. The 94 day period is not a very strong peak, but the long period 1,700 days (4.5 years) and the 29.46 day period could be of interest and could be caused by orbiting bodies. Note – because the maximum negative RV is very large, this orbiting companion may be a small star as opposed to a massive planet.

HARPS:

- HD100777 - A period of 381 days is found in the BFP and GLST when searching for one signal. This is not the most significant peak in the LS, but we trust the BFP more, especially as it agrees with one of the others. The secondary peak at around 190 days is likely a resonance of the 381 day peak (it is half the period). This is tested by searching again for 3 signals this time. The 381 day peak remains (though it shifts slightly to 383.7 days), while the 190 day peak disappears. The other periods that appear when searching for 3 signals in the BFP are 126.5 days and 2.293 days. The 126.5 day period might also be a resonance of the 380 day period (it is one third of this), and the 2.293 peak is not very significant (not far above the dotted line). Therefore, these other periods are less interesting for us and we focus on the 380 day period as possibly being caused by a planetary orbit.

Downloading data from NASA's Exoplanet Archive

Earlier, you learnt how to make by-eye measurements of Kepler's transit data - an important step in confirming any discoveries. It is useful and necessary though to create periodograms for this data, just as you have done for radial velocity measurements. This is especially true for data where it may be hard to measure any period by-eye. NASA's Exoplanet Archive allows for the creation of periodograms on their website, however more accurate results can be obtained by downloading this data and using it in Agatha. You can also download radial velocity data from NASA's site.

To download the RV data click on the star's name and scroll down to the 'Literature Time Series' table as you did before. Under the 'File' column you will see the option to 'Download' this data. Clicking this link opens up a new tab containing a list of all the data points collected. Three columns of data exist: the time of the measurement, the RV recorded and the error on this RV measurement. These columns of data can be copied and saved locally just as you did with the UH data resource. You can now follow the same steps as before to analyse this data in Agatha.

Obtaining transit data in the same correct format is slightly more complex. First select your target, hover over the 'i' button and click 'Time Series and Periodogram', as you did earlier. Change the settings so you are only plotting one dataset (choose one with a long period of observation) and then click 'Download table of plotted data'. The file 'plot.tbl' will be downloaded which contains 3 columns of information: set (simply a column of repeated zeros), time and flux. This file can be opened in any text reader. Unfortunately the error is not included in this file, but it is necessary to include it for Agatha to run properly.

To download the error data return to NASA's Exoplanet Archive and change the Y-axis variable from 'PDCSAP_FLUX' to 'PDCSAP_FLUX_ERR'. Redraw the graph and then download then data as before. Now you have the 'time', 'flux' and 'error' downloaded but in different documents.

You can select vertical columns of data by holding down the 'ALT' key on your keyboard and dragging over the text you wish to select. This ability varies depending on your choice of text editor. Try again using a different text editor, such as Word, if your initial choice does not work. Use this new skill to delete the column of zeros under the 'set' heading in the first document you downloaded (containing the flux measurements). Next, highlight and copy the column of error values from the second file and copy them into the first. Paste these values in the space where the first recorded error should sit at the top of the document. Ensure the errors are copied in as the third column of data, separated from the flux values by a space. Your data is now in the correct format and can be read by Agatha!

Try downloading both transit and radial velocity data in this way. Perhaps you can find a target where both sets of data exist for the same star, or download data for 51 Peg to see if you obtain the same result as that found with Systemic.

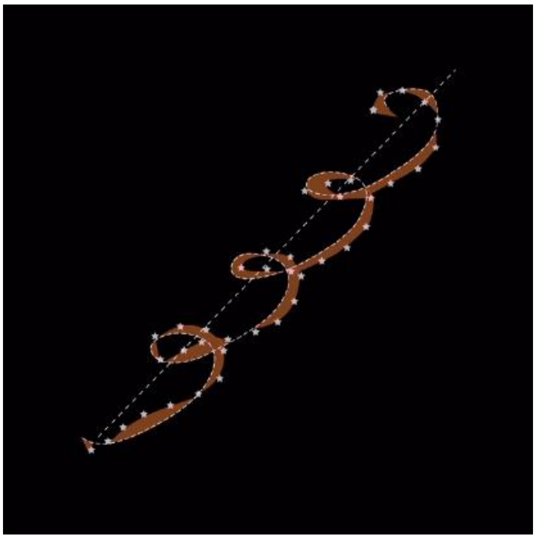
Astrometry and Gaia

At the start of this guide, Astrometry was mentioned as being one of the many exoplanet detection methods available to Astronomers. Astrometry involves making very precise measurements of a star's position and motion over a long period of time. If any unexpected change occurs between measurements then this could be evidence of an unseen planet orbiting the star. Watch this short video https://www.youtube.com/watch?v=4u_dVKKRoPw, created by the European Space Agency (ESA), to see the type of signal that might indicate the presence of an exoplanet.

Making precise astrometric measurements does not come without difficulties and disadvantages, but there are many advantages to making such measurements. The main advantages include:

- We do not need line-of-sight alignments like transit measurements require.
- We can calculate an accurate mass of the planet, unlike the minimum mass which is calculated using radial velocity methods.
- Astrometry excels at detecting small planets at large distances from their host star and with long orbital periods. This means it is complimentary to transit and RV methods of detection, filling the 'gaps' left by the other methods' observational biases.
- The ability to detect smaller planets at larger distances also means that the chances of detecting potentially habitable worlds are also higher.

The Gaia mission has succeeded in mapping the positions and distances of over 1 billion stars and other astronomical objects in our galaxy! This mission has provided astronomers with an unprecedented amount of data which will take many years or decades to analyse and appreciate fully. The official Gaia website, http://sci.esa.int/gaia/28820-summary/, offers a wealth of information about the mission goals and the history of astrometry, while the exoplanets page, http://sci.esa.int/gaia/58784-exoplanets/, describes how
Gaia data can be used to detect exoplanets using both astrometry and transit methods. It is expected that Gaia will detect tens of thousands of exoplanets within just a couple of thousand lightyears of the Earth!



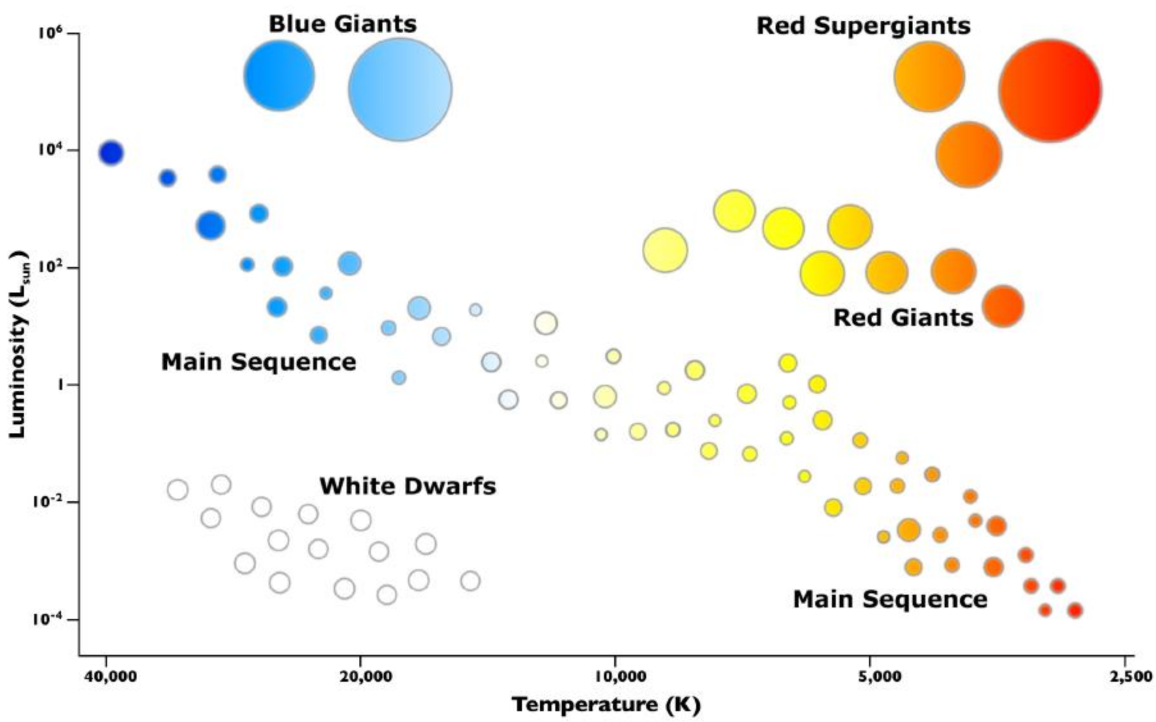
A still from ESA's astrometry video. The brown areas highlighted show the deviations of observations from the predicted path the star would follow if there were no planet orbiting it.

Hertzsprung-Russell diagram and Gaia

Gaia's interest does not lie solely in detecting exoplanets. A huge variety of stellar information is being collected that will be of great use to a number of research areas. Included in this information is data regarding the luminosity of stars, their magnitude, their temperature and their colour. Note - the more negative a star's absolute magnitude, the more luminous it is. This data can be plotted in a Hertzsprung-Russell (HR) diagram, which is a fundamental tool used by astronomers to study populations of stars and their evolution.

ESA has created their own HR diagram from data collected from Gaia. This diagram and further information surrounding HR diagrams can be found here http://sci.esa.int/gaia/60198-gaia-hertzsprung-russell-diagram/, while a simplified cartoon version is provided below for you to make comparisons with. Our Sun would sit approximately in the middle of the plot below, lying in the yellow area on the 'main sequence' branch.

The HR diagram is interesting in itself as it shows us how different types of stars are distinct from one another. However, most relevant to this guide is where do the stars which have already been confirmed to host planets lie in this diagram? Do they cover a broad range of star types or only a narrow selection? Is the distribution of planet-hosting stars a result of observational biases or is it due to certain types of stars being more or less likely to host planets than others?



Discussion - Absolute and Apparent Magnitude

When we look at stars in the night sky from the Earth we see how bright they 'appear' to us i.e. we see their 'apparent magnitude'. The further away an object is, the dimmer its apparent magnitude. This means that a very bright, distant star can have a dimmer apparent magnitude than a less luminous but closer star. The reason that we often use a logarithmic scale, rather than a linear one, to measure the brightness of stars is because our eyes are approximately logarithmic detectors.

'Absolute magnitude' eliminates the distance consideration, calculating the magnitude a star would have if it were placed 10 parsecs (≈32.6ly) away from the Earth. By offering a star's magnitude at a set distance, the brighter a star's absolute magnitude, the more luminous it truly is. For both apparent and absolute magnitude, the smaller or more negative this number, the more luminous the star appears/is.

To convert between apparent and absolute magnitude requires the following formula:

$$\mathrm{M} = \mathrm{m} - 5\log_{10}\left(\frac{\mathrm{d}}{10}\right)$$

Where 'M' is the absolute magnitude, 'm' is the apparent magnitude and 'd' is the distance to the star given in parsecs. Though this formula may seem complicated, if you are told the apparent magnitude and distance of a star it is simple to calculate its absolute magnitude using your calculator. This formula is sometimes seen rewritten as:

$$\mathrm{M} = \mathrm{m} + 5\log_{10}(\mathrm{p}) - 10$$

Where 'M' and 'm' have the same meanings as before and 'p' is the 'parallax' of the star given in micro-arcseconds. The parallax of a star is the angle through which it appears to move relative to background stars as the Earth orbits the Sun. The above formula is derived from the first one using the laws of logarithms (http://www.bbc.co.uk/bitesize/higher/maths/algebra/logarithms/revision/1/) and the relation between distance and parallax:

$$\mathrm{d} = \frac{1}{\mathrm{p}}$$

Where 'd' is the distance to the star given in parsecs and 'p' is the parallax of the star given in arcseconds (note - not micro-arcseconds). For further information on parallaxes see https://www.space.com/30417-parallax.html.

Exoplanet hosts and the HR diagram

To plot only confirmed exoplanet hosting stars in a HR diagram requires the use of NASA's Exoplanet Archive (Gaia's archive does not tell us whether a star hosts a planet or not).

On https://exoplanetarchive.ipac.caltech.edu/ click 'confirmed planets' at the top of the screen. Of the many columns of data available, we are only interested in three: 'G-band (Gaia) [mag]', 'Distance [pc]' and 'Effective Temperature [K]'. The effective temperature will be used as the x-axis for our HR diagram and we need to use the absolute magnitude of the stars for the y-axis. Unfortunately the magnitude recorded by Gaia is the apparent magnitude, so this must be converted using the formula on the previous page before it can be used.

	Row ID	Distance [pc]	G-band (Gaia) [mag]	Effective Temperature [K]
		not null	not null	not null
☑	2	$119.47^{+6.22}_{-6.95}$	4.723	4213±46
☑	4	$18.15^{+0.19}_{-0.20}$	6.325	5338±25
☑	5	21.41±0.23	6.021	5750±8
☑	18	$39.43^{+1.64}_{-1.79}$	6.938	6331±61
☑	36	18.11±0.24	4.867	5531±11
☑	38	159.1±11.0	6.494	4847±7
☑	43	$50.03^{+3.73}_{-4.38}$	9.270	4864±101
☑	44	774±165	9.912	4649±30
☑	45	>175.44	8.651	4796±117
☑	46	200.00	9.120	4259±64
☑	47	200.00	9.120	4259±64
☑	48	$1083.637^{+504.102}_{-261.}$	8.811	4296±10
☑	51	751.865832077	8.20230237256	4534±8
☑	52	$407.627^{+47.128}_{-38.277}$	8.934	4943±30
☑	53	$20.10^{+0.65}_{-0.69}$	8.999	4324±100
☑	54	$20.10^{+0.65}_{-0.69}$	8.999	4324±100
☑	55	$42.09^{+2.67}_{-3.06}$	9.417	4816±114
☑	56	$42.09^{+2.67}_{-3.06}$	9.417	4816±114
☑	57	80±10	9.772	5393±44
☑	58	27.3	9.379	4475±100
☑	59	766	9.600	4545±71

Showing records 1 to 21 of 550 (3774 total)

On NASA's website, get rid of all the columns that aren't of interest using the red crosses. Next, in the white boxes under the magnitude, distance and temperature column headings, type 'not null'. This requirement will eliminate all stars which do not have known values for these three parameters. At the time of writing, this reduces the total number of stars left from 3774 to 550 - this is means our sample size is around 10,000 times smaller than the 4,000,000+ stars used to create the HR diagram on ESA's website! Also note that some of these stars will be repeat entries if they host more than 1 exoplanet. Despite this far smaller sample of stars, it is still interesting to create a HR digram to compare to Gaia's.

Creating this HR diagram is not possible using the Archive's built-in plotting tool as first the apparent magnitudes must be converted to absolute magnitudes. Therefore, this data must instead be downloaded and plotted in some other tool. Any plotting tool you have access to can be used. The following example is based on the use of Excel.

Exoplanet hosts and the HR diagram

Using the menu at the top of the page select 'Download Table'. Ensure the following are ticked: 'CSV Format', 'Download Currently Checked Columns' and 'Download Checked (and Filtered) Rows'. Also tick 'Values only (no errors, limits, etc)' - it is important to remember that errors do exist on all these values, but we want to plot a simple HR diagram so we will ignore these errors for now. Open this downloaded file using Excel. Delete any excess information at the top of the downloaded file so that you are left with only the 3 columns of data.

Start a new column where you will now calculate the absolute magnitude for all the exoplanet hosting stars. In the first box under this new heading type the equation shown in the top right of the image shown. This is the same equation shown in the discussion section earlier where 'B2' is the apparent magnitude and 'A2' is the distance given in parsecs. Copy this equation and highlight all the remaining cells in your new column. Paste this equation into the other cells, calculating the absolute magnitude for all your data points. Note that the equation will automatically 'adapt' to read in the correct information for each star.

E2 =B2-(5*LOG10(A2/10))

	A	B	C	D	E	F
1	st_dist	gaia_gmag	st_teff		Abs_Mag	
2	119.47	4.723	4213		-0.66329432	
3	18.15	6.325	5338		5.03061685	
4	21.41	6.021	5750		4.36791666	
5	39.43	6.938	6331		3.95886611	
6	18.11	4.867	5531		3.57740775	
7	159.1	6.494	4847		0.4856491	
8	50.03	9.27	4864		5.77384749	
9	774	9.912	4649		0.4682952	

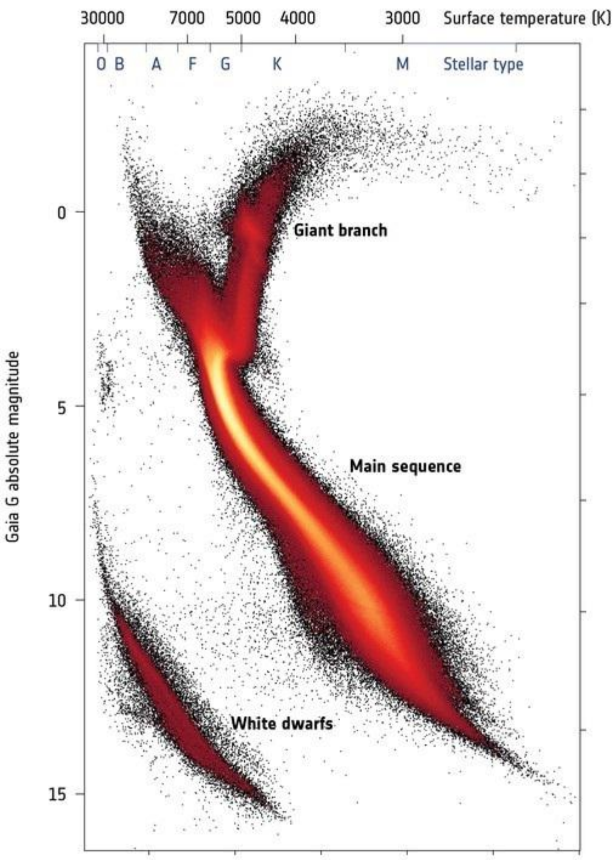
Now that you have the correct data - both stellar temperatures and absolute magnitudes - you can plot the HR diagram for exoplanet hosting stars. The HR diagram is effectively a scatter plot. To create a scatter plot of the data select 'Insert' from the top menu and the select 'Scatter' from the 'Charts' menu. Thus will create a blank white box.To fill this blank plot with your data click 'Select Data' (ensure the blank box is selected for this option to exist). A menu will appear allowing you to 'Add' data. Click this and enter "Exoplanet hosting stars" in the 'Series name' box.

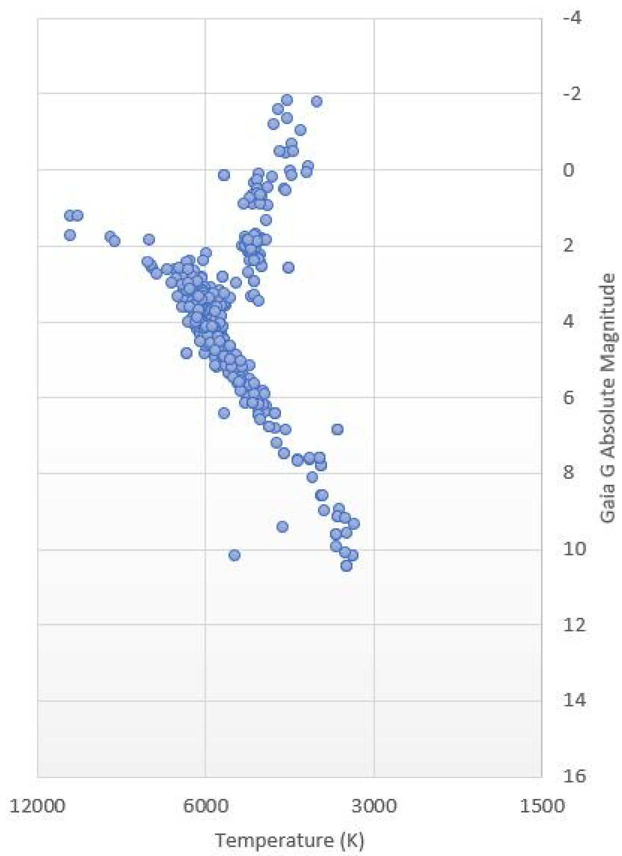
To plot the temperature on the x-axis and absolute magnitude on the y-axis, first click your mouse in the 'Series X values' box and then highlight all the exoplanet masses in your table (excluding the column header). Do the name for the 'Series Y values', this time highlighting all the exoplanet radii. Note - you may need to delete any text that automatically appears in these boxes before highlighting your data. You should now have a plot and you are most of the way there to creating your HR diagram! The final step is the format the graph layout so that it more closely resembles that of other HR diagrams.

Exoplanet hosts and the HR diagram

To reformat your plot's axes right click on each axis and select 'Format Axis'. For the y-axis, alter the range to run from -4 to 16 to better match ESA's offical HR diagram. Also change the 'Horizontal axis crossing' to 'Maximum axis value' and alter the axis so that it shows 'Values in reverse order' (remember that negative magnitudes correspond with more luminous stars). Next, format the x-axis and change the axis so that it has both a 'logarithmic scale' and shows its 'values in reverse order'. Change also the minimum and maximum bounds to 1500 and 12000, alter the 'Base' of the logarithm to '2' and reduce the 'Major units' to '2' as well. Your plot should now very closely resemble the HR diagram created by ESA using Gaia data! Add a title and axis labels to complete your plot.

The official Gaia HR diagram is shown side-by-side with the exoplanet hosting star one below. Note - axes are scaled similarly but not identically. How do these diagrams compare with one another? What similarities and differences exist between the two and how might these be explained?





Discussion - Exoplanet HR diagram

How do these diagrams compare with one another?

There is broad agreement between the HR diagram you have just created for exoplanet hosting stars and the HR diagram created by ESA. Though several features do seem to be missing, the main sequence branch and the giant branch of the HR diagram for exoplanet hosting stars are both clearly present, indicating that exoplanets are found orbiting a range of these stars.

What similarities and differences exist between the two and how might these be explained?

The white dwarf branch of the HR diagram is not present in the plot on the right. There are a number of factors contributing to this absence. First, and most importantly, is the absence of any data points dimmer than approximately 10mag. This lower magnitude floor is largely dictated by telescope limitations - it is much harder to make the many good quality measurements necessary to detect exoplanets around faint stars. However, even with improved observations, few exoplanets would likely be observed orbiting white dwarf stars. This is because planets may not survive the disruptive process of a star becoming a white dwarf.

Having no white dwarfs, the exoplanet HR diagram is composed of only main sequence and giant stars. We observe a larger number of main sequence stars than giants in both the full Gaia HR diagram and the exoplanet one. This inequality stems from the fact that scientists estimate around 90% of all stars in our galaxy lie on the main sequence branch.

It is interesting that a similar population distribution also exists in the exoplanet HR diagram, indicating that main sequence and giant stars seem to be equally likely to host planets. The planets that orbit these giant stars likely formed while these giants were still main sequence stars, meaning they have managed to survive the rather dramatic change a star experiences when it enters the red giant phase.

The exact proportion of exoplanets orbiting main sequence and giant stars cannot simply be read off the HR diagram though, as other factors must be considered. These factors include giants having a greater luminosity than main sequence stars - this makes giants easier to detect. Giants are also larger than main sequence stars and so transits are more likely than around main sequence stars. Countering this is the fact that exoplanets will block out less of a giant star's surface area, causing a smaller percentage dip in the star's light. These and many other factors affect the proportion of each star type we detect, but the important point to take away is that exoplanets can and do exist orbiting a huge variety of stars.

Querying Gaia - Introduction

You may not have realised it, but you have already been 'querying databases' at various points throughout this guide. This may sound a bit complicated, but all this means is asking a database that contains some information to provide some of this for you. This is often simply done by clicking buttons e.g. you asked the Kepler database for light curves of different stars by typing the target name in the designated box and hitting enter. Likewise, you queried the NASA Exoplanet Archive for a list of stars that have both a measured magnitude and effective temperature to create a HR diagram.

Clicking buttons is the user-friendly way to query databases. Behind the curtains though, these button clicks are translated into computer code which the database is able to understand. Sometimes you may want to skip the button clicking stage and write the code directly yourself - this is particularly useful if you wish to make a very specific query that may not be 'allowed' using the user interface, but is possible when bypassing this stage.

Gaia provides a vast database holding information on over a billion astronomical objects. Learning how to write short queries could help you to better take advantage of this huge amount of data. This can help in searching for exoplanets, as well as other astrophysics research. BBC Bitesize, https://www.bbc.com/education/guides/z37tb9q/revision/1, offers an introduction to queries, databases and SQL (Structured Query Language) - a popular query language used with many databases.

Computer code and the associated terminology can seem daunting if you haven't come across it before. However, with some short tutorials, you will soon be able to write basic bits of code yourself!

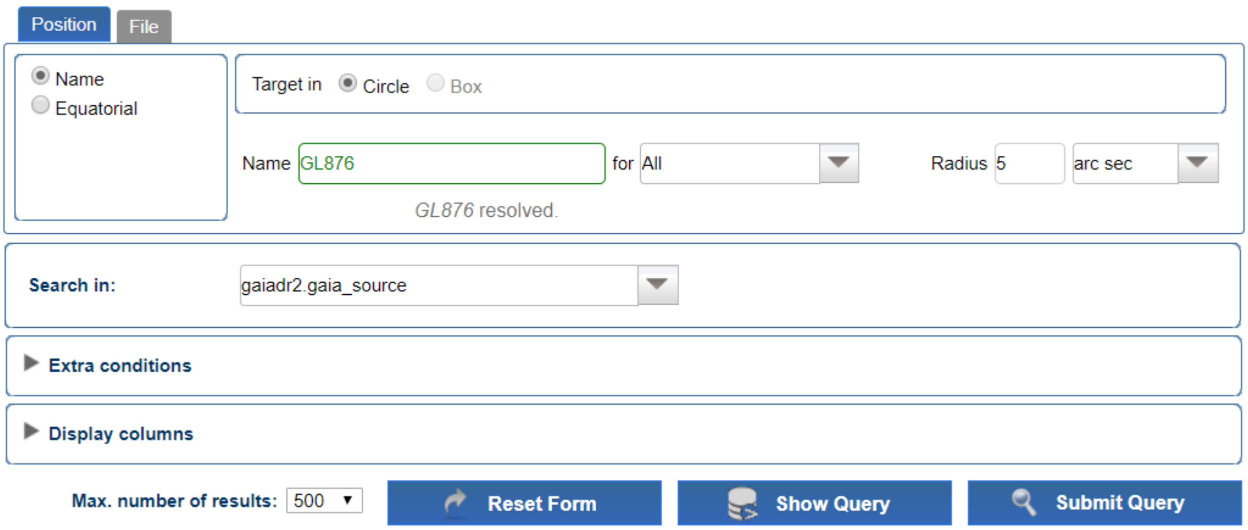
Querying Gaia - Basic queries

SQL is perhaps the most widely used and therefore useful query language to know how to write. However, in order to query Gaia databases you need to use a slight variant of SQL called ADQL (Astronomy Data Query Language). Gaia provides an online guide on how to use ADQL here https://www.gaia.ac.uk/data/gaia-data-release-1/adql-cookbook.

First though, you may want to try making basic queries using the user interface, just as you have before. http://gea.esac.esa.int/archive/ is the home page of the Gaia Archive which holds all of the publicly accessible data collected by Gaia. Click 'Search' and you will be able to make basic queries using the interface provided. You can enter a specific target name (e.g. GL876), search a variety of databases (the default, Gaia DR2, is the most recent data release from Gaia) and add certain conditions to your search. Finally, you can pick and choose which columns of data you would like to display. Clicking 'Submit Query' will then return your results for you. Congrats - you've just queried the Gaia database!

Returning back to the 'Basic' tab at the top of the page you can now click 'Show Query'. This will take you to the 'Advanced (ADQL)' tab which will show you the code that was created through clicking the buttons earlier. Switch between the Basic and Advanced tabs to compare the two. Having a real example like this is often the best way of learning how to build queries yourself. Visit the Gaia 'Help' page http://gea.esac.esa.int/archive-help/index.html for additional guidance.

Basic Query



Advanced Query

```
SELECT TOP 500 source_id,ra,ra_error,dec,dec_error,parallax,parallax_error
FROM gaiadr2.gaia_source
WHERE
CONTAINS(POINT('ICRS',gaiadr2.gaia_source.ra,gaiadr2.gaia_source.dec),CIRCLE('ICRS',COORD1(EPOCH_PROP_POS(343.319723,-14.263699611,213.2800,959.8400,-675.3300,-1.5190,2
000,2015.5)),COORD2(EPOCH_PROP_POS(343.319723,-14.263699611,213.2800,959.8400,-675.3300,-1.5190,2000,2015.5)),0.001388888888888889))=1
```

Query Result

source_id	ra	ra_error	dec	dec_error	parallax	parallax_error
	deg	mas	deg	mas	mas	mas
2603090003484152064	343.32397371221697	0.06716570825798016	-14.26659581558406	0.052252137917698206	213.86686187906741	0.07583484267852367

Querying Gaia - DIY

The example query on the previous page shows a query searching for information about one specific star (GL876). The fourth line of the Advanced Query (CONTAINS...) picks out the specific portion of the sky that contains the star - these coordinates can often be quite long and is the main reason the Advanced Query looks so messy. The three lines before that are relatively simple though. The first line asks for the top 500 stars (limits the results to show a maximum of 500 stars) that have a source ID, RA and Dec coordinates etc. The second line states the database where you want to search for the information, and the third line includes any requirements/cuts that you wish to apply (no cuts have been applied in the above example).

This is just one example of a query that can be made. The previous example is very specific, searching for information about just one star. However, much broader queries can be made and one such example is given below. Further examples are provided in the ADQL guide described earlier.

Suppose you want to find the ten brightest stars that pass directly above London in the night sky. The short query shown to the right will return such a list.

```
SELECT TOP 10 source_id,ra,dec,phot_g_mean_mag,lum_val
FROM gaiadr2.gaia_source
WHERE dec BETWEEN 50 AND 52 AND phot_g_mean_mag IS NOT NULL
ORDER BY phot_g_mean_mag ASC
```

The first line asks for only the 'top 10' results to be listed, while the final line asks for them to be ordered from brightest to dimmest (remember, the smaller or more negative a star's magnitude is, the brighter it is). The rest of the top line asks the query result to list the source IDs, their RA and Dec coordinates, and the apparent magnitude and luminosity of the stars. The second line of the query asks for this information to be taken from Gaia's DR2 database and the third line limits the search to Dec coordinates between 50° and 52° (as London sits at 51°). The third line also requires that all the stars have a known magnitude. The result of this query is shown below. Note - some of these stars do not have measured luminosities (perhaps because they are too bright for Gaia's detectors or the distances to these stars are not known). If you require the luminosity to be known too then you can specify this in your query.

If you wanted to know the more common name of the first object in the list using Simbad you would enter 'Gaia DR2 1018776176871826048' as the object name and find the star's more commonly used name as 'tet UMa' which is an abbreviation for Theta Ursae Majoris.

source_id	ra deg	dec deg	phot_g_mean_mag mag	lum_val solLum
1018776176871826048	143.20775047522528	51.67498131593744	2.9734643	
2136270970157966464	292.42663757339056	51.73032873225254	3.6592455	34.470543
1988193348339562880	337.8238475644936	50.282567015441394	3.680603	
1604859511344338816	216.2975092984241	51.84902282007886	3.8195388	4.4913144
405987526028673536	25.915325875270103	50.68867108824562	3.984561	
451517958938598784	36.40609289769835	50.27866459746976	4.0474215	558.0687
247637579387146368	61.6459212038643	50.351105145776614	4.1879816	
1985791121590368640	346.04687332855127	50.052812590889395	4.269454	54.29981
2135110401277424384	294.1105150830124	50.2222367127253	4.3387284	4.560856
1016370651588789632	137.21678680549653	51.60450498804848	4.360804	9.747106

Discussion - Querying Gaia HR diagram

Earlier it was mentioned that Gaia offers no 'easy' way to plot your own HR diagram. This is true, however it is possible to plot one. The paper https://arxiv.org/pdf/1804.09378.pdf provides information regarding how Gaia's official HR diagram was created. The authors include a query in the Appendix that is used to generate a reasonably clear HR diagram. This query is shown below (though it has been modified slightly).

```
1 SELECT TOP 50000 phot_g_mean_mag+5*log10(parallax)-10 AS mg, bp_rp FROM gaiadr2.gaia_source
2 WHERE parallax_over_error > 10
3 AND phot_g_mean_flux_over_error>50
4 AND phot_rp_mean_flux_over_error>20
5 AND phot_bp_mean_flux_over_error>20
6 AND visibility_periods_used>8
7 AND phot_bp_rp_excess_factor < 1.3+0.06*power(phot_bp_mean_mag-phot_rp_mean_mag,2)
8 AND phot_bp_rp_excess_factor > 1.0+0.015*power(phot_bp_mean_mag-phot_rp_mean_mag,2)
9 AND astrometric_chi2_al/(astrometric_n_good_obs_al-5)<1.44*greatest(1,exp(-0.4*(phot_g_mean_mag-19.5)))
```

You can input this query into the Advanced Query box in the Gaia Archive. However, it is useful to better understand what exactly you are asking the archive for! Each line of the query is discussed further below:

Line 1: 'SELECT TOP 50000' asks the database to return the top 50000 results for the query you are asking. Note, the example given in the paper asks for only the top 5 results, but if you want to plot a reasonable looking HR diagram you will require more data points! Remember though that asking for more results will cause the query to take longer to run.

'Phot_g_mean_mag' is the apparent magnitude of the star at a certain wavelength (called the 'g-band'). This isn't the absolute magnitude that is plotted on the y-axis of the HR diagram. To convert between apparent and absolute magnitude the following formula can be used. See the previous discussion box for more information on the difference between absolute and apparent magnitude.

$$M = m + 5\log_{10}(p) - 10$$

Where 'M' is the absolute magnitude, 'm' is the apparent magnitude and 'p' is the parallax of the star given in micro-arcseconds. This formula is recreated in the ADQL query above, where the result (the absolute magnitude) is ASsigned the label 'mg'.

The penultimate part of line 1 also asks for the colour of the stars which can be used instead of the stellar temperature on the x-axis of the HR diagram. The colour index, BP-RP, has values ranging from around -2, indicating a very hot blue star, up to around 6, characteristic of cooler red objects. The final part of line 1 asks for this information to retrieved from the latest Gaia database 'gaiadr2.gaia_source'.

Discussion - Querying Gaia HR diagram

Line 2: This line 'cuts' the data, asking the database for only high quality data where the ratio of the parallax value over its error is greater than ten. In other words, the error on the measured parallax must be less than 10%. It is important that the parallax is known accurately as it used to calculate the absolute magnitude used in the HR diagram. The remaining lines of the query provide additional cuts to the data. These other lines could all be included on this one line, but have been spread over multiple lines to make them easier for humans to read.

Lines 3, 4 and 5: These lines limit the results to include only relatively stable stars with small errors in their measured flux. This criteria may help to remove variable stars in addition to improving the overall precision of the data include in the HR diagram. Line 3 should help to ensure only stars with well known absolute magnitudes are included, while lines 4 and 5 place constraints on the precision of the colour measurements.

Line 6: This provides a requirement that each star included must have been observed on 9 or more separate occasions. The variable 'visibility_periods_used' is defined so that these observation times must also be separated by at least 4 days to ensure even sampling. This requirement should help to remove strong outliers.

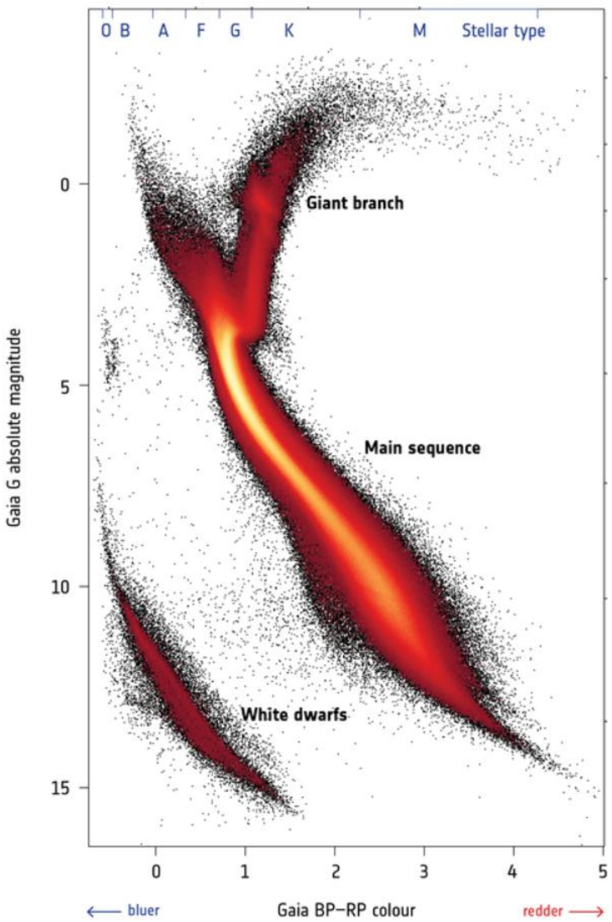
Lines 7, 8 and 9: These cuts are more complex and will not be explained further in this guide. They do offer improved accuracy though. You may try eliminating these cuts yourself and plotting the data that is returned by the shortened query. You should notice an excess of stars at dimmer magnitudes when these cuts are removed.

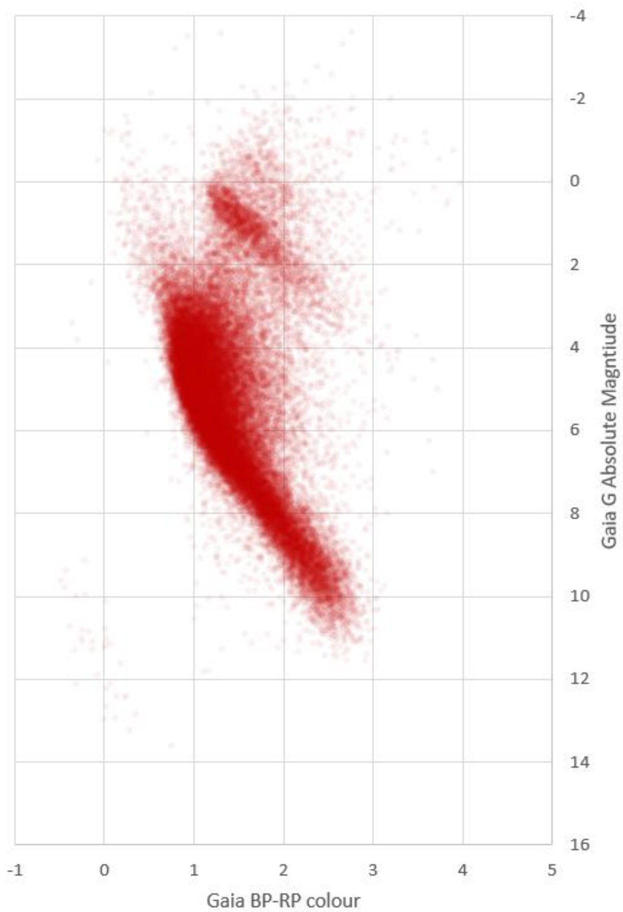
Submitting the full query shown on the previous page will generate two columns of data, 'mg' and 'bp_rp', which are the absolute magnitude and colour for the first 50000 stars stored in the Gaia DR2 database that meet the selection criteria. The Gaia archive offers no way of plotting this data so it must be downloaded and plotted using another plotting tool, in the same way as the exoplanet HR diagram was created earlier. The Gaia data is simple to download using the option at the bottom of the 'Query Results' page. Download this data in CSV format and open it in Excel or another plotting tool. Note - you may ask for fewer results (less than 50000) if your query is taking too long to run.

Discussion - Querying Gaia HR diagram

Follow similar instructions as those used to create the exoplanet HR diagram earlier. You should obtain a plot that looks like the one below. Tips:

- Plot only the first few data points initially and change the formatting to your liking before adding in the rest of your data. This will speed up the 'thinking time' for Excel and reduce the likelihood that it will crash.
- Ensure you select the correct columns of data for the x and y axes. Set the maximum and minimum values manually so that they provide a close comparison to the official Gaia HR diagram.
- Alter the transparency of the markers. The transparency of the markers in the plot to the right are set at 95%. This allows you to obtain some gradient effect, though it does make it very hard to see the white dwarf stars to the bottom left of the plot. The transparency and colour of the markers can be altered by double clicking on them and then selecting the 'paint tin' option to the right of the screen.





Discussion - Querying Gaia HR diagram

What similarities exist between the two diagram?

The main sequence branch dominates both diagrams. This is to be expected as both diagrams should be representative of the wider stellar population within the Milky Way. The greatest concentration of main sequence stars coincides too, peaking around a BP-RP colour of 1 and an absolute magnitude of 5.

The giant branch is also present in our HR diagram. The elongated vertical shape is less obvious, but the higher concentration of giants with magnitudes around 1mag is clearly visible.

The white dwarf branch is extremely faint due to setting the marker transparency at 95%, but it is present in our HR diagram. It is most easily seen when looking at the diagram at an angle on a computer screen.

What differences exist between the two diagram?

The dimmest main sequence stars and white dwarfs are not visible in our diagram. This is unsurprising as we are using a smaller dataset (around 1% of the size of that used in the official Gaia HR diagram).

The shape of the main sequence branch and the more subtle features of the giant branch also differ in our HR diagram. Improvements in the match between figures requires a more time consuming selection of more stars along with careful scaling of the transparency.

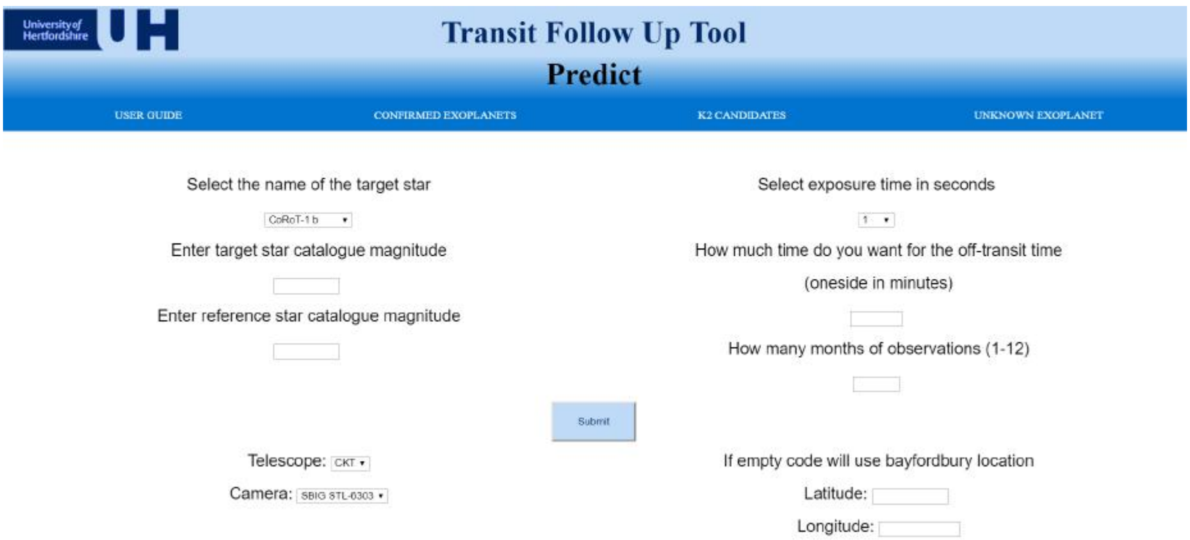
Out of the 50,000 stars included in our HR diagram, visual examination shows that only around 30 of these lie on the white dwarf branch (around 0.06% of the total sample size). This contrasts to the 35,000 white dwarfs present in Gaia's HR diagram, which comprise approximately 1% of the 4 million star sample size. This disparity could be due to simple statistics - by chance, fewer white dwarfs than average were observed in the top 50,000 results we returned. Alternatively, the 'SELECT TOP' command may penalise fainter stars.

Observe a Transit tonight!

With impressive prediction tools available online, it might look relatively easy to plan and predict when it is best to observe exoplanet transits yourself. Actually observing these transits is extremely tough though, and could take months of effort with no guaranteed success at the end of it! This is not to say you shouldn't try to observe them as you will learn so much in the process, but it is important that your expectations remain realistic from the start.

Listed below are some useful prediction tools available online:

- http://var2.astro.cz/ETD/index.php This link will take you to the Exoplanet Transit Database, where you are able to click on the 'Transit predictions' link near the top of the page. Here, you will be able to enter your longitude and latitude (find these here: https://www.gps-coordinates.net/) and select which date you would like to make your observations. Applying these criteria will return a list of exoplanets that will technically be visible from your location, but how realistic is it that you will actually be able to witness these?
- http://observatory.herts.ac.uk/exotransitpredict/ The Transit Follow-up Tool, allows more scope to provide a realistic list of targets that could be visible and enables adjustment for observing capabilities. The 'Predict' page under 'Confirmed Exoplanets' will show you a list of planets that has been narrowed down to include only those that block out at least 0.5% of the star's light. The list is also constrained to include only stars above a minimum brightness. Both these requirements should limit the list to include only targets that will have relatively clear signals.



Transit Follow-up Tool - Predicting

A summary of the basic steps involved in using the website is provided below. First, select the name of the exoplanet you wish to observe - this may be one from the Exoplanet Transit Database, or an interesting target that you examined with the Kepler and Agatha websites earlier. Remember to look at the Simbad website for alternative names for these stars and planets. For this example, we will look at WASP-2 b.

Next, open Simbad and search for your chosen star (not planet). Copy and paste the the 'V-band magnitude' (the number found next to 'Flux V') into the 'Target Star Catalogue Magnitude' box. For WASP-2, this value is 11.98.

Now copy the star's right ascension (RA) and declination (dec) coordinates which define the star's position in the sky. These coordinates are the two numbers in bold on the 'ICRS coord' line. Click the 'Coordinate Query' tab at the top of the page and paste these two numbers into the 'Coordinates' search box, 'define a radius' of 9 arc minutes and click 'Submit Query'.

You will see, listed below, the stars that lie within 9 arc minutes of WASP-2. We require one of these stars to be our 'baseline' against which we measure the variation in brightness of WASP-2. It is useful to choose a reference star that has a similar brightness (Mag V) to ours, and which is located close to it as well (small 'dist'). The star TYC 522-1676-1 satisfies these criteria. Copy it's Mag V value of 11.95 into the 'Reference star Catalogue Magnitude' box.

Leave the 'exposure time' set to 1 second for the time being, change the 'off-transit time' to 30 minutes and the 'observation time' to 12 months. Your entries for the final two steps - the 'telescope/camera' and the 'longitude and latitude' of the telescope - will vary depending on what equipment you have available and where you are observing from.

Transit Follow-up Tool - Observing

It is hard, but not impossible to make exoplanet observations yourself. If you or your school possess a telescope and camera then you can enter their specifications in the Transit Follow-up Tool. This will tell you whether it is physically possible to make an observation with the tools you have at your disposal.

If you do have the capabilities to observe exoplanets yourself then do look further into the possibility of actually doing so. Start first with making observations of planets in our Solar System - if you can obtain some good images of Saturn and Jupiter and their moons then you can have the confidence to try to detect the faint signal of a transiting exoplanet. After observing Solar System planets, try to observe specific stars in the night sky and then try to identify binary star systems. Transiting binary stars are the perfect training ground to hone your transit detecting skills. These binaries will have a similar signal shape to that of a transiting exoplanet, but the size of the signal will be much larger. Finally, attempt to detect the transit signature of some of the brightest exoplanets visible to you.

If you do not have access to the right equipment, there are alternatives available. Depending on where you live, there may be an astronomy society that meets nearby - check out the following website to see if that's the case http://fedastro.org.uk/fas/members/google-map/. You may find that members of such groups would be willing to assist you in making observations, providing guidance and use of their equipment, though this should not be assumed to be the case.

Alternatively, the possibility does exist to use professional telescopes remotely. The Faulkes Telescope Project (http://www.faulkes-telescope.com/GettingStarted/) offers this chance, where upon registering with the site you will be able to book an observing slot. The National Schools' Observatory (https://www.schoolsobservatory.org/) and the Las Cumbres Observatory (https://lco.global/) also have similar offerings. Use the Transit Follow-up Tool to determine what exoplanets it is possible to view and when the best time to observe them would be. You may only end up with an image of the host star at the time of transit, but that is still an impressive thing to do.

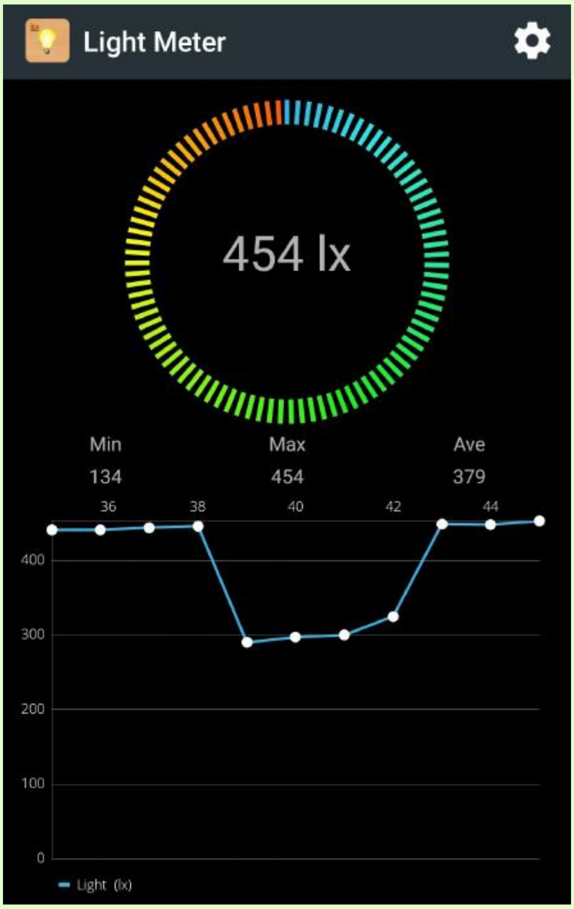
Regardless of which approach is taken, do bare in mind that results are never guaranteed. If, even after months of trying, you find yourself with no evidence of a transit, this is still significant as you will have picked up a host of new skills in the process. Remember, professional astronomers have only recently been able to make these measurements themselves!

Discussion - Measuring transit signatures using your phone

Making exoplanet transit measurements can seem daunting, especially when needing to use unfamiliar equipment. However, similar measurements can be made at home or in a classroom using a simple light bulb and a phone application. Note - this activity this activity is designed for a mobile phone with a camera.

'Light meter' or 'Lux meter' apps ('lux' is a unit of intensity) can be found within mobile app stores and basic versions of these are often free to download. These light meters use sensors in your phone to measure the intensity of light that is falling on it. A high recorded 'lux' value indicates a large light intensity, while a small recorded value indicates a low light intensity. Download one of these apps and cover different areas of phone to discover where the light sensor is located.

Next, create your 'star' i.e. your light source. This light source could simply be a light bulb, or, to create a larger 'star', you could cut a large circular hole in a piece of card and block all daylight entering your windows expect for through this hole. Fix the positions of your light source and phone sensor and then pass different sized objects in front of your light source. You should record a fall in intensity when less of the light source is visible to your phone, just like a planet orbiting a star. You can experiment with different distances between the light source and sensor, as well as using different sized 'planets'. You may even wish to create a set-up where the transits are automated i.e. you have a planet attached to a string and a motor which causes the 'planet' to orbit your 'star' periodically. Further resources detailing how to perform similar experiments can be found on the Institute of Physics website http://www.iop.org/exoplanets.



Exoplanet Properties

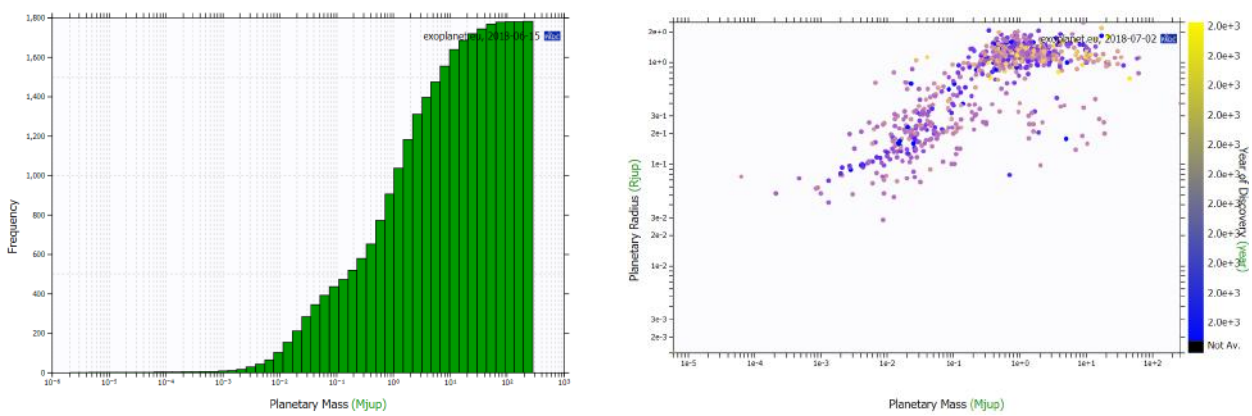
You have now explored, quite comprehensively, some of the main methods used in detecting exoplanets. You may have been thinking that these methods of detection aren't very 'fair', and you'd be right. Transits only detect exoplanets with a very narrow range of orbital inclinations. Radial velocity measurements face a similar problem, as we only detect the star's movement in the direction along our line of sight. It is impossible to detect planets with orbits perpendicular to our line of sight using this method and it is very hard to detect planets with orbits that are close to perpendicular.

The orbital inclination isn't the only bias in our measurements, we preferentially detect large planets using the transit method as they block out more of the star's light. Similarly, it is easier to detect very massive planets using the radial velocity method as these massive planets cause the star to move faster around their common centre of mass.

It is possible to create plots of such data to easily visualise the statistics involved in detecting exoplanets. The following websites allow the creation of both scatter plots and histograms containing information on all confirmed exoplanets:

- http://exoplanet.eu/diagrams/
- http://exoplanets.org/plots
- https://exoplanetarchive.ipac.caltech.edu/cgi-bin/IcePlotter/nph-icePlotInit?mode=demo&set=confirmed

Try creating a variety of both scatter plots and histograms. Do you see any correlations or interesting results? Do you think the sample of confirmed exoplanets should be representative of all exoplanets in our galaxy and universe? Why?



Cumulative exoplanet mass histogram (left) and exoplanet mass vs radius scatter plot (right). The right plot includes a colorscale, showing the earliest discovered exoplanets in yellow and the latest discoveries in blue.

Exoplanet Properties - Advanced

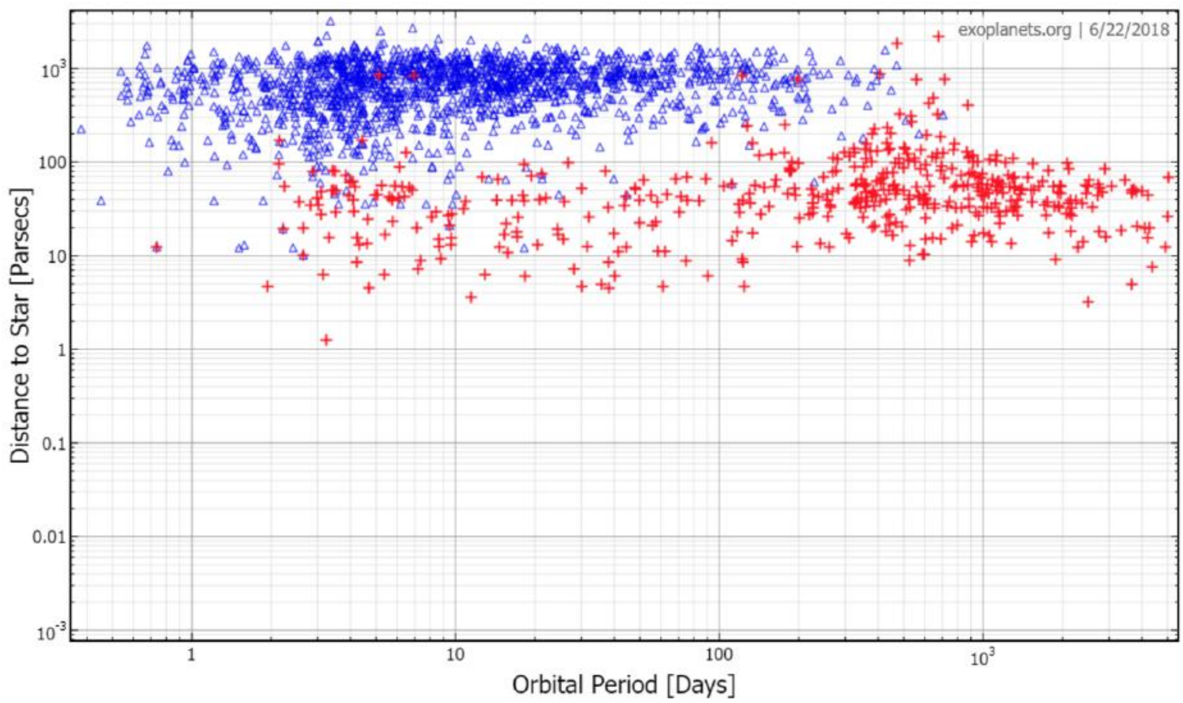
Exoplanets.org has an 'advanced' option when plotting graphs. Useful tutorials explaining how to use all these features can be found here http://exoplanets.org/help/plot/scatter_plots, but an example is also run through below.

Open Exoplanets.org, select the plotting tool and then switch from 'simple' to 'advanced' plotting within the scatter plot option. Select the variables 'Orbital Period (PER)' and 'Distance to star (DIST)' as your 'x' and 'y' variables. Tick both 'log' boxes to rescale the axes so that the data is more clearly visible.

The data shown is already interesting as it shows how far away most of the exoplanets we have discovered lie, as well as their periods. The very observant may notice that there appears to be two 'groups' to the data - one in the top left of the plot and one in the bottom right. These groups correspond to distant, short period planets and nearer, longer period planets accordingly. We can apply filters to this data to try to unravel the origin of these two groups.

Using the tutorials given in the link above, apply two filters. First, select only planets with known transits - this should be the first filter option in the drop down list. For your second filter, select only planets discovered using the radial velocity method. Choose distinct colours and shapes to represent these two subsets of the data.

You should see that there is a very clear divide between the types of planets discovered using the transit method as opposed to the radial velocity method. These groups match with the split in the original data and is a result of the inherent biases in each detection method.



Blue markers show exoplanets with known transits, while red markers show those discovered using the RV method.

Discussion - Detection biases

The plot on the previous page shows that, in general, transit measurements have led to the detection of short orbital period exoplanets, while radial velocity measurements have allowed the discovery the longer period planets. Planets discovered using transit methods also tend to lie 10 times further away from the Earth than those detected through radial velocity observations. So, why do these disparities exist?

The main cause of the observed split in the data is due to the observational constraints of each method and the experimental design limitations that come with these. Firstly, radial velocity observations require a high signal-to-noise ratio. As the noise of radial velocity measurements increases with observational distance while the signal size remains the same, the most precise observations are made of stars that are close to us (within a couple of hundred light years from the Earth). This explains why most of the red dots are found below 100 parsecs (approximately 300 light years) in the previous plot.

Transit observations on the other hand can probe stars out to further distances as they are less affected by increasing noise. The Kepler mission was designed to search for stars within the Orion spiral arm of our Milky Way Galaxy. Our Sun is located towards the inner rim of this spiral arm, but the arm itself is a few thousand light years wide! This means the mission was able to search for planets located over a wide range of distances. The abundance of planets found at large distances is simply due to maths - the volume, V, of a sphere of radius r is given by $V = \frac{4}{3}\pi r^3$. This means that a sphere of radius 3,000 light years has a volume 1,000 times larger than a sphere of radius 300 light years, despite it's radius only being 10 times larger! Therefore, if stars were evenly distributed throughout these two volumes, you would expect to observe 1,000 times more stars in the larger sphere compared to the smaller sphere!

The Kepler mission does have various limitations though, one of which is its rather small field of view. This has been somewhat overcome in the K2 mission where it has moved location every few months though in K2 mode the periods of observation for most targets are less than 90 days. Thus Kepler-K2 excels at detecting short period exoplanets where multiple transits are recorded during each observation window. Radial velocity measurements have the scope to look anywhere in the sky and detect longer period orbits though observations taken over many years.

Using both transit and radial velocity measurements, scientists are able to gather data about a large range of exoplanets. However, both transit and radial velocity measurements share the same bias towards detecting large, massive planets. Other methods, such as astrometry, are required to fill in the gaps in our understanding of the wider exoplanet population in the Milky Way.

Exoplanet Properties and our Solar System

Having seen the variety of planets we detect orbiting other stars, it is interesting to compare these to our own Solar System. This comparison allows us to see how 'average' we are in the wider context of the universe.

Although it is very convenient to plot exoplanet properties using the websites stated earlier, they do not contain information about planets in our Solar System. Therefore, in order to create a plot containing both sets of data, we have to use a separate plotting tool. The example below uses Excel.

Open the Exoplanet.eu catalog page. Download this data in CSV format using the button at the top of the page and open the downloaded data using Excel. You can delete or ignore any columns of data that aren't of interest to you at this time e.g. if you are only plotting planetary masses and radii, like in this example, then you could keep only these columns. Next, copy the column headings and start a new table to the right of your existing one (leave a one column gap to easily distinguish the two tables). Below these new headings fill in the corresponding information for the planets in our Solar System - this will require you to search the internet for the relevant values. Remember to keep the units the same for both tables as you will be plotting both sets of data on the same axes! You should end up with a spreadsheet that looks like the one below.

	A	B	C	D	E	F	G
1	# name	mass (mjupiter)	radius (rjupiter)		# name	mass (mjupiter)	radius (rjupiter)
2	11 Com b	19.4			Mercury	0.000174	0.0342
3	11 Oph b	21			Venus	0.00256	0.0847
4	11 UMi b	10.5			Earth	0.00315	0.0892
5	14 And b	5.33			Mars	0.000337	0.0475
6	14 Her b	4.64			Jupiter	1	1
7	16 Cyg B b	1.68			Saturn	0.3	0.843
8	18 Del b	10.3			Uranus	0.0456	0.358
9	1RXS 1609 b	14	1.7		Neptune	0.0538	0.346
10	1SWASP J1407 b	20					
11	24 Boo b	0.91					
12	24 Sex b	1.99					
13	24 Sex c	0.86					
14	2M 0103-55 (AB) b	13					
15	2M 0122-24 b	20	1				
16	2M 0219-39 b	13.9	1.44				

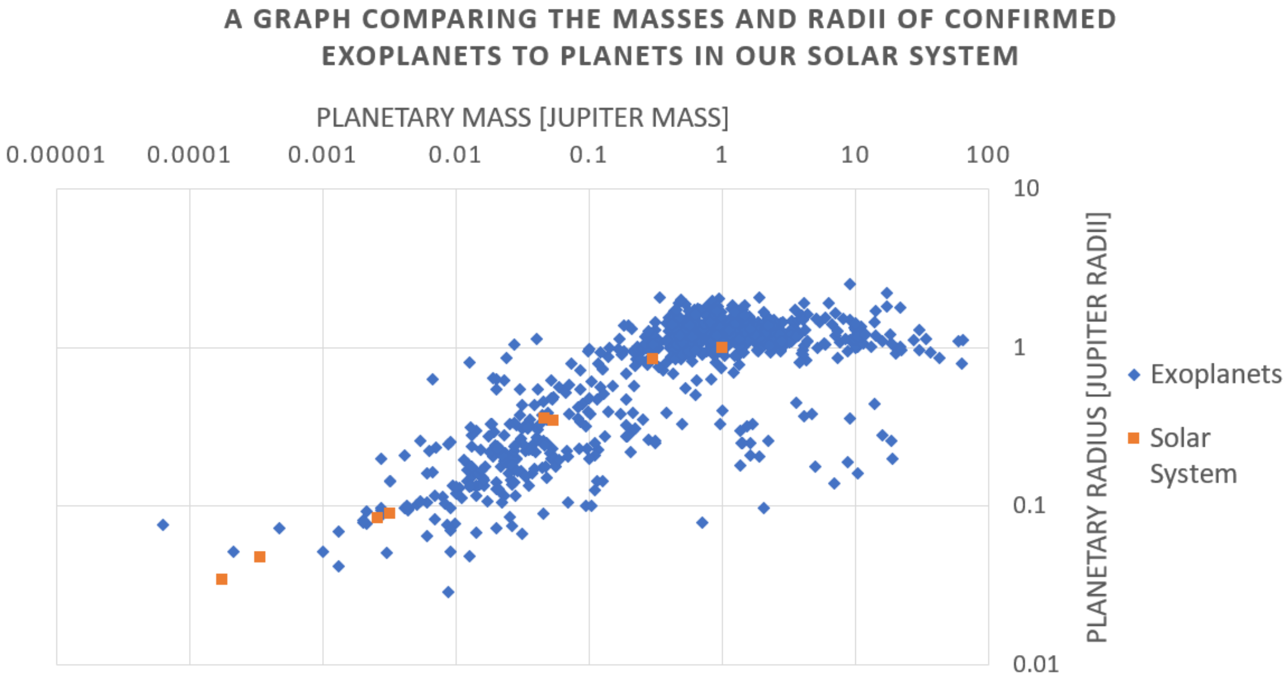
Exoplanet Properties and our Solar System

To create a scatter plot of the data select 'Insert' from the top menu and then select 'Scatter' from the 'Charts' menu. This will create a blank white box. To fill this blank plot with your data click 'Select Data' (ensure the blank box is selected for this option to exist). A menu will appear allowing you to 'Add' data. Click this and enter "Exoplanets" in the 'Series name' box.

To plot mass on the x-axis and radius on the y-axis, first click your mouse in the 'Series X values' box and then highlight all the exoplanet masses in your table (excluding the column header). Do the same for the 'Series Y values', this time highlighting all the exoplanet radii. Note - you may need to delete any text that automatically appears in these boxes before highlighting your data.

You should now have a plot of all exoplanets where both the mass and radius is known. Follow the same steps as above to now add the Solar System data to your plot, this time changing the 'Series name' to "Solar System" and highlighting the relevant columns. This data will automatically be plotted in a different colour to make the two datasets distinguishable.

It is useful to restyle the plot so that the data is more clearly visible. Right click on each axis and select 'Format Axis'. Select 'Logarithmic scale' and change the 'Vertical/Horizontal axis crosses' options to 'Maximum axis value'. The axes numbering may also be changed from 'General' to 'Scientific'. Selecting the 'paintbrush' option to the right of the graph will allow you change the 'Chart Style' and colour, allowing you to create greater contrast between the two datasets. Finally, it is important to add axis titles, a chart title and a legend so that others may easily understand your graph - these can be added with the 'plus' sign that is also located to the right of the plot. Compare this plot to the mass-radius plot created with Exoplanet.eu earlier.



Discussion - Exoplanet Properties and our Solar System

What do you notice about the orange and blue data points? What similarities and differences exist between the two?

The exoplanets we have discovered tend to follow a similar mass-radius relationship as those in our Solar System. However, far more exoplanets have been discovered that are Jupiter size than Earth size. This is evident from the concentration of blue data points at large masses and radii. It should also be noted that some of the stated exoplanet masses are in fact their minimum possible masses, and so some blue data points will be shifted slightly 'right' (after division by sin(i)) in the plot when their true masses are determined. Note - 'i' is the angle of inclination of the exoplanet orbit to our line of sight. An angle of i=90° corresponds to an 'edge on' orbit i.e. the planet passes perfectly in front of the star. Conversely, i=0° corresponds to a 'face on' orbit i.e. if the planet were orbiting around the edge of a CD we would observe the full circular face of the CD (with the star in the centre).

What could cause the disparity between the distribution of masses and radii of exoplanets and planets in our Solar System?

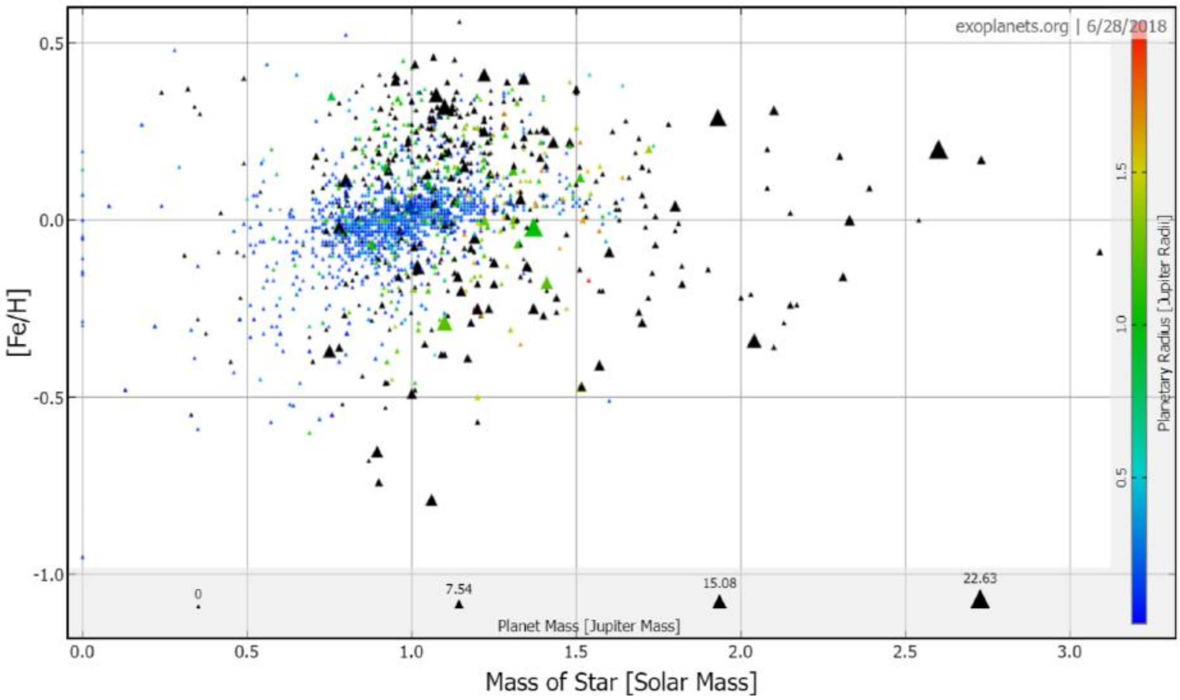
Larger planets may be more prevalent in the above plot due to an abundance of more massive exoplanets in our galaxy compared to small planets. In reality though the large excess is caused by biases in our observations - it is far easier to detect large exoplanets using both transit and radial velocity methods.

Exoplanet Properties and our Solar System

The final comparison we can make between our Solar System and exoplanet systems is to compare the host stars of these other worlds to our own Sun. Do these other stars tend to be larger, younger or brighter than the Sun? All these comparisons are relatively simple to make using the cumulative histogram plotting tool on Exoplanet.eu e.g. plotting a cumulative 'Mass of Host Star' histogram shows, at the time of writing, that approximately 2,300 stars have masses below the mass of our Sun, while approximately 1,300 have masses greater than one solar mass. What do you think is the cause of this?

Complex looking plots can be created using Exoplanets.org which incorporate up to four different variables. To create a scatter plot like the one below, plot an 'Advanced' scatter plot with stellar mass on the x-axis and stellar metallicity on the y-axis. 'Metallicity' provides a measure of how much iron (a heavy element) is present in a star compared to hydrogen (a light element). The Sun would be located on this graph at the coordinate (1.0, 0.0). A 'Colorscale' and 'Marker Scale' can also be added corresponding to the size and mass of the planets found orbiting these stars. This graph provides a huge amount of information. There appears to be a slight excess of data points below one solar mass, as expected after plotting the cumulative mass histogram earlier. Meanwhile, the fraction of stars with metallicities higher and lower than our Sun appears to be relatively even.

What is particularly interesting though is that despite the majority of exoplanets being found orbiting small stars, most large planets are found orbiting massive stars. This isn't solely down to observation bias as if that were case we would expect to detect less small planets around high mass stars, but we would still expect to detect large planets orbiting small stars. Instead, it appears that large planets are most easily formed orbiting high mass stars. Why do you think this is the case?



Discussion - Exoplanet Properties and our Solar System 2

Why are more planets found orbiting low mass stars as opposed to high mass stars?

This discrepancy, or some of it, may result from the fact that there are simply more small stars being looked at, or that small mass stars are more likely to host planets than large mass stars. Alternatively, this majority may exist due to observational biases - planets of a given mass will give a relatively larger radial velocity signal around low mass stars and so be easier to detect. Also, since the smaller stellar mass likely corresponds to a smaller radius then these stars will provide greater transit signatures too, as a given planet would be able to block out a greater proportion of its surface area.

Why do some stars have more heavy elements in them?

Heavy elements can only form when stars explode in supernovae. This is because these elements are created through fusion - when light elements join together to form one heavier element. Huge amounts of energy are needed for this process to happen and these conditions only occur during supernovae. This means that stars that were formed during the early universe, before many stars had exploded, formed in a metal-poor universe. Conversely, stars that formed later, after stars had died and spread heavy elements throughout the universe, were able to incorporate some of these heavy elements in their formation.

Why are large planets predominantly found orbiting high mass stars?

Stars are formed when huge clouds of gas and dust in the interstellar medium collapse in on themselves due to gravity. This gas and dust heats up as the cloud collapses, eventually allowing fusion to occur and the star to be born. The size of the initial cloud of gas dictates how large the star can be that forms from it - a small cloud allows the creation of only a small star. The formation of the star will use up the majority of the gas present (the Sun holds 99.8% of the entire Solar System's mass!), however there will likely be some gas left over from which planets can form. A larger cloud of gas means there will likely be more left over after the star is born which can then be used to build planets. Note - this is a working hypothesis and is being modelled in great detail e.g. https://planetplanet.net/2018/05/30/the-mojo-videos/

Exoplanet Atmospheres and Habitability

As far as we know, an atmosphere is required for life to survive on a planet. However, not any old atmosphere will do the job. For a planet to be habitable, its atmosphere must also have certain elements present in it and be sufficiently thick for life to exist as we know it.

In order to better understand exoplanet atmospheres it is first interesting to examine the atmospheres of planets within our own Solar System. Understandably, we have far more knowledge of the Earth's atmosphere than those of other planets. Our atmosphere is composed of approximately 78% Nitrogen and 21% Oxygen, with small amounts of Argon, Carbon Dioxide, water vapour and other gases also present. The majority ($\approx 75\%$) of the atmosphere lies within just 11km of the surface of the Earth. However, the thinner outer atmosphere continues out much further, with atmospheric effects felt by spacecraft re-entering the atmosphere stretching out to 120km above the Earth's surface.

The Earth's atmosphere is not representative of all rocky planet atmospheres though. Venus, our nearest neighbour, has an incredibly dense atmosphere composed mostly on Carbon Dioxide (96.5%), with traces of Nitrogen and Sulphuric Acid - not very human friendly! Due to it's incredible surface pressure, over 90 times that of the Earth, spacecraft visiting the planet have to be specially reinforced. They must also be capable of surviving the toasty 460°C surface temperature that results from a runaway greenhouse effect.

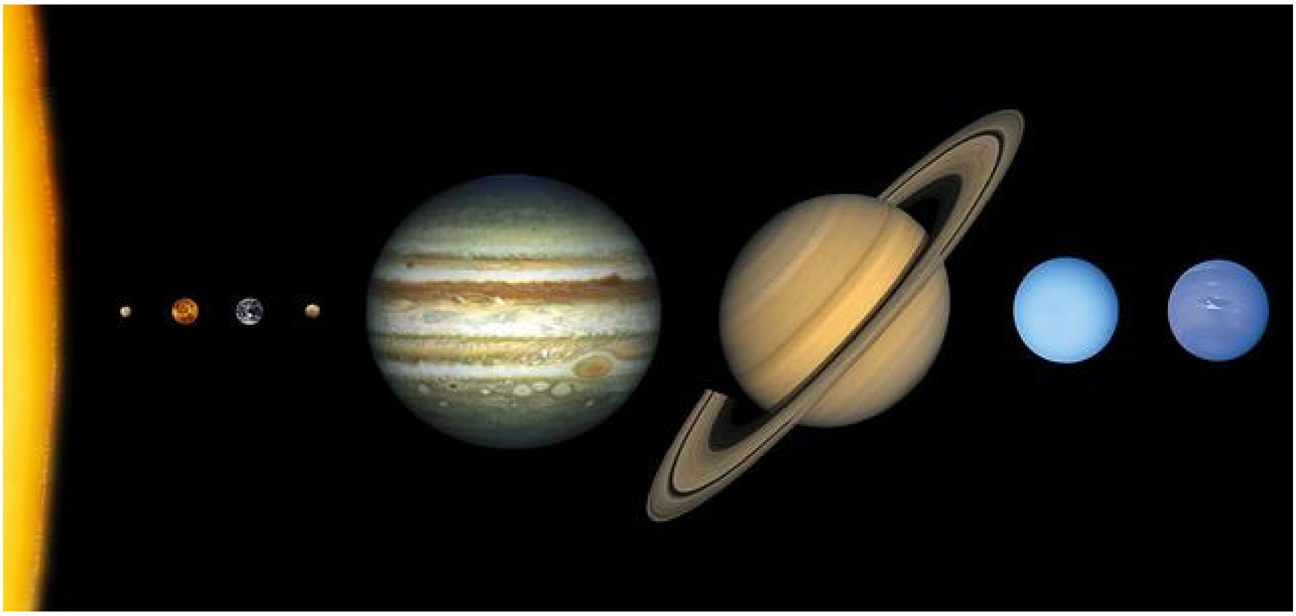
Mars has a similar atmospheric composition to Venus, but its atmosphere is far thinner, approximately 100 times thinner that the Earth's. This thinner atmosphere means Mars is susceptible to great daily and seasonal temperature swings, with temperatures ranging from a pleasant 20°C down to a chilly -125°C. Of course, atmospheres can change over time. If liquid water did ever exist on the surface of Mars then this would require a more substantial atmosphere capable of maintaining a warmer, more stable temperature. Strong stellar winds may have stripped away much of this atmosphere over the past few billion years.

The Solar System's innermost rocky world, Mercury, has the thinnest atmosphere of all planets in our Solar System. In fact, the small amount of gas that does surround Mercury is so thin that it is technically referred to as an exosphere, rather than an atmosphere. Mercury struggles to support an atmosphere due to its small size - the gas is less strongly gravitationally bound that the gas surrounding the Earth. The planet is also located extremely close to the Sun and so is constantly hit by strong stellar winds which strip Mercury of what little gas it would otherwise be able to hold on to. The size of exoplanets and their distance from their host stars must therefore both be carefully considered when searching for other worlds that may be able to support life.

Exoplanet Atmospheres and Habitability

Based on our one example - ourselves - we imagine that life would be most likely to exist on rocky planets like the Earth. However, perhaps alien life can exist in far more exotic locations than we could ever imagine, floating around in distant gas giants, far larger than Jupiter. It happens that it is actually easier for us to measure the atmospheres of gas giants using current technology, so it is interesting to examine Jupiter's atmosphere for comparison.

Jupiter is the king of our Solar System, more massive that all other planets combined. Once planets become this large they are almost certain to be gas giants as opposed to rocky worlds. Jupiter may well have a rocky core are it's centre, but the majority of the planet is thought to consist of metallic, liquid and gaseous Hydrogen. Humans certainly could not survive in such an environment, but perhaps basic forms of life could exist on similar worlds. Crash Course Astronomy (https://www.youtube.com/watch?v=Xwn8fQSW7-8) offers some interesting background about Jupiter and its composition, in addition to a range of other topics surrounding astronomy.



A comparison showing the relative sizes of all the planets in our Solar System. Note that the sizes of the planets are to scale, but their separations are not! A 'tediously accurate' scale model of the Solar System, with correct separations, can be found here http://joshworth.com/dev/pixelspace/pixelspace_solarsystem.html.

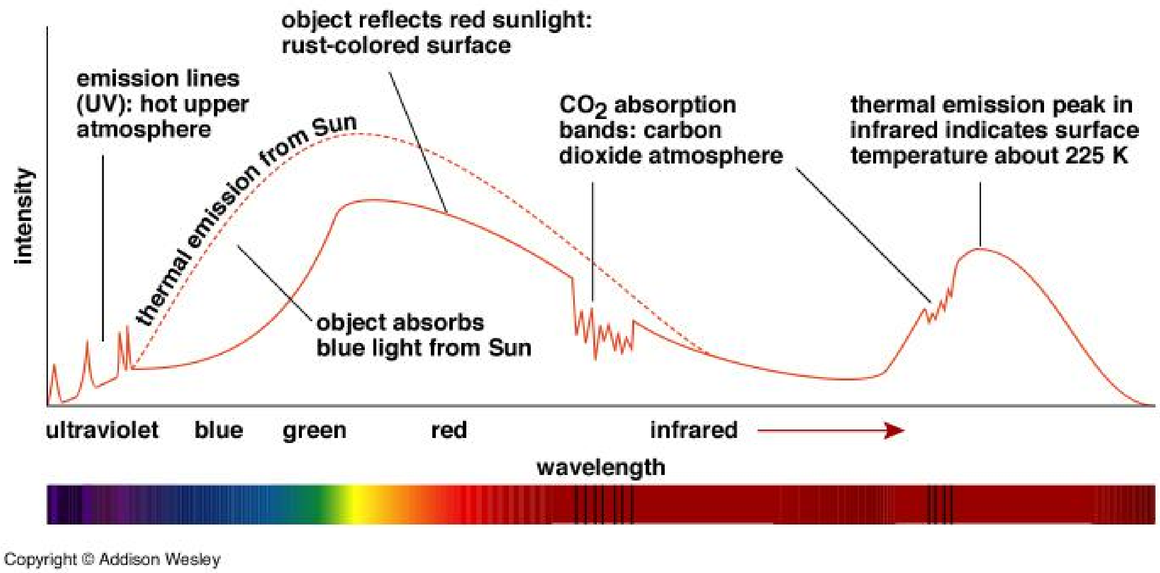
Exoplanet Atmospheres and Habitability

It is easy for scientists to measure the composition of our own atmosphere as we live inside it! Likewise, probes have been sent to study the atmospheres of Mars and Venus. However, it is also possible to study the atmospheres of other worlds without sending a probe to measure them directly. This is achieved using spectroscopy.

All objects above absolute zero (0K, -273.15°C) emit energy in the form of electromagnetic (EM) radiation e.g. radio waves, infra-red, visible light, ultraviolet, X-rays etc. Spectroscopy involves measuring and analysing this EM radiation which originates from astronomical objects.

The light we measure from stars is emitted from them directly due to fusion occurring within the star. Planets emit some light too, but at lower energies and shorter wavelengths e.g. infra-red as opposed to visible light. In addition to emitting light, planets also reflect light from their host stars. This reflected light is the same high energy/short wavelength light that is emitted from the star. The combination of this reflected and emitted light results in planetary spectra resembling the one below.

Within both the reflected and emitted light it is possible to have absorption lines. Absorption lines were first encountered earlier in the guide when exploring Doppler shift and the radial velocity detection method. When measuring the radial velocity of stars it is the cooler gas in the outer regions of the star which absorbs the light emitted from the hotter inner regions. However, the gases contained in the atmospheres of exoplanets can also absorb light in the same way! See `http://lasp.colorado.edu/~bagenal/3720/CLASS5/5Spectroscopy.html` for more information. The presence and strength of different absorption lines can be used to determine which molecules are present in a planet's atmosphere.



The above spectrum describes Mars. Note the cooler surface temperature of the planet (the Earth is around 300K) and the dominant red component of the reflected light giving Mars its characteristic rust coloured surface.

Discussion - Spectroscopy

What is Spectroscopy?

Spectroscopy is a remote sensing technique suitable for the measurement and analysis of most objects. 'Remote sensing' involves making measurements without physically touching the object being measured. The absorption lines in a planet's spectrum are measured to determine the molecules present in their atmosphere. The absorption lines may be present in the thermal emission of the planet or in the reflected light of the star.

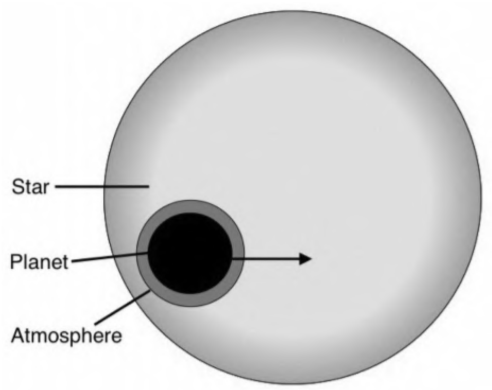
Do humans emit light?

Yes! Humans, like planets, reflect visible light from the Sun and emit infra-red radiation. When the Sun sets at night we can no longer reflect the visible light from the Sun and so struggle to see each other (some of the Sun's light will still reach us if reflected off the Moon). However, our body temperature does not change between day and night, and so we still emit thermal infra-red radiation. Our eyes are not sensitive to these wavelengths of light but we can build special tools that are! Night vision goggles can detect human emitted infra-red radiation and create a false-colour visible light image allowing us to see in the dark!

Make your own spectrometer

A spectrometer is an instrument designed to measure the spectrum of a light source. The instructions provided on NASA's website https://www.jpl.nasa.gov/edu/teach/activity/using-light-to-study-planets/ allow you to create a simple spectrometer yourself using only a cereal box and a CD! Once assembled, you will be able to analyse which elements are present in different light sources such as the Sun, a candle and a ceiling light. The spectrometer will separate the white light from these sources into a spectrum similar to the one shown on the previous page. Dark fringes should be visible in these spectra. By recording the position of these fringes and comparing them to the known spectra of different elements you will be able to determine some of the elements present in each light source.

Exoplanet Atmospheres and Habitability



When trying to examine the atmospheres of rocky worlds, the most promising situations occur when the planet transits the star. This is because rocky worlds are often smaller and cooler than gas giants and so their own thermal emission is very small. Therefore, instead of analysing the thermal light emitted by the planet, we rely on the light from the star passing through the atmosphere of the planet and being absorbed. The image to right illustrates how this situation works. If no planetary atmosphere is present then the planet would appear the same size at all wavelengths (the dark circle). However, if an atmosphere is present then the planet would appear larger (it would block out most of the star's light) at certain wavelengths which are absorbed by molecules in the atmosphere. By recording the wavelengths at which a planet appears larger the composition of the atmosphere can be determined!

This method of measuring exoplanet atmospheres is challenging. Firstly, the size of the signal is extremely small. Imagine the Earth was the size of an apple. At this scale the Earth's atmosphere would be many times thinner the skin of an apple! As a planet itself blocks only a tiny amount of a star's total light, the atmospheric contribution to this is minuscule! In addition to the small signal size, the presence of clouds in exoplanet atmospheres tend to reflect most of a star's light. This means all wavelengths of light are unable to pass through the planet's atmosphere, making meaningful measurements impossible.

Gas giants offer an additional detection method that can help to overcome the cloud issue. Young hot gas giants can have significant internal temperatures, either resulting from their formation or arising due to their proximity to their host star. These high temperatures result in non-negligible infra-red emission from the planet. This emission always has to pass through the atmosphere of the planet to escape and so it too can contain absorption lines, revealing what gases may be present in their atmospheres. Note that the transit method for atmospheric analysis also works for gas giants.

Discussion - How giant are gas giants?

Many things in life have a 'maximum size' - build them any larger and our definition of what that thing is changes. A 10 mile wide pond would instead be called a lake; floor length shorts are called trousers; and you'd struggle to find anyone that would describe Mt Everest as a 'large hill'. The previous examples are of course exaggerations, but try thinking about the middle ground. Is there a certain size of these objects where our definition of what they are changes, or is there a 'grey area' where it is hard to categorise an object into either group. Perhaps new names have even been created to help categorise such objects.

A similar problem arises when trying to determine the upper limit on planet sizes. Everyone is happy calling Jupiter a planet, despite it being over 300 times more massive then the Earth. However, how much larger than Jupiter can planets be?

One definite cut off does exist that describes the lower mass limit a star can have for hydrogen fusion to occur. Any object below this mass will therefore be unable to turn into a star like our Sun. This mass limit exists at around 8% of the Sun's mass, or 80 times the mass of Jupiter. However, what kind of object exists at 50 times Jupiter's mass? What about 70 times?

Defining objects in this intermediate mass range is still somewhat under debate. Broadly speaking, objects with masses between 13 and 80 Jupiter masses are designated 'Brown Dwarfs'. Unlike stars in the main sequence (like our Sun), brown dwarfs are not massive enough to fuse Hydrogen into Helium. However, they are massive enough to fuse Deuterium - a Hydrogen atom with an extra neutron in its nucleus. Any object with a mass below 13 Jupiter masses is unable to fuse Deuterium, so this can also be thought of as a reasonably strong separation between planets and brown dwarfs. See Crash Course Astronomy's video on Brown Dwarfs for more information on their defining qualities https://www.youtube.com/watch?v=4zKVx29_A1w.

Despite this seemingly strong separation criteria this classification between planets and brown dwarfs is still a slight grey area. Look on Exoplanets.eu and you will find many exoplanets listed which have masses greatly exceeding 13 Jupiter masses. This is because the defining criteria of brown dwarfs is still under debate as the properties of 12 Jupiter mass planets are not currently distinguishable from a 14 Jupiter mass brown dwarf. The similarities between the two are particularly present in the absorption spectra of large gas giants and cool brown dwarfs. These spectra are examined more closely in the following section.

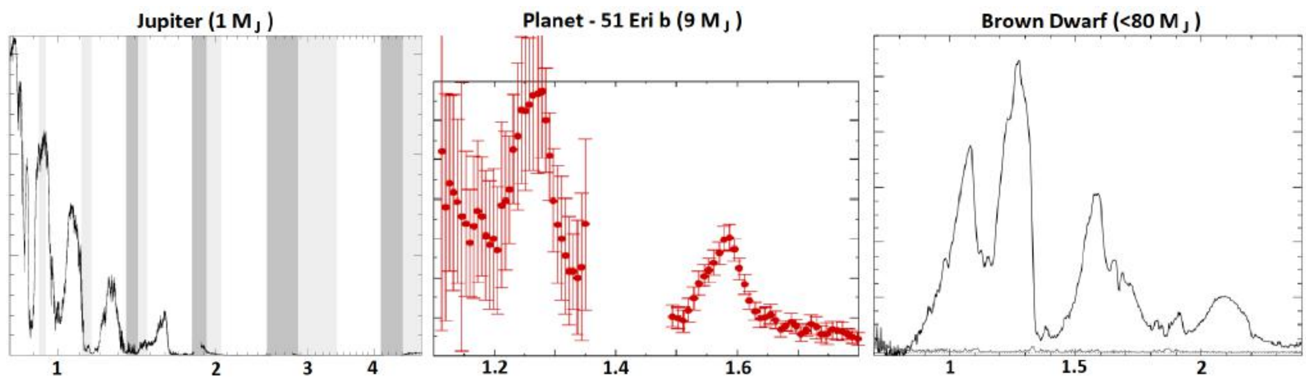
Exoplanet and Brown Dwarf spectra

The spectra of Jupiter and other Solar System gas giants can be found here http://irtfweb.ifa.hawaii.edu/~spex/IRTF_Spectral_Library/References_files/Planets.html. These spectra do not examine visible wavelengths. Instead, the wavelengths of light that are examined are in the 'near infra-red'. The spectrum of Jupiter available on this website shows the measured flux between 0.8μm and 4.9μm. For comparison, the visible light wavelength range runs from around 0.4μm to 0.7μm, which would appear just to the left of the near infra-red graph plotted.

The recorded light curve of Jupiter is not a simple continuous spectrum. Over the wavelength range plotted the measured flux increases and decreases at specific wavelengths. The drops in flux observed are absorption bands caused by molecules present in Jupiter's atmosphere. By comparing the position of these bands to known molecules scientists have determined that they are caused, largely, due to the presence of water vapour (H_2O) and methane (CH_4).

The spectrum of another gas giant, 51 Eri b, has also be measured. Through searching Exoplanet.eu you can discover that 51 Eri b is approximately 9 times more massive than Jupiter, though not much larger in size, and far hotter at around 700K. Its spectrum can be found here http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=J/other/Sci/350.64. Open both Jupiter and 51 Eri b spectra and compare the two. What similarities and differences exist between them?

In addition to gas giants, it is also possible to examine the spectra of Brown Dwarfs. The spectra of cool, T-type Brown Dwarfs, gas giants' slightly bigger brothers, can be found here http://pono.ucsd.edu/~adam/browndwarfs/spexprism/html/tdwarf.html. T-type brown dwarfs are some of the coolest Brown Dwarfs found in the universe, with temperatures around 1000K, meaning that they are only slightly hotter than 51 Eri b. Compare the spectra of some of these Brown Dwarfs to that of Jupiter. You should find that they look similar - they share common absorption bands. These similarities start to fade as Brown Dwarfs become hotter and more massive. This is because methane can only survive at 'cool' temperatures e.g. methane absorption is not expected at all in main sequence stars such as our Sun.



Left to right shows the NIR spectra of Jupiter, 51 Eri b and a T-type Brown Dwarf. Here the axes labels have been removed/simplified. The y-axis shows the flux/normalised flux for each object. The wavelength (μm) is shown on the x-axis. Download the data from websites provided above to make comprehensive comparisons between them.

Discussion - Planet spectra & habitability

What similarities exist between the spectra of Jupiter and 51 Eri b?

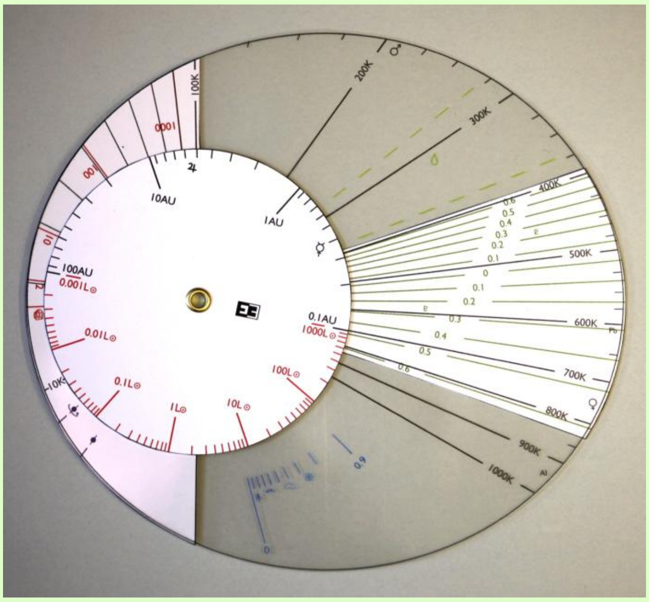
All absorption lines match in location, though their relative depths do vary. Be careful to examine the scales of the two plots - Jupiter's spectrum range covers 0.8-4.9μm, whereas 51 Eri b only covers 1.1-1.8μm. The spectrum of Jupiter is known more precisely than that of 51 Eri b as Jupiter is far closer to us and has been studied in more detail.

Which molecules correspond to the various absorption bands present in Jupiter's spectrum?

Try searching the internet yourself to find the answer. You can Google 'T dwarf infra-red spectra' as these spectra are often annotated, showing which molecules cause each absorption band. Compare these to the spectrum of Jupiter. You should find that most of the absorption bands are caused by the presence of water and methane in Jupiter's atmosphere.

Create a 'Brunometer' and find which planets might have the potential to support life as we know it!

A Brunometer is a hand-held mechanical device that you can make yourself out of card and acetate (a thin transparent plastic sheet). Once assembled, the device can be used to calculate the surface temperature of an exoplanet with certain properties. You can see how this temperature varies with changing albedo, planetary spin, stellar luminosity, atmospheric thickness, star-planet separation and orbital eccentricity. Through altering these, you can establish which combination of values result in a potentially habitable planet i.e. one where liquid water can exist on its surface. The templates and instructions for creating your own Brunometer can be found here http://star.herts.ac.uk/RoPACS/brun.html.

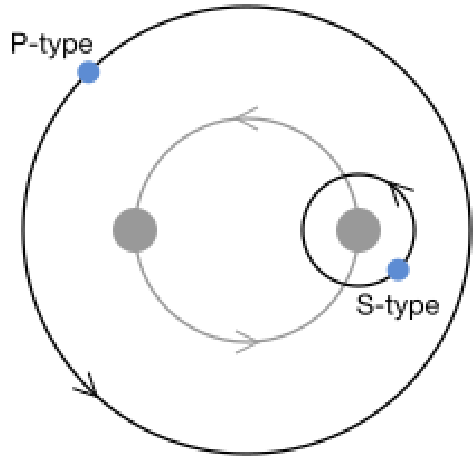


An assembled Brunometer

Binary stars and their habitable zones

The Brunometer exercise listed on the previous page allows you to estimate the temperature of an exoplanet orbiting a single star like our Sun. However, it is thought that over half of all stars in the universe exist in binary systems - two stars orbiting their common centre of mass. Previously, astronomers believed the gravitational disruption caused by such a system would prevent planets from forming in these scenarios. However, we now know that this is not the case. Not only can planets form around binary stars, they can have orbits that allow the planet to exist in the habitable zone where liquid water can exist on the surface of the planet.

Habitable zone orbits can exist if the exoplanet orbits either both or just one of the stars in the binary system. The planet will likely achieve a stable orbit most easily around both stars (P-type) if they orbit close to one another, or around one star (S-type) if they are separated by a large distance. The figure to the right illustrates these two scenarios (not to scale).



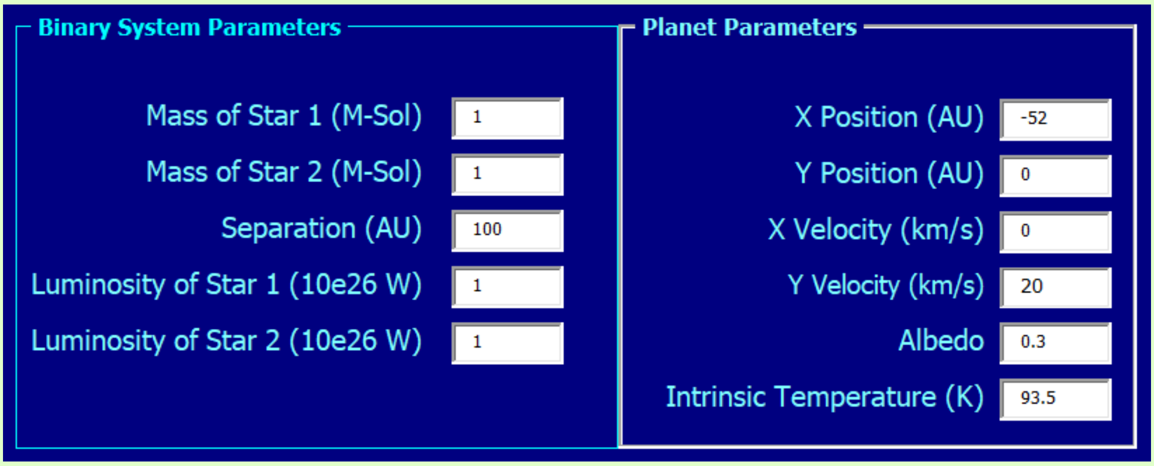
The maths involved with a planet orbiting in a binary system is more complex than of a planet orbiting in a single star system. However, a simulation does exist that allows you to model a binary system. Within the simulation you can alter the masses of the two stars, their separation and their luminosity. You can also alter planetary parameters such as its initial position and speed, its albedo and its intrinsic temperature. The simulation can be made to run for as few or as many years as you would like. Note that you should increase the number of 'time steps' to gain more accurate results but this will increase the run-time considerably. Once the simulation has completed you will be able to see the path the planet followed over the run time and how the temperature of the planet varied throughout its journey.

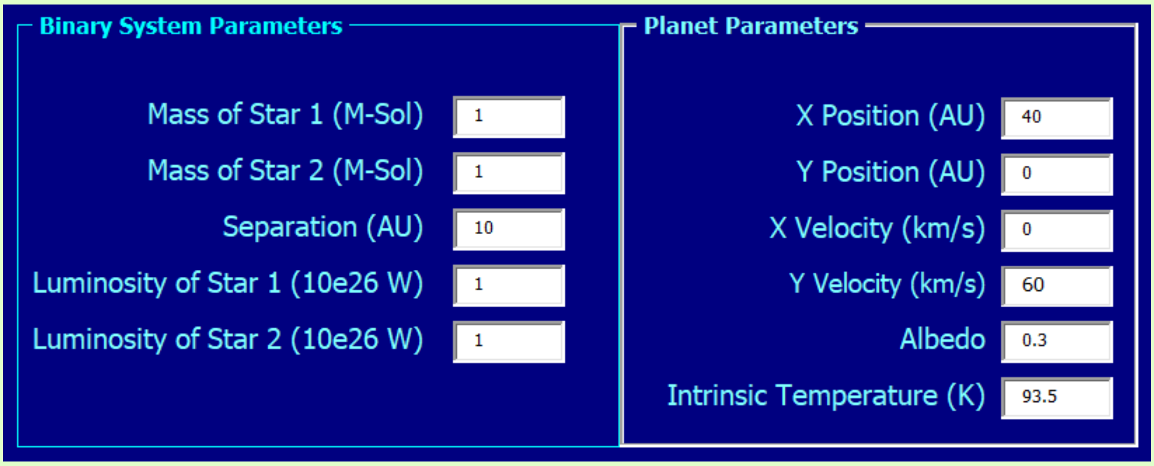
The simulation `https://www.herts.ac.uk/h2h/resources/life-around-binary-stars` can be found here and runs in Excel. The instructions included are designed to be understood by university students, so do not worry if these look complex! Use trial and error to try to establish a stable orbit around both and just one of the stars. Once the orbit is stable (i.e. the planet does not crash into a star or shoot off very far away) try altering the parameters so that the temperature of the planet remains between 273K and 373K (0°C and 100°C). Once you have succeeded, you will have successfully modelled an exoplanet that could hold liquid water and have the potential to support life!

Discussion - Binary simulation

The purpose of this exercise is to demonstrate that habitable planets can exist in binary systems. The possibility of a planet existing that is similar to Luke Skywalker's home planet, Tatooine, is far from science fiction!

If trial and error is proving unsuccessful, the parameter values given in the examples below provide stable planetary orbits for both S-type and P-type orbits respectively. Once you have achieved a stable orbit you can then try to alter these parameter values so that the planet orbits within the habitable zone. For both scenarios set the run-time to 1000 years and increase the number of time steps to 1,000,000.





Tips: you can rescale your axes to zoom in and out on the orbital path of the planet. It might be easy to obtain a habitable planet by changing its intrinsic temperature, but try to do it by changing the distance of the planet from the stars instead. Remember that the closer the planet is to a star the faster it has to travel in order to resist its gravitational attraction and not spiral inwards.

Extended Project Work

You have now seen how to detect and characterise planets based on transit and radial velocity data. Exoplanet atmospheres and other properties have been explored as well. In addition, you have also learnt how to predict when transits will occur and how to detect them, given the right equipment. You are now encouraged to come up with an independent project of your own.

Before rushing into your work, you should research what area you wish to explore further and create a formal project proposal. Once you have a plan in place, discuss this with your supervisor to help clarify your goals and identify any issues you may face early on.

Work through your project, making sure you always have your aims and objectives in mind. Document your work as you go along so that both you and your supervisor have a way of monitoring your progress.

Once you have completed your work, prepare a presentation summarising your findings and be prepared to answer questions about what you have done too. Remember, scientists all have to go through the same processes.

Finally, perform a self evaluation of how you believe your project went. Did you achieve the goals you set out to accomplish at the start? What do you think you would do differently given the chance to perform the work again? A template for the form a self evaluation might take is provided after the project suggestions.

The following pages list some ideas for the form an Extended Project may take. You should change these to suit your preferences or you create your own proposal. Remember, extended projects don't have to, and often don't, lie solely within one defined subject e.g. you could explore the history, politics, engineering or ethics involved in exoplanet research if you wish. Take your time in making this decision. Research your options and pick one that both interests you and is achievable with the resources and time you have available.

Extended Project Work - Suggestions

- Try to make measurements of an undiscovered or unconfirmed exoplanet! The website https://keplerscience.arc.nasa.gov/k2-approved-programs.html contains a record of the different observation campaigns undertaken by the K2 mission, as well as a list of any upcoming missions. Notable targets for each campaign are mentioned on the website, but you are able to download a list of the thousands of targets observed at any one time if you wish. Exoplanet.eu and the NASA Exoplanet Archive also easily display all unconfirmed and candidate exoplanets.

  Interesting transits can be searched for either by name or by their RA and Dec coordinates on the K2/Kepler websites. If you don't have the star's name, you can search its coordinates on Simbad to discover the name of the star and further information about it.

  Make your own measurements of the orbital period, stellar rotation period and size or minimum mass of the potential planet and record these clearly. Use any of the websites mentioned previously in this guide to do this. Compare your values to any that may exist in literature. Repeat this process until you have a few interesting observations/comparisons - your observations do not have to agree with others. Understand and write about the difficulties involved in analysing such large amounts of data. Explain the importance of making 'by eye' measurements.

- Research the conditions that make a planet potentially habitable. Criteria to consider might include whether the planet is rocky, like the Earth, or a gas giant, like Jupiter. The temperature of the star and the distance of the planet from it will also be of importance.

  Apply filters to all the confirmed exoplanet data to find out what fraction of those discovered may have the potential to hold life. Is this fraction large or small? Examine some of the transit and RV curves for these targets to see how easy they are to detect. Try to account for detection biases to find out how many habitable planets you expect to find in the entire Milky Way galaxy. How about within 100 light-years of the Earth?

- Space exploration and research can be very expensive and the results are never guaranteed - the James Webb Space Telescope continues to run over budget and behind schedule. In your opinion, would this money be better spent elsewhere, either funding alternative scientific research, supporting charitable causes or invested in a variety of different projects?

  You may want to consider both the short and long term impacts of such research. How many people are employed in the sector and how many people are affected by their work directly or indirectly? The scientific, economic and political ramifications surrounding this subject are considerable and maybe explored in a variety of ways.

Extended Project Work - Suggestions

- Explore the most extreme or most average exoplanets we have discovered - find these using the plotting features on the websites listed in the Exoplanet Properties section earlier. e.g. You could try examining the most massive, the largest and the densest exoplanets ever discovered. How do these compare to planets in our own solar system?

  You could also try to determine the typical qualities of the most 'average' exoplanet that we detect - do they tend to be larger than the Earth or further from the Sun? Is the host star similar or not to our own Sun? Examine the light curves/radial velocity data for some of these 'average' exoplanets - is there a particular reason we detect these more frequently - are their signals larger than most?

- What is the nearest confirmed exoplanet to the Earth? How far away is this planet from us and how long would it take to travel there using current technology? How fast would a spacecraft need to travel in order for it to reach the planet in our lifetime? Consider the feasibility of both manned and unmanned missions.

  Examine the data collected on this exoplanet. Does this planet look Earth-like or not? Does it hold the potential to support life as we know it? If not, what is the nearest potentially habitable planet to us? How long would it take for us to reach this planet?

- There are many methods for detecting exoplanets. How successful has each method been at discovering exoplanets? Which methods could be used in tandem with one another to provide greater confidence in a discovery? Which methods can be used to constrain different planetary parameters?

  Given your research, what method of detection do you think will be most worthwhile investing in? Consider how many planets can likely be detected, whether these planets will be different or similar to those already discovered and compare the costs involved to other methods of detection.

Extended Project Work - Suggestions

- Make real life observations yourself. If you have access to the right equipment then you could spend your time planning out which targets you would like to observe, learning how to use the equipment and making your observations. The data that you collect should then be analysed to check if your results agree with previous measurements. Are the signals you detect as large as previous measurements? What factors limit the precision of your measurements?

  As with all projects, it is important to carefully document your work as you progress. Take photos of the equipment set up, record when you take you measurements and the weather at that time. Even if you don't observe a clear signal, or any signal at all, this is still significant as it highlights the importance of investing in the most advanced telescopes for the purposes of planet hunting, amongst many other reasons. The following public projects may be of interest: `http://www.britastro.org/vss/`; `https://www.aavso.org/observers`; `https://reddots.space/`; `https://palereddot.org/`. These projects include observations of nearby rocky exoplanets and variable stars - these stars can sometimes be observed with a pair of binoculars or a very small telescope, and so may provide a more realistic target for your observations. You may contribute photometry data to any of these projects if you wish.
- Explore the history of exoplanet research. Although the first exoplanets were only discovered several decades ago, much has happened in that time. Multiple missions have been launched, successes and failures have occurred, and our knowledge and theories surrounding exoplanets have continued to advance and change. You may choose to focus on just the past few decades, or look further back in time and explore a wider variety of astronomical observation techniques.

  Alternatively, or additionally, you may wish to look to the future. Can our current methods of detection continue to prove effective? What are the most promising avenues of exoplanet research suggested for the next 10 years or longer?

Self evaluation template

As you complete your work, it is important to ensure you remain on track to achieve the goals you set yourself from the start. To maintain this focus, it might be useful to keep the following questions in mind as you will have to answer these same questions, or similar ones, once you have completed your project.

- Did I achieve what I set out to do?
  ....
  ....
  ....
- Do my results match any predictions I may have had from the start or are they different?
  ....
  ....
  ....
- How thorough has my research been?
  ....
  ....
  ....
- Did I face any challenges or difficulties in completing the project? What were they and how did I overcome them?
  ....
  ....
  ....
- What skills have I developed through completing my work? Are any of these skills transferable?
  ....
  ....
  ....
- How well did I manage my time throughout the project?
  ....
  ....
  ....
- What would I do differently if I were to complete the extended project again?
  ....
  ....
  ....

Exoplanets and the Curriculum

Hopefully you agree that exoplanets are interesting enough to study in their own right. However, it is useful to see how such work might link into different curricula, be that Physics, Maths or Computer Science. Links to the specifications for different exam boards are also provided below the descriptions.

A-level Physics: Astrophysics options exist within most exam boards' specifications. Detection of exoplanets often falls under this umbrella, containing material on transit and radial velocity detection methods, Doppler shift and angular resolution.

- AQA - http://www.aqa.org.uk/subjects/science/as-and-a-level/physics-7407-7408
- EdExcel - https://qualifications.pearson.com/en/qualifications/edexcel-a-levels/physics-2015.html
- OCR - http://www.ocr.org.uk/qualifications/as-a-level-gce/as-a-level-gce-physics-a-h156-h556-from-2015/

GCSE Physics: Astrophysical properties are explored, including our Solar System, circular orbits and red-shifted light.

- AQA - http://www.aqa.org.uk/subjects/science/gcse/physics-8463
- EdExcel - https://qualifications.pearson.com/en/qualifications/edexcel-gcses/sciences-2016.html
- OCR - http://www.ocr.org.uk/qualifications/gcse/gcse-gateway-science-suite-physics-a-j249-from-2016/

A-level Maths and Further Mathematics: Statistics and Mechanics are prominent in all syllabuses. These broad areas can include topics ranging from data presentation and interpretation to the equations of circular motion.

- AQA - http://www.aqa.org.uk/subjects/mathematics/as-and-a-level
- EdExcel - https://qualifications.pearson.com/en/qualifications/edexcel-a-levels/mathematics-2017.html
- OCR - http://www.ocr.org.uk/qualifications/by-subject/mathematics/

GCSE and A-level Computer Science: Knowledge of storing and accessing data in different formats, including querying databases using SQL. Note - Gaia uses ADQL, a special variant of SQL (https://www.gaia.ac.uk/data/gaia-data-release-1/adql-cookbook).

- AQA - http://www.aqa.org.uk/subjects/computer-science-and-it
- EdExcel - https://qualifications.pearson.com/en/qualifications/edexcel-international-gcses-and-edexcel-certificates/International-GCSEs-from-2016-and-2017/computer-science-and-ict-subjects-explained.html
- OCR - http://www.ocr.org.uk/qualifications/by-subject/computing/