Transit of Venus – the last in our lifetime

John S. Reid

Department of Physics, University of Aberdeen

Notes to accompany PowerPoint slides, some of whose images are embedded here. The actual talk may have differed in places from these pre-written notes.

Good evening and welcome to this Jubilee Lecture, though the Transit of Venus and the transit of 60 years of Elizabeth's reign is a complete co-incidence.

Public interest 2012

Exceptional events in the sky fascinated our ancestors. Indeed, they frequently attributed to them a significance they didn't really have. In centuries past exceptional events in the monarchy and the sky might have been speciously linked together. We still have the curiosity that created a sense of awe for earlier generations; today we have something else as well to help us understand what is going on – more knowledge.

In early June 2004 many people were lucky enough to witness first-hand an astronomical phenomenon not seen before by any person then alive. The May 2012 edition of the National Geographic magazine featured a picture of what people saw – Venus transiting across the face of the Sun. Tomorrow morning is the second and last time any of us may see Venus as a black spot against the brilliant screen of the Sun's disk, clouds permitting. In recorded history, the event has only ever been witnessed on six occasions, the first time by only two people. It is a rare event, which in itself is a bit odd since Venus is a planet that orbits between us and the Sun.

After a pre-amble on why people have been interested in these transits, I'm going to tell say why transits occur when they do, what we hope to see, how best to view it. I'll cover some of the history of previous observations of the phenomenon and finish with why planetary transits are a hot topic in today's astronomy.

Venus's orbit

To get a handle on what's going on, let's look first at an animation of the orbits of Earth and Venus, courtesy of public domain software called Porbits. Looking down on the solar system, Venus appears to come between us and the Sun every 1.6 years. Actually it crosses the face of the Sun much more rarely, and I'll say why later.

Astronomical interest

The *Transit of Venus* has played a more important rôle in the history of astronomy than you might expect. Indeed a famous Astronomer Royal in the 19th century billed it as being able to solve *the most noble problem in astronomy*. That rôle has now passed and as far as astronomers are concerned the forthcoming event is for the most part a re-enactment of a bit of history of our subject. Think of it like a car enthusiast admiring a fine quality Bugatti that turns up at the local rally. Nothing wrong with that, but the Bugatti is no longer going to push the frontiers of car design. The transit of Venus isn't going to push the frontiers of astronomy like it once did but other transits are changing our view of the universe, just as other cars are hot news in a today's rally. I'll say something on this near the end.

Our ancestors, though, did get very excited about the Transit of Venus. Expeditions were launched to far-flung places to observe the transit, sometimes at risk to life. Some of these journeys had far-reaching effects and unplanned consequences. Tomorrow's event is the nearest we'll get of a repeat of the 1769 transit that was the main reason for James Cook to go to the antipodes, an expedition in which he mapped almost the whole coast of New Zealand and laid the foundation for it and Australia to become crown colonies.

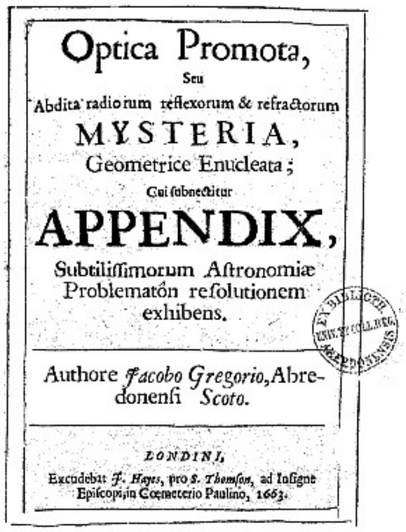
Why has the phenomenon played a significant part in the history of Astronomy? For three reasons: One can

- ★ refine the elements of Venus' orbit using observed timing. The elements are the parameters that describe the orbit.
  - ➢ 17th century result
- ★ determine the absolute scale of the solar system
  - ➢ 18th century result
- ★ find an accurate value for 1 AU (the astronomical unit of distance)
  - ➢ 19th century interest

1 AU is the metre-stick for measuring the distance to the nearest stars and beyond to the Universe at large. The distances to all nearby stars are measured by a celestial surveying technique, using as a baseline the average distance between the Earth and the Sun, a distance known as one Astronomical Unit (AU for short).

James Gregory (1638 – 1675)

James Gregory was a brilliant NE mathematician and astronomer who held chairs of Mathematics first in St Andrews and then in Edinburgh. He invented the reflecting telescope that was first described in his book 'Optica Promota', in which **he also said how the distance of Venus could be found by observations of a transit of Venus**. The slide shows the only painting of Gregory, which is in the University of Aberdeen, and the title page of Optica Promota from King's College library. It's fitting that the translation from the Latin of Gregory's influential book that you will find on the web has been done by Ian Bruce, an Aberdeen University Natural Philosophy graduate working in Australia. You'll see that Gregory was only 1 year old when Horrocks observed the transit and the 121.5 years before the next one in 1761 ensured that Gregory wouldn't be alive to see it.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Seu
Abdita radiorum reflexorum & refractorum
MYSTERIA,
Geometrice Enucleata;
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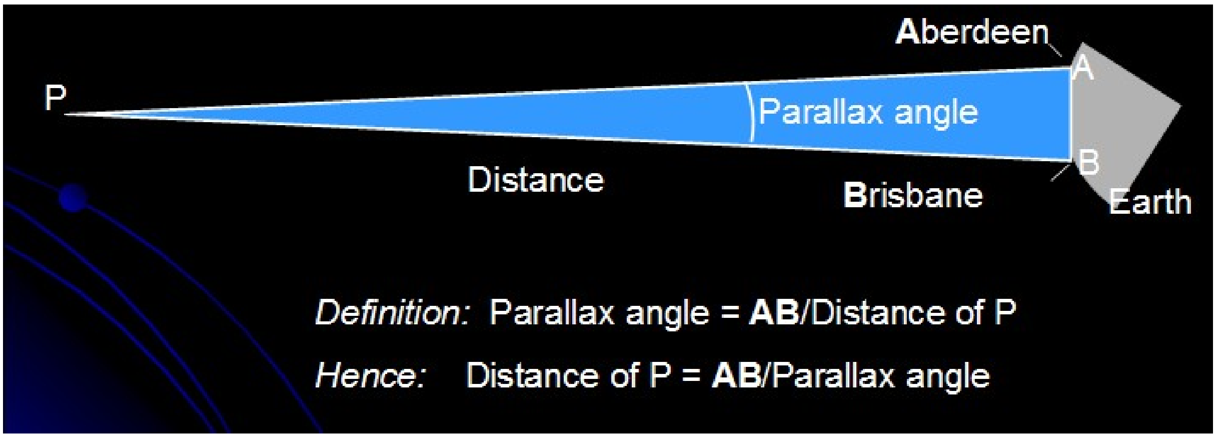
APPENDIX,
Subtilissimorum Astronomiæ
Problematôn resolutionem
exhibens.

Authore *Jacobo Gregorio*, Abredonensi *Scoto*.

LONDINI,
Excudebat *J. Hayes*, pro *S. Thomson*, ad Insigne
Episcopi, in Cœmeterio Paulino, 1663.

Thanks to Johannes Kepler's planetary laws discovered in the first quarter of the 1600s, astronomers could draw a scaled chart of the solar system but couldn't put the scale on it. All it needed, though, was for any one distance to measured and we could find them all, including the distance between Earth and Sun.

Parallax of a planet

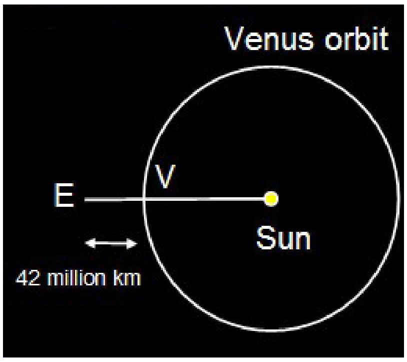


Distances between planets are enormous by terrestrial standards and the unit that we use to measure distances is the metre, a distance that you can easily encompass between outstretched arms. How do you measure a distance of a hundred thousand million metres, which doesn't even get you to the Sun but does reach past Venus? You can't put even 1000 million metre sticks end-to-end. The key distance measuring technique in astronomy is the method of parallax.

The method is essentially one used by surveyors. Angle is what is measured. You need a line of sight (provided by the telescope), a ruler and a protractor. Parallax is the change in angle of view when you change your observing position by a known amount. If I note the direction of an object at the back of the room in front of me, then move aside by 1 metres and note the change in angle of view, it is easy to work out how far away the object is. If the change in angle of view is 5°, then the object is about 11 m away and I needed only 1 metre stick to find out.

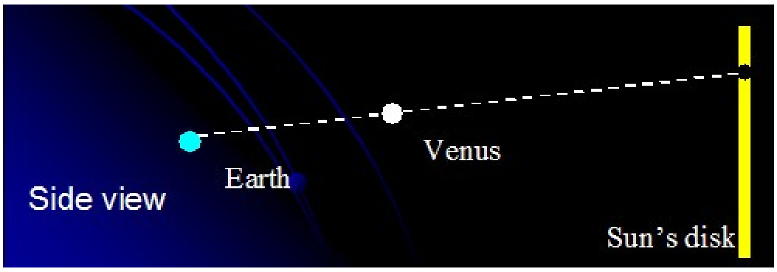
For a planet, we need to find the change in the angle of view of an agreed feature like the centre of its disk from two points a known distance apart on the Earth. Then using the geometry of a thin triangle we get the distance in km. Job done. [e.g. Take Aberdeen to Buenos Aires distance as 10,000 km, parallax angle of Venus as 1/200° (18" arc) gives the distance to Venus of 115 million km.]

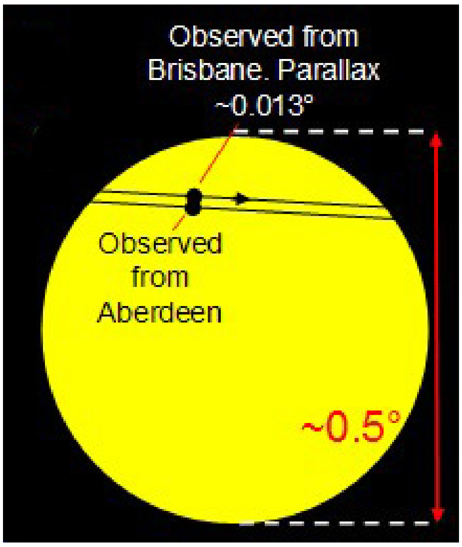
Parallax of Venus



Venus orbit brings it to within 0.28 AU on average from the Earth, and sometimes a bit closer. This is the closest any planet gets to us. Venus should be the best planet for finding the scale of the solar system, if we can measure its parallax when it is in the direction of the Sun. However, normally it can't be seen then because of the glare of the Sun. In the special circumstance of a transit in front of the Sun, Venus can be seen.

The master plan





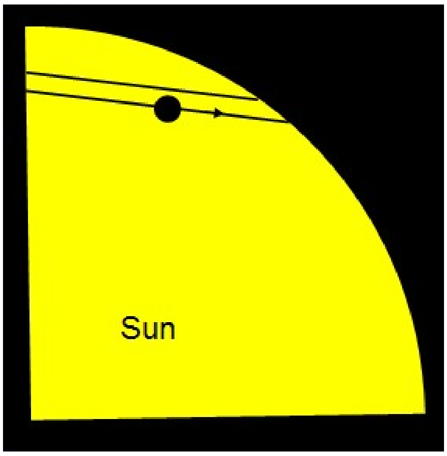
This is the plan. We'll use the Sun as a background screen. Watch Venus crossing in front of the Sun from different places on Earth. If we're nearer the North Pole, then the track of Venus will be lower on the Sun's face. If we're further South, the track will be higher up. Distances on the Earth are taken to be calculable from the differences in latitude and longitude of the two observing sites and the known radius of the Earth. By measuring the angular distance between the two tracks, we can find the parallax of Venus, hence its distance from the Earth and hence the value of the astronomical unit and the distance to the Sun.

Edmond Halley (1656 – 1742)

Gregory pointed out the usefulness of transits for finding the astronomical unit but it was Halley who became enthusiastic about it after observing the transit of Mercury from St Helena, where he had been sent to take a survey of the Southern heavens by the Royal Society of London. His survey was somewhat clouded out from his base on St Helena but his very good view of the transit of Mercury convinced him that the transit of Venus would be an excellent way of determining the astronomical unit. He devised the details of a method of using the timings between ingress and egress of the planet to find the AU and his publication of this in 1716 was very influential in creating enthusiasm for it half a century later. Based on his experience of the transit of Mercury, he predicted that an accuracy in determining the astronomical unit of some one part in 500 should be obtainable if well-chosen measurements of the transit were made.

This certainly spurred on his successors, who would all be sadly disappointed that they couldn't achieve this promise.

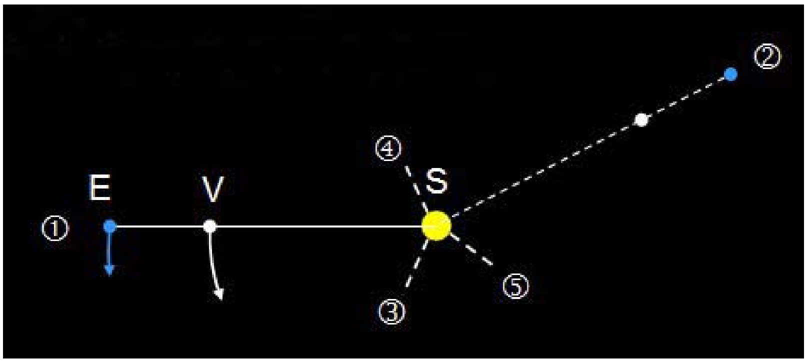
The refinement



Refinements use the fact that our screen has a curved edge and is in effect calibrated in terms of angle. If we time the transit across the chord, i.e. determine the time between Venus first ingressing the disk to its egress at the other side of the Sun, then we should be able to measure this time to better than a second. This will be more accurate than trying to measure angles directly, for time is something we know how to measure very precisely. This is what our ancestors did in the 18th and 19th centuries and from the measurements they learnt the size of the solar system.

Alignments of Earth, Venus and the Sun

Now we come to one of the fascinating puzzles of the Transit of Venus. Since Venus orbits between us and the Sun, shouldn't Venus be in the direction of the Sun quite often? Why will it be over a century after tomorrow before there is another opportunity to see the transit of Venus? What's going on is not much different from a more familiar astronomical problem. The Moon orbits the Earth between us and the Sun, coming between us and the Sun every 28 days, roughly, and yet an eclipse of the Sun by the Moon is quite a rare event. The reason for the rarity of eclipses is the same as the reason for rarity of the Transit of Venus.



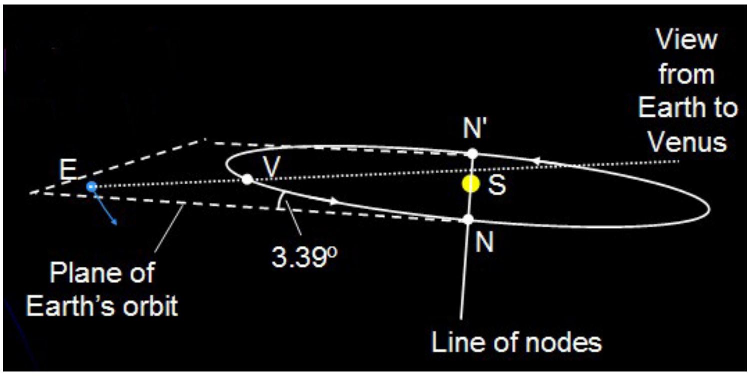
So how often are the Earth, Venus and the Sun aligned? I've put the periods of the two planets on the slide. Looking down on the planets, you would see them going around like the two hands of a clock. You might think that there would be no relationship between the two hands but there is. Venus is making a circuit around the Sun close to 1.625 times quicker than the Earth. If you were brought up on rulers that divided inches into eighths, you'll recognise 1.625 as 13/8 and it's immediately obvious that 13 revolutions of the Venus correspond to 8 revolutions of the

Earth. It's not hard to show that if this is the case then Venus and the Earth will align every 1.6 years (which is exactly 8/5 years). [In reality, the time between successive alignments is 1.5987 years and this difference from 1.6 has important consequences in our story.]

Going back to the alignment time of 8/5 years, this implies that if the Earth, Venus and the Sun are aligned along one direction, then there are only 4 other directions in space in which this alignment occurs before the pattern repeats again. Or at least there would be if the fraction were exactly 1.6. The directions are labelled ①, ②, ③, ④ and ⑤ in the diagram. So the problem is almost solved then. We can measure the parallax of Venus every 584 days, can't we? Unfortunately, it's not that simple.

The Earth

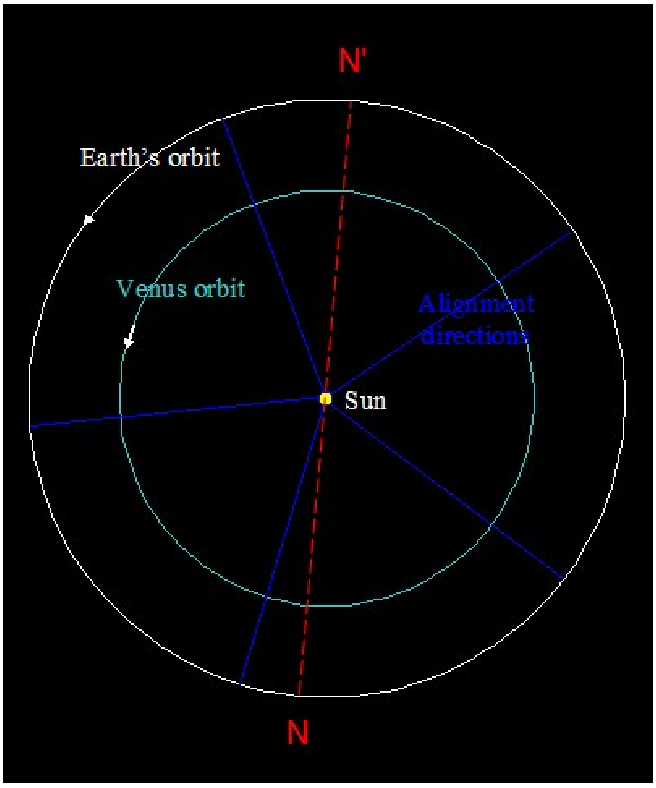
Just as the Moon's orbit is tilted relative to the Earth's, so Venus orbit is tilted relative to the Earth's (at 3.39°). When the Earth – Venus – Sun appear to be in line looking down on their orbits they don't in fact lie on a straight line. The 3rd dimension is important. Venus is usually above or below the Earth. Looking from the Earth, Venus won't transit the face of the Sun.



In fact there are only two points on Venus orbit that lie in the plane of the Earth's orbit. These are called the nodes of Venus orbit and if they are not nearly on the Sun-Earth line then there will be no transit.

The problem

The slide shows what I've just said. In the picture, Venus is above the plane of the Earth's orbit when it is in line with the Sun and hence the view from the Earth towards Venus will not intersect the Sun.

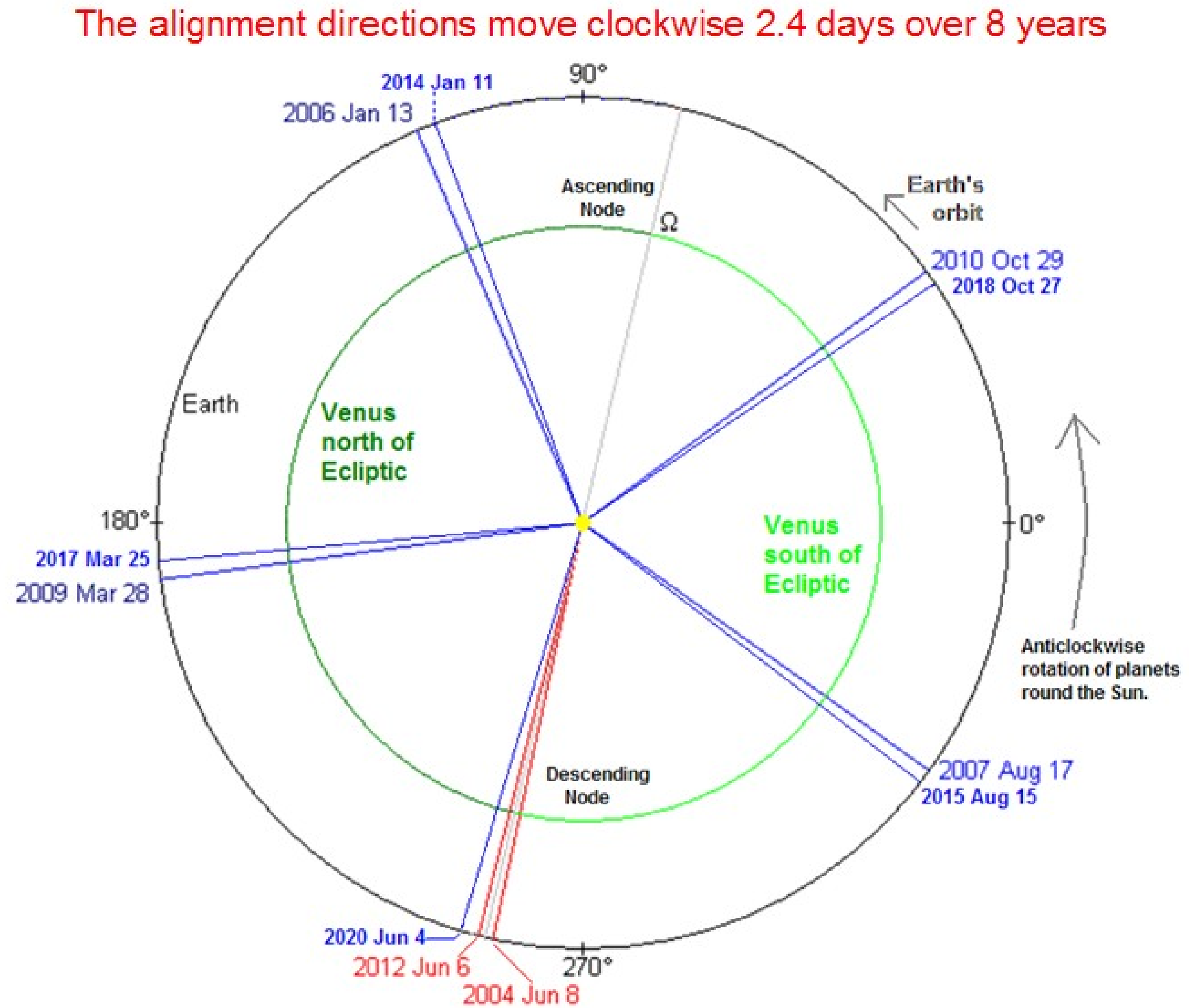


The final complication

The alignment of Earth-Venus-Sun occurs only in 5 directions, 72° apart. One of these isn't very close to a node then there will be no transit. If one does coincide with a node then it would seem that transits should occur every 8 years. Since neither of these things happen, the solar system must be more subtle.

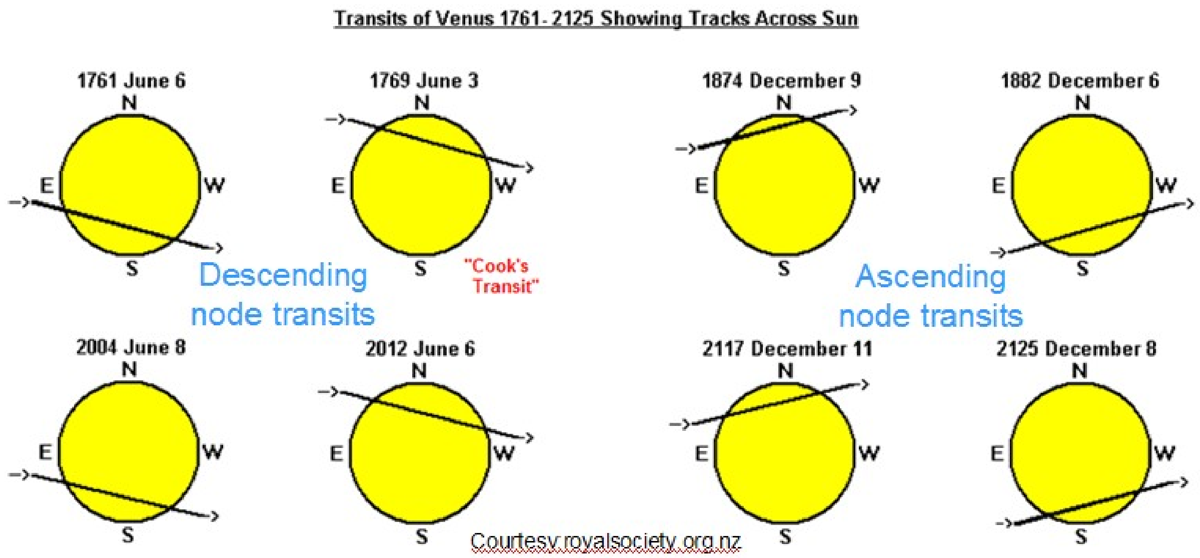
The alignment directions move clockwise 2.4 days per year

Because Venus's year isn't exactly 8/13 of the Earth's year but only very nearly, the alignment spokes rotate clockwise by 2.4 days every 8 years (about 2.36° in angle).



Courtesy: http://www.rasnz.org.nz/2012Transit/Transits.html

We can now see why there won't be another transit for 115.5 years after this one. We have to wait for the next alignment spoke to rotate close to the ascending node. When Venus passes its descending node it goes from an evening planet to a morning planet.

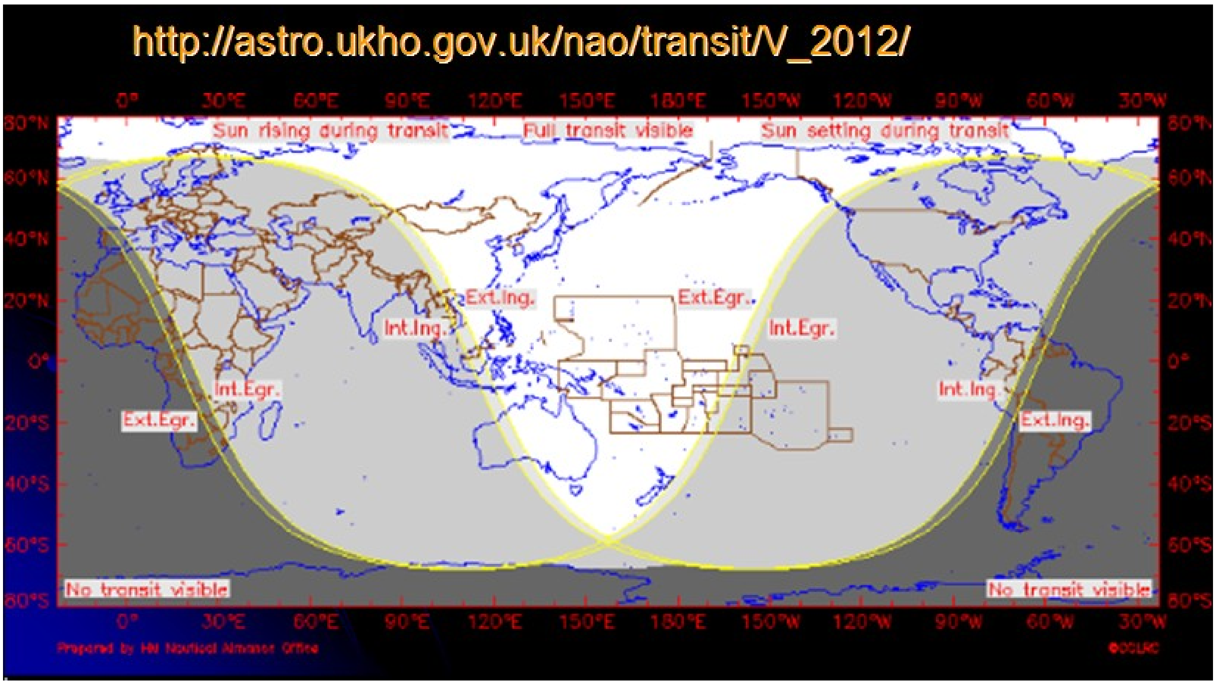


Courtesy royalsociety.org.nz

Past and future transits

The slide shows the transits in the 18th, 19th, 21st and 22nd centuries. This shows why tomorrow's transit is nearly a re-enactment of Cook's transit, one of the consequences of which is that English is the national language of Australia and New Zealand.

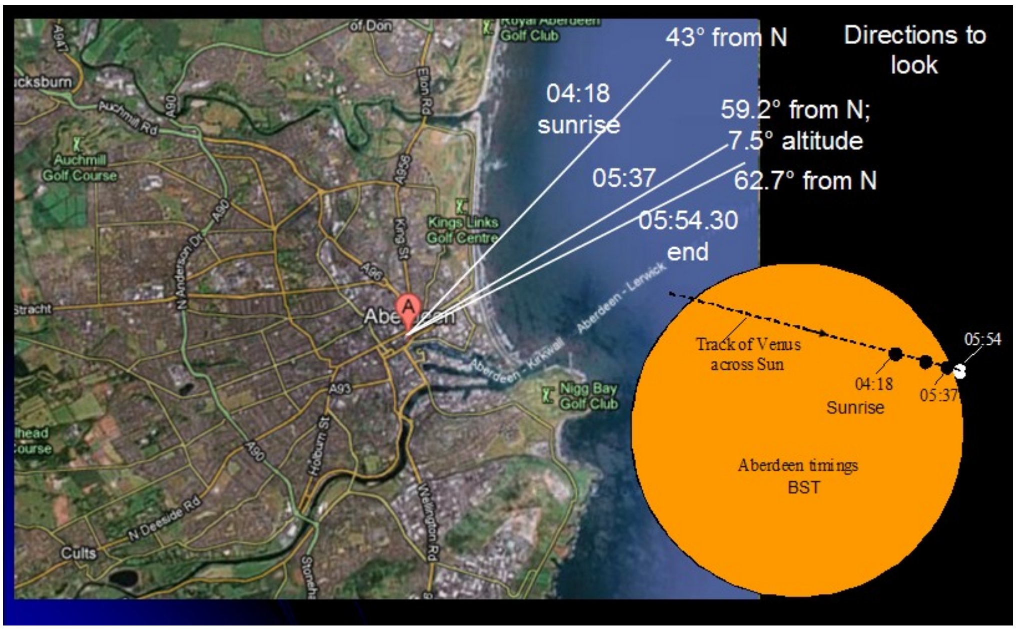
The World-wide scene

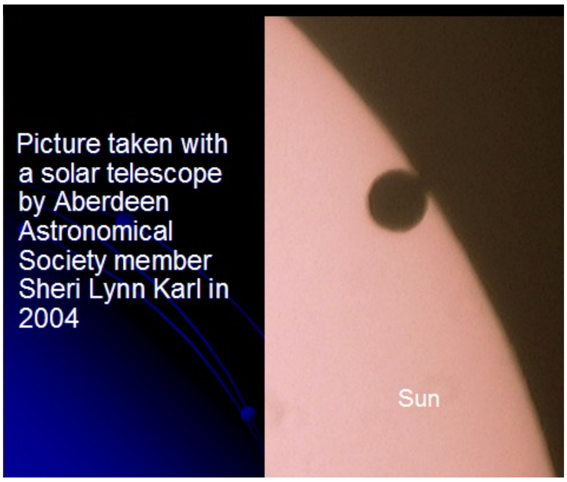


The transit of Venus will be visible in its entirety from all parts of the world shown in white in this picture from the UK Nautical Almanac office. In the UK most of the transit happens when the Sun is below the horizon, at night. The Sun will rise with the transit well in progress.

Where and when to observe

Look in the NE, at sunrise over the sea at 4.18 am (BST). The Sun will rise up (at an angle of about 26° so that as the transit finishes around 5.50 the Sun is some 10° above the horizon.



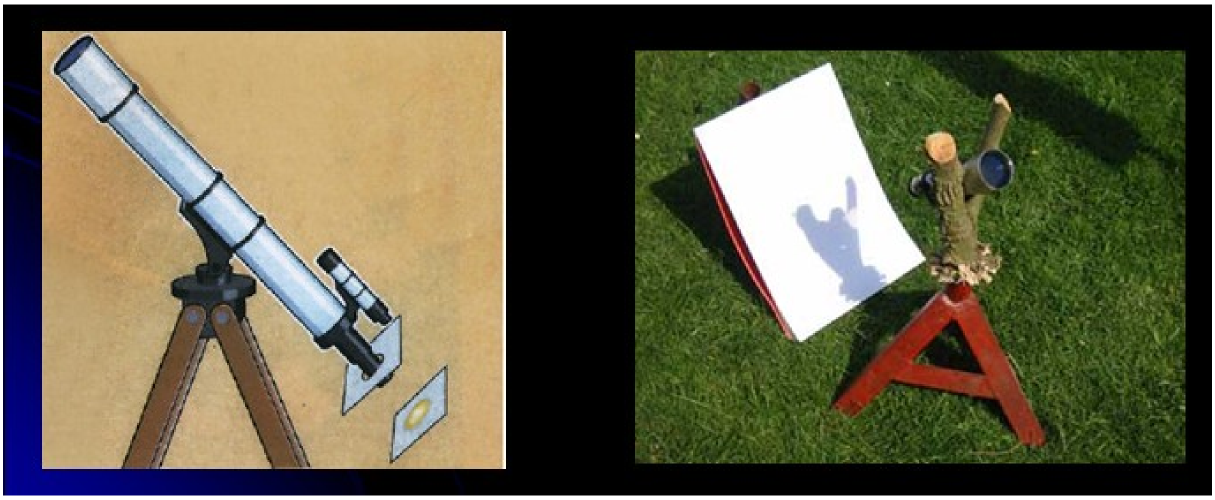


Observing the Spectacle

If you have eclipse glasses then if you have good eyesight you might just be able to see Venus against the Sun’s disk but I don’t recommend direct viewing. 1' arc, the size of Venus, is about the diameter of a tennis ball held up 250 m away. It’s very small.

Observing the spectacle

Projection is the best method. Using a pair of binoculars or a small refracting telescope one doesn’t need a solar filter. One does need a stand to hold the telescope steady, a screen to project on to and a screen to create a shadow region in which to see the Sun’s image more clearly.



Other methods

The pinhole method, using a mirror, was employed for the 2004 transit but you need a long, quite dark room. No filter needed.

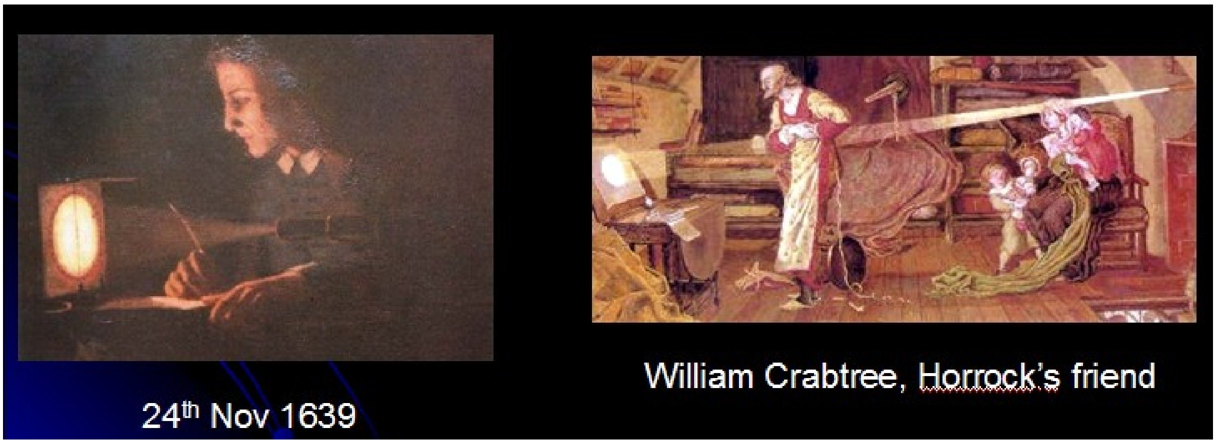
One can also photograph with a camera but you do need a solar filter or you’re likely to fry the image sensor.

Public viewing

The University library on Bedford Road. Park nearby. Assemble at 4 am!

Jeremiah Horrocks

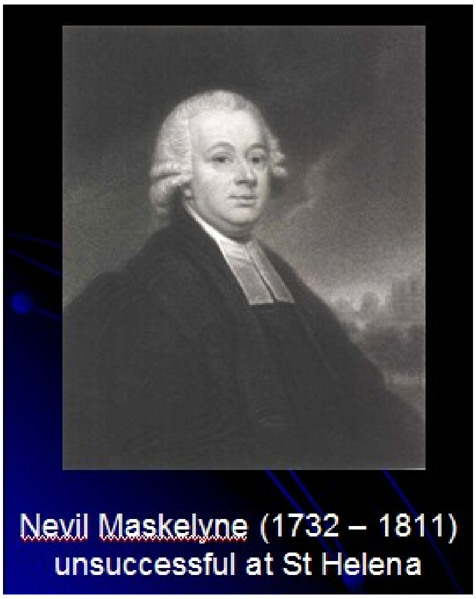
The transit was first observed in November 1639 (old style calendar) having been predicted by a 20 year old astronomical enthusiast, Jeremiah Horrocks, a few months before. Planetary prediction was the subject of the era, a subject that was to separate the old astrology from the new astronomy. In the first quarter of the 17th century, Kepler had produced new planetary



prediction tables based on his new planetary laws of motion. Horrocks became one of the first enthusiasts for Kepler's laws in England and noted that Kepler had predicted a transit of Venus in 1631 that no-one had seen, partly because Kepler had died the year previously. Kepler hadn't predicted the 1639 transit but Horrocks realised that using Kepler's laws and the data he had available that it would likely occur. He urged his friend William Crabtree to look out for the event and as it transpired these were the only two people in the world who recorded details of the 1639 transit. Remember that this was in the same decade that the Inquisition of the Church of Rome condemned Galileo for even believing in the heliocentric view of the Universe.

He refined the parameters of Venus's orbit needed to make Kepler's tables agree with the observations, notably changing the size of the orbit to a value extremely close to the modern value. He didn't measure the parallax of Venus (you need widely spaced observers to do this and it hadn't occurred to him). Tragically he died little more than a year after his transit observations and in fact it was several decades before Horrock's work was recognised. There is now a memorial tablet to him among the great and the good in Westminster Abbey.

The 6th June 1761 transit

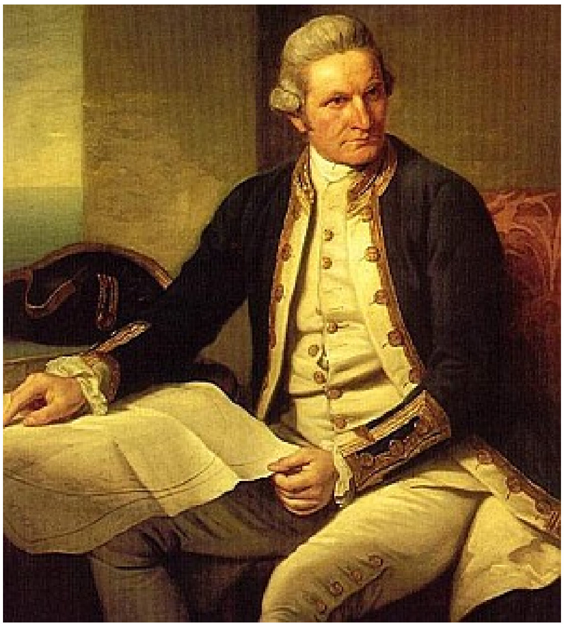


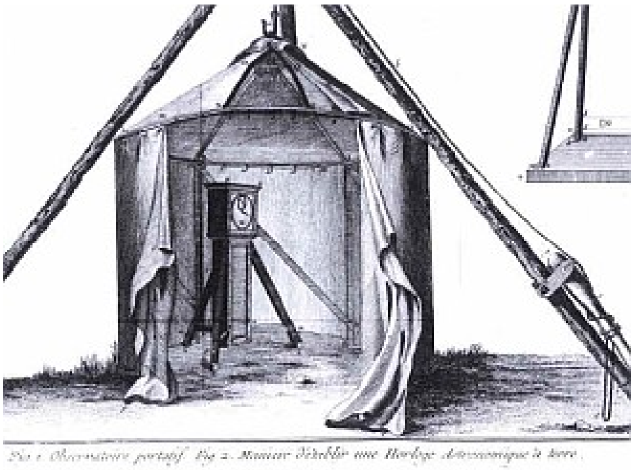
Such was the interest in the 1761 transit, and the hope that observations would nail the AU to much better than 1%, that expeditions were sent out to the 4 corners of the globe, if you'll forgive the mixed metaphor. Nevil Maskelyne, who was to become Astronomer Royal for about half a century, went back to St Helena with a complete set of observing equipment, not apparently having learned Halley's lesson that it was a very cloudy place. He missed the transit. One of the best set of data was that obtained by Mason & Dixon from near Cape Town. They had been dispatched by the Royal Society to Sumatra but after their ship was attacked by the French and they were lucky to escape with their lives, the re-started venture only got as far as South Africa, then in Dutch hands.

Astronomers didn't get the accuracy they were hoping for because of discrepancies in their timings and this turned out to be a real problem in future years. There is a nice story from the

1761 transit that when all the international results were being collected, this effect was conspicuous at all observatories with multiple observers except Greenwich, where the results agreed to within a second. Upon investigation whether the English astronomers had overcome the problem it turned out that 3 timers had been present, with Charles Green as the senior astronomer. When he had said 'now', the others all stopped their watches too, in deference to his seniority - a case of science failing to break free from social constraints.

3rd June 1769





James Cook's great voyage of exploration in the Endeavour from 1768 to 1771 was largely motivated by the desire of the Royal Society of London, his sponsor, to observe the 1769 transit of Venus. Captain Cook and his crew camped for months in Tahiti at what is now called Venus Bay. With his astronomer Charles Green, Cook made good observations. His clock and telescope by Edinburgh man James Short can still be seen in London's Science Museum. Cook's and Green's results highlighted a serious problem with timing the transits that is known as the 'black drop effect'. At ingress, the dark image of Venus appears to get stuck on the edge of the disk of the Sun and then suddenly separate, instead of smoothly crossing the disk. It is a real effect, mainly due to the Earth's atmosphere on the image but not helped by the combined influence of the atmospheres of Venus and the Sun. A similar effect happens at egress, hindering the exact transit timings to the extent that it can make a difference of 15 seconds between different observers at the same site.

David Gill

David Gill was an Aberdonian born and bred, the 3rd generation in the Gill clockmaking and retailing dynasty with a well-known premises in Union Street. He attended James Clerk Maxwell's lectures at Marischal College and during his career in astronomy rose to become one of the world's leading observational astronomers in the 19th century.

Gill under the patronage of Lord Lindsay, owner of the huge Dunecht estate where he had established an observatory as good as any in the world, observed the

1874 transit with Lindsay in Mauritius. This convinced Gill that the transit of Venus wasn't the best observation for determining the Astronomical Unit and more accurate measurements could be made by measuring the parallax of suitable asteroids, without any aid from transits. These came nearer the Earth, they had no atmosphere and they were smaller bodies. Gill's subsequent measurements determined the astronomical unit to much higher precision than any transit measurements and his result became the international standard until the modern era.

The Maritime Museum here is planning an exhibit to celebrate the life and work of David and Isobel Gill in 2014, the centenary of David Gill's death.

Movies

The well-known magazine *Sky & Telescope* have animated a set of glass-plate slides of the 1882 transit.

The Belgian movie shows the 2004 transit.

The 'impromptu' movie was made in Switzerland by an amateur with a domestic video camera and a solar filter. It shows clearly the shimmer on the Sun's image and the kind of resolution one is likely to get from an 'ordinary' camera.

Extra-solar planet transits

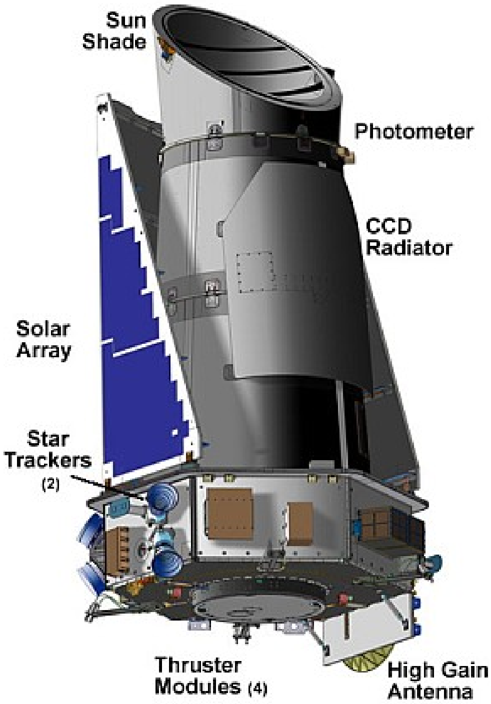
Transits are back in astronomical fashion. The reason is that by observing a regular dip in light from a distant star, one can infer the passage of a planet in front of the star.

If you were an alien near almost any of the stars visible in our night sky, you wouldn't detect any planets around the Sun by this method because it's necessary to be almost in the same plane as the orbit of the planet. If you were rightly placed for Venus, for example, you'd see the light from the Sun being dimmed by about 0.1% for a period that depended on exactly how the transit was placed. This would vary from about 11 hours for a transit across the Sun's diameter to a small dip if Venus clipped the top or bottom of the Sun

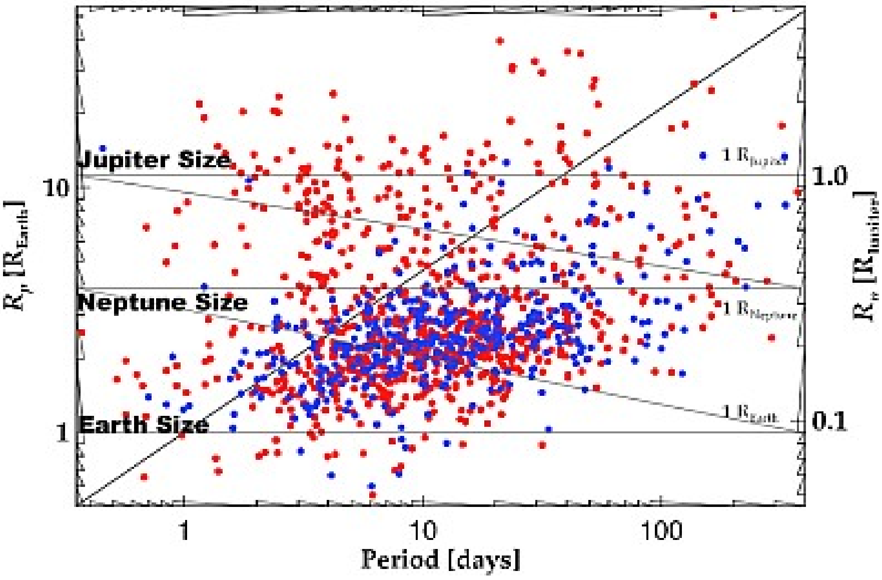
The Kepler mission

The Kepler mission is at the forefront of modern astronomy and is telling us of the existence of many, many planetary systems around other stars, just using the transit method.

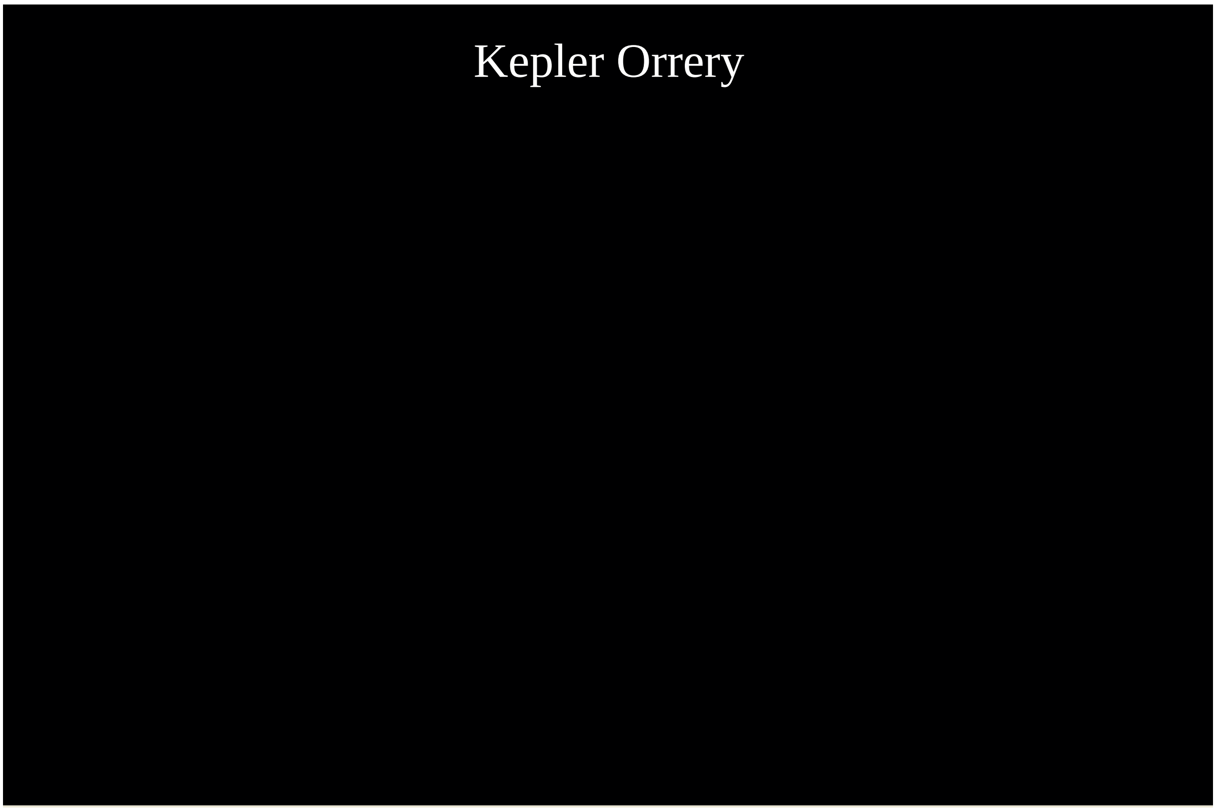
It consists of a very respectable 1.4 m telescope in orbit around the Sun, staring unblinkingly at a small region in the northern hemisphere constellation of Cygnus, measuring precisely the starlight received from some 100,000 stars. The background image on the slide shows some of the Kepler field of view taken from the probe. The ~100 Mpixel camera is extremely stable and can measure light intensities to at about 1 part in 100,000.



Kepler results



There have been more planetary systems discovered than anyone thought was likely; many more multiple planetary systems discovered. No-one could discover the 8 planets in our solar system by this method because the planetary orbits are tilted with respect to each other. For the method to work for multiple planetary systems, the systems must be very flat and we must see them edge on. 48 planetary candidates are shown in this diagram.



Detecting exo-planets by transit was a rarity in 2004. Now it is a frontline topic in astronomy. There is only one planet with an atmosphere that transits the face of our Sun – Venus. This is astronomers' only opportunity to see how much information can be found out about a transiting planets atmosphere by observing a transit. There is more astronomical excitement about the 2012 transit than the 2004. The Kepler orrery (animated) can be found at *http://kepler.nasa.gov/news/nasakeplernews/index.cfm?FuseAction=ShowNews&NewsID=128*

And now for tomorrow's transit

No-doubt there will be more on this and other modern interests in the BBC 2 Horizon program at 10 pm tonight.

After that, set your alarm for a very early rise, to see the spectacle live, either first-hand or on the internet. 400 years ago no-one had enough knowledge of planetary motions to even predict such a transit on time. Now I'm confident our knowledge is good enough to be on time to a fraction of a second but it's always good to see for ourselves that nature is working as we think it should. This transit in particular has a lot of history associated with it and it's not finished yet. I hope you enjoy it. You'll never get another chance.

JSR June 2012

Postscript

A vigorous low pressure are with associated thick cloud and rain-band passed across the country that night and over the following day so the Transit of Venus was not only clouded out here in Aberdeen but over much of the UK. There were, though, live TV broadcasts from more favourable sites from North Finland to the Pacific. The parallax between images from N. Finland and Hawaii was quite noticeable as was the timing of the finish of the transit between the two sites.