The Human Orrery

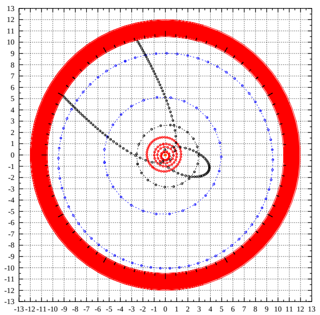
"Everything should be made as simple as possible, but not simpler."

Albert Einstein[1]

What is an Orrery?

An orrery is a dynamic model of the solar system: a simple 'planetarium' designed to show the positions, relative orbits and distances of the planets about the Sun. It can be used to show the orbital periods of objects revolving around the Sun, and to illustrate phenomena such as planetary alignments, conjunctions and transits. It can also be used to explain the laws of orbital mechanics and to show these laws in action.

The Human Orrery is located to the south-east of the main Observatory building. It shows the orbits of the first six planets from the Sun, the asteroid Ceres and comets Halley and Encke. All these objects are visible from Earth at various times. A key feature is that the orbits are shown on the ground with precision, on a scale of one metre to the *astronomical unit* (AU), or approximately 1:150,000,000,000. It shows the relative positions of the planets at any given time, and where they appear in the sky.



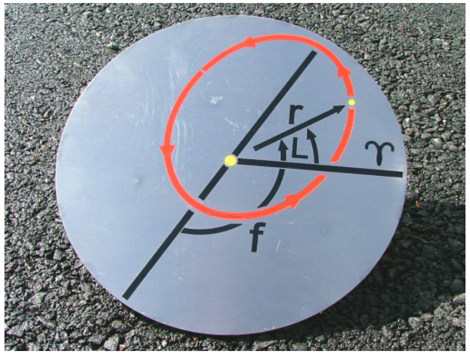
The Human Orrery (scale in metres). The positions of the orbital tiles for the terrestrial planets, the asteroid Ceres, the outer gas giants, Jupiter and Saturn, and two comets (Encke and Halley). The outer annulus, marked in red, provides a scale of ecliptic longitude, and indicates the directions to more distant objects.

A special feature of this scale model is that it opens the door to understanding the motion of celestial bodies and the Earth's changing position in space. A two-dimensional model is possible because all the objects shown here move in roughly the same orbital plane as the Earth, called the *Ecliptic*.

[1] 1879–1955. German physicist. Nobel Prize for physics 1921.

Sun Tile

The easiest activity is to reproduce the motion of the planets about the Sun, moving from one tile to the next at strict 16-day intervals. This is known as *Walking the Orrery*. To get your bearings, first find the Sun tile. This is located at the centre of the orrery (see Figure). The yellow dot on the Sun tile represents the size of the Sun on the same scale as the model.



The Sun tile. This provides a key to the information on the orbital tiles and shows the direction of the First Point of Aries.

The position of any object on our map can be obtained from its distance r from the Sun, measured in AU, and one of two angles. The first, known as *ecliptic longitude* (L), is analogous to a compass bearing, except that it is measured anticlockwise from a fixed point known as the *First Point of Aries* (Υ). This is the direction towards the Sun as seen from Earth at the Spring equinox (currently March 20). On the Human Orrery, Υ (i.e. $L = 0$) lies towards the centre of the Robinson Dome.

The second angle is known as the *true anomaly* (f). This is the angle to the object, measured around the orbit, from the object's *perihelion*, the point closest to the Sun. Looking down on the solar system all the planets revolve anticlockwise. The only object shown on the Human Orrery that revolves in the opposite 'retrograde' sense is Halley's comet.

Standing at the Sun tile, you will notice that the orbits of the surrounding bodies are not perfectly circular — they are actually *ellipses*, which are oval-shaped. A circle is a special type of ellipse. Some of the planets, such as Venus, have nearly circular orbits; others, like Mercury, have more eccentric elliptical orbits, placing them noticeably closer to the Sun at perihelion than elsewhere.

The comets move on highly eccentric ellipses — especially Halley's comet, which swings close to the Sun approximately every 76 years before being flung far beyond the inner planetary region. The discovery of elliptical orbits is associated with the name of Johannes Kepler (1571–1630), who formulated three laws about them — Kepler's laws — which are described in a separate leaflet. Kepler's *first* law refers to the elliptical shapes of the planetary orbits.

Walking the Orrery

Now find the Earth's 'zero' tile (marked with a '0'). The zero tiles for the planets and Ceres represent their positions at 2005 January 1. The zeroth tile for Comet Halley shows its position at perihelion on 1986 February 9, whilst that for Comet Encke (2003 December 30) is not shown as it lies beneath Mercury's 5th tile.

Each tile displays seven pieces of information: the symbol and name of the object; the tile number (showing how many 16-day time steps have passed from the zero time); the date when the object is first at that tile; and its position in terms of ecliptic longitude, distance from the Sun and true anomaly. In astronomy, calendar dates are shown in descending order from year to month to day, after which can follow hours, minutes and seconds.

Two orbital tiles. Values of L, r and f for Mercury and Earth are shown at the given dates.

Now find the Earth's next tile, numbered '1'. You have travelled 16 days along the planet's orbit, which defines our nearly $365\frac{1}{4}$ day year. As you move anticlockwise towards successive tiles, you follow the Earth's track during 2005 (or any other year).

You can now walk the orbits of the other planets. For the inner planets — Mercury, Venus, Earth and Mars — each tile represents a 16-day time-step. For the comets on their eccentric orbits, and the asteroid Ceres, the intervals are 80 days (5×16), while for Jupiter and Saturn they are 160 days (10×16).

The more distant objects require longer time-steps because they move around the Sun more slowly owing to the weaker gravity (or curvature of space in modern terms) at greater distances from the Sun. Kepler's *second* law describes how their speeds are such that they sweep out equal areas of their orbit in equal times.

The result that objects move more slowly when farthest from the Sun (i.e. at the *aphelion* points of their orbits) also explains why Comet Halley spends just six months of its 76-year orbit within the region of the inner planets, and the rest of the time in the far reaches of the planetary system. Kepler's *third* law describes the relative orbital periods of the planets about the Sun, and explains mathematically how the orbital period of any object depends on its average distance from the Sun.

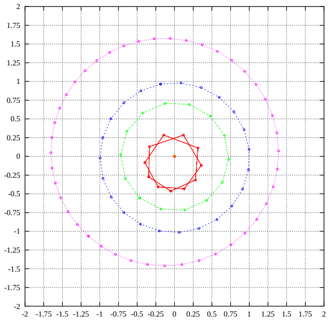
If several people walk the Orrery in lockstep, one can immediately see the different speed of each planet in its orbit. One person can call for the others to move at regular time-steps. The inner planets should move one tile at every call, the asteroids and comets at every fifth call and the outer planets every tenth call. Little Mercury whizzes round, while Mars, Jupiter and Saturn move at a crawl.

This shows the differing lengths of a ‘year’ for each body, the year being the time for the object to orbit the Sun. The greater the average distance of an object from the Sun, the longer its year. Mercury revolves around the Sun once every 88 Earth days, while Saturn takes almost 29.5 Earth years. The orbit of Halley’s comet is not fully shown because it moves so far from the Sun. Its year lasts for 76 Earth years.

Another activity is to locate the position of the Earth and planets at today’s date. Just stand on the Earth tile and look away from the ‘Sun’ to identify which planets are visible in the night sky. Check your result the next clear night. You can also turn round and look back towards the Sun tile in order to identify whether Mercury and Venus might be visible as morning or evening stars, either to the right or left of the Sun respectively.

Leap Steps

Can you spot a slight inaccuracy in the Human Orrery? Look at the number of tiles marking the Earth’s orbit. If each tile represents a 16-day interval and it takes 23 steps to complete one orbit, then Earth’s year is 368 days long, not $365\frac{1}{4}$! Following Earth’s orbit from one tile to the next for several revolutions produces an inaccuracy that grows by almost three days per year.



The orbits of the inner planets. Two full revolutions are shown for Mercury, the tiles for one being interleaved with those of the other. Surrounding Mercury are the orbits of Venus, Earth and Mars, the other terrestrial planets.

A similar ‘error’ occurs for all bodies. There is no single time-step that perfectly suits all the objects; and multiples of 16 days were chosen because this is a convenient whole number that results in the smallest errors overall.

The errors for Mercury’s orbit have been reduced by choosing 11 tiles to represent precisely two revolutions of this planet, whose orbital period is almost exactly 88 days. As with the other planets, you walk this orbit by proceeding numerically from tiles labelled $0 \to 1 \to 2$ and so on, but in this case each time you reach the zeroth tile you will have completed two trips around the Sun. With this arrangement, Mercury’s position is given with reasonable precision for up to 520 revolutions.

The remaining error in the Orrery can be reduced by using the method of ‘leap steps’, analogous to the insertion of a leap day in our modern calendar. Since the Earth has a year almost three Earth days shorter than 23×16 days, a person walking the Earth’s orbit at strict 16-day time-steps will return to the zeroth tile after 368 days, therefore falling behind where they should be. Every sixth orbit, once an error of approximately $16\frac{1}{2}$ days has accumulated, they must move one extra step to reduce the error.

This is a leap step. It brings the user to approximately half a day away from the correct position. After a further 6-year period, and another leap step, the accumulated error is about a day, and so on. After 27 such leap steps (or 162 orbits) the user must take a double leap step to bring the Human Orrery and the real Earth back into agreement with each other. Mercury and Mars require leap steps like the Earth (after 520 and 16 revolutions, respectively), whereas Venus, Ceres, Jupiter and Saturn require ‘leap stops’, which necessitate standing still for one turn, after 23, 50, 13 and 4 revolutions respectively.

The idea of the leap step is the same as that for the leap day, February 29, used in our modern calendar every four years. Like our leap steps, this system is not perfect and the leap day has to be omitted every 100 years (e.g. 1900) unless it is divisible by 400 (e.g. 2000), which is why 2000 was a leap year. In this case we are correcting for the fact that the year based on the Spring Equinox (currently March 20) comprises 365.2424 days.

The Human Orrery can thus be used to identify the planetary positions with reasonable accuracy for many years either side of the present. Such leap-step corrections are only necessary if you want to find the exact positions of the planets at times far removed from the present day, perhaps at some interesting date in history, or when you were born.

It is interesting to note that the motions of the solar system (for example, the rotation of the Earth on its axis and the period of its orbit about the Sun) define our days and years. There is no reason why these independent periods of time should fit together as neatly as the mechanisms of our modern clocks and calendars which try to imitate them.

Glossary of Terms

Aphelion: The point in its orbit where a body is farthest from the Sun.

Astronomical Unit: A yard stick for measuring solar system distances. It is almost exactly the average distance between the Earth and the Sun, approximately 149.6 million kilometres.

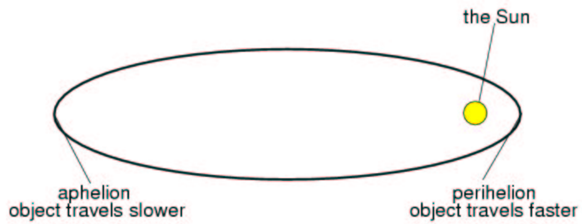
Conjunction: A coming together of two or more bodies in the sky as seen from a separate location.

Eccentricity: A measure of how stretched an ellipse is. The eccentricity of an ellipse lies between 0 and 1, where 0 represents a perfect circle and 1 represents the transition to an open orbit called a parabola. The planets are on fairly circular orbits, but asteroids and especially comets often have highly eccentric orbits. Encke has an eccentricity of 0.847, and Halley an eccentricity of 0.967.

Ecliptic: The plane of the Earth’s orbit around the Sun, and therefore the path in the sky followed by the Sun against the distant stars.

Ecliptic Longitude: Analogous to longitude on Earth, the ecliptic longitude is measured anticlockwise along the ecliptic from the First Point of Aries to the projection of a line from the Sun to the body.

Ellipse: Bodies that orbit the Sun under gravity mostly follow elliptical paths with the Sun at one focus of their orbit.



The elliptical orbit of an object about the Sun. The object is shown at perihelion and aphelion and the Sun lies at one focus of the ellipse.

First Point of Aries: The direction of the Sun as seen from Earth on the Spring Equinox (March 20). In the Human Orrery, the direction of the First Point of Aries, ♈, is towards the Robinson Dome.

Perihelion: The point in its orbit where a body is closest to the Sun.

True Anomaly: The angle, measured in the direction of a body’s motion along its orbit, between the perihelion and a line from the Sun to the body.

Transit: The passage of a body in front of a larger one, as seen from a third location.

The Transit of Venus across the Sun on 8th June 2004. Image taken by Mark Purver at 7 a.m. from Nottingham, England.

This is the first of a series of leaflets on the Human Orrery, edited by David Asher, Mark Bailey and Apostolos Christou. Astronomy at Armagh Observatory is supported by the Northern Ireland Department of Culture, Arts and Leisure (DCAL). Production of this leaflet was supported by the UK Particle Physics and Astronomy Research Council.

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