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Ground-based astronomy for all

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The Human Orrery: Ground-based astronomy for all

Mark Bailey, David Asher and Apostolos Christou describe an interactive, open-air model for explaining the motions of the planets and the position of the Earth in space, which was formally opened at the Armagh Observatory on 26 November 2004.

Abstract

The Armagh Observatory Human Orrery is the first major addition to the Observatory grounds and Astropark for more than a decade. This is believed to be the first large outdoor exhibit designed to show with precision the elliptical orbits and changing relative positions of the planets and other solar system bodies versus time. The Human Orrery provides a dynamic map of the positions and orbits of the six classical planets, an asteroid and two comets, as well as an indication of the 13 zodiacal constellations through which the Sun passes in the course of a year, and pointers to more distant objects in the universe. This article describes the key features of its design and construction, and indicates how educators may use the exhibit as an innovative tool to communicate astronomy, mathematics and space science to people of all ages.

1: Charles Boyle (1674–1731), the Fourth Earl of Orrery, possibly after Charles Jervas (1707). (Image © National Portrait Gallery, London)

Nowadays almost everyone is taught that our home, the Earth, is just one of nine planets orbiting a fairly average star, that it spins on its axis once per day, and that it revolves around the Sun in a year of 365.25 days. By contrast, the Earth appears to be very much at rest, located at the centre of a fixed celestial sphere on which are set untold thousands of stars and galaxies, with the other planets wandering along roughly parallel paths to the Sun, tracing out the zodiacal belt.

This "geocentric illusion" is hard to overcome. Four hundred years ago religion played a part in the debate, with Martin Luther (1483–1546) reported to have described Copernicus as this "new astrologer", saying: "The fool will overturn the whole science of astronomy. But, as the Holy Scriptures state, Joshua bade the Sun stand still and not the Earth." Even such an eminent figure as Galileo could be threatened with torture for promoting an alternative heliocentric world-view. And nowadays, despite impressive progress, there remain gaping holes in many people's understanding of space and of the Earth's place in the solar system.

The problem can be illustrated by asking a simple question: "How far can you see on a clear day?" People worry whether the answer is 10 or 20 miles, or perhaps 200 miles to the contrail of a distant aircraft. Relatively few people immediately grasp that the answer is 93 *million* miles, the distance to the Sun; fewer still realize that on a clear night one can often see as far as 2 million *light years*: to M31, the nearest major galaxy to our own Milky Way.

Similarly, while we can hardly fail to notice that winter mornings in the northern hemisphere remain dark for a surprisingly long time after the solstice, few of us understand why. And we notice that the change of the seasons brings a welcome change to the familiar pattern of stars visible in the evening sky, but we are surprised by the different appearance of the morning sky before dawn. By the same token why does the Moon, or a prominent planet, sometimes appear high in the sky when at other times it seems barely to rise above the horizon?

These and other changes in the sky are related to the orbits of the planets and the movement of the Earth in particular. But because we appear to be at rest, it takes imagination to realize that our conventional frames of reference are like the marks on a spinning disc on a roundabout.

Thus, when addressing questions concerning the Earth's position in space, such as "Where are we today?" or "In which direction is the Sun?", it is hardly surprising that most people fail to get off first base. Not only are we unaware of the Earth's movement, but we have a bias towards a geocentric point of view that is difficult to shift.

The Orrery

An orrery is a simple "planetarium": a mechanical or digital model designed to illustrate the motion of the planets around the Sun and their changing positions in the sky. The first example, invented some 300 years ago, was an attempt to dispel the geocentric illusion in an entertaining way, and to introduce what then was still a relatively new idea: that the Earth and planets revolve around the Sun with essentially clockwork precision. An important function of a planetarium, therefore, is to correct the geocentric illusion. But when visitors take their comfortable seats near the centre of a modern dome, their first impression is precisely the opposite! When astronomers, and those who teach the subject, find it so difficult to eschew the older view of the world, who are we to criticize others' lack of understanding?

In this way, although the Sun can be seen on any clear day, and the planets and stars similarly at night-time, it remains remarkably difficult for people to appreciate that these objects – mostly mere points of light – are distant, three-dimensional objects in a vast universe. The main purpose of an orrery is to provide a visual, dynamic model of the solar system; likewise, the Human Orrery (figure 4). It should also be fun to use: a "toy" with the capacity to present fundamental ideas in astronomy, mathematics and space science to as wide a range of people as possible.

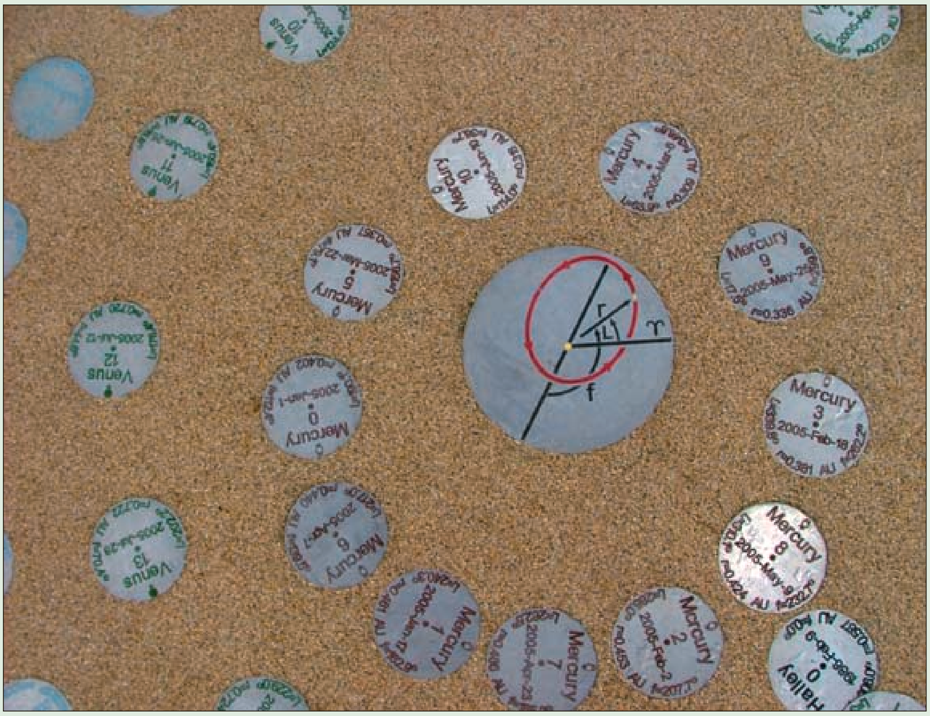
Charles Boyle

It is accepted that the first orrery was invented by the English clockmaker and inventor George Graham (c.1674–1751) around 1704. Perhaps

Orreries Old and New

2 (top): One of the first orreries ever made, this device was the first to be called an orrery. It was commissioned to John Rowley by Charles Boyle, the Fourth Earl of Orrery, c.1712, and presented to his son John (later the Fifth Earl of Orrery). (Image © Science Museum, London)

3 (above): Brass orrery by Gilkerson and Co., Tower Hill, London (c.1810), in the archives of the Armagh Observatory. (Image by Miruna Popescu)



4 (right): Aerial view of the centre of the Human Orrery at the Armagh Observatory, including the Sun-tile with key.

an orrery should be called a "Graham", but the word does not slip so lightly off the tongue, and the first example was in any case only a simple model showing the Earth–Moon system orbiting the Sun. Graham gave the first model (or its design) to the celebrated instrument maker John Rowley of London to make a copy for Prince Eugéne of Savoy. Rowley was then commissioned to make another copy (figure 2) for his patron, Charles Boyle (1674–1731), the fourth Earl of Orrery (figure 1), and this was presented to his son, John, later the fifth Earl.

Charles Boyle was a member of the extraordinarily gifted Boyle family, the grandson of Roger Boyle (1621–1679), the first Earl of Orrery, who was a son of Richard Boyle (1566–1643), the first (or Great) Earl of Cork. Richard Boyle was a self-made man, originally from

5: David Asher "walking" the Dynic Astropark Orrery, near Kyoto, Japan, around the time of the 1997 IAU General Assembly. Bill Napier, in the background, is pretending to be a massive Centaur: a planet-crossing comet heading towards an unsuspecting inner solar system. Here, a suboptimal 11-day time step was chosen, and the planetary orbits were taken to be circular.

6: The Human Orrery under construction during July 2004, looking northwest towards the main Observatory building with the Robinson Dome on the left. Shown (left to right) are Bertie McClure, Apostolos Christou, Mark Bailey and Philip Miller. (Image by Miruna Popescu)

Canterbury, Kent, who, it is said, rose from humble origins to become one of the richest men on the planet. Another of the Great Earl's sons was Robert Boyle (1626/1627–1691), the famous "philosopher" Boyle: the father of chemistry and a founding member of the Royal Society of London.

Charles Boyle was primarily an author, soldier and statesman, but his patronage of Rowley led to Graham's invention becoming much more widely known and to its elaboration to show all the known planets, and some moons, of the solar system. One such rests in the archives of the Armagh Observatory (figure 3). The name "orrery" for such a dynamic model of the solar system was popularized by the Irish essayist Sir Richard Steele (1672–1729), and the moniker has since been attached to any device designed to show the planetary motions.

The Human Orrery

In the Human Orrery people play the role of the moving planets. Users gain a better understanding of the principal parts of the solar system (Sun, terrestrial planets, outer planets, asteroid belt and comets) through games and activities. They are immediately presented with the elliptical orbits of the various objects and their different speeds around the Sun, as well as their differing directions in space as seen from the Earth, the Sun, or any other point in the model. An early example of a Human Orrery, although not laid out with the precision of the one at Armagh, is that constructed a decade ago at the Dynic Astropark, near Kyoto, Japan (figure 5). The Human Orrery allows activities such as establishing Kepler's laws by direct measurement, and the introduction of concepts such as planetary alignments, conjunctions and transits. The disposition of the planets at any date in history can also be used to discuss concepts such as leap years and Gregorian calendrical reform.

Design and construction

The Armagh Human Orrery lies close to the main Observatory building, between the Robinson Memorial Dome and the library (figure 6). The base is compacted hardcore covered with bit-mac, while the orbital tiles and other fixtures are embedded in a top layer of fine, resin-bonded gravel. The model (figure 7) is 25 m across and shows the six classical planets, the main-belt asteroid 1 Ceres and the two comets 1P/Halley and 2P/Encke. It contains more than 200 individually engraved orbital tiles that show the positions of each object at fixed 16-day time steps or multiples thereof.

Each tile is placed with a precision better than 1 cm. This means that the elliptical shapes of most of the planetary orbits and the slowly changing distances between adjacent tiles for a single object can be seen at a glance. The perhaps surprising result that Earth-crossing comets spend less than half a year within the orbit of Mars can also be obtained simply by inspection of the orbits of the two very different comets.

The scale of the model, one metre per astronomical unit, or 1:150 billion, was primarily determined by the available space, although factors such as cost, tile size and tile spacing were important considerations. On this scale the diameter of the Sun, indicated by a yellow disc at the centre of the "Sun-tile", is 0.93 cm. Each orbital tile, and the 32 cm diameter Sun-tile in the middle of the orrery, was fabricated by welding together two 3 mm thick stainless steel discs. The back-plate holds a fixing that enables the tile to be permanently secured to the ground. The upper plate has information cut with a high-pressure water jet. The Sun-tile's information consists of a schematic elliptical orbit that acts as a key to data on the surrounding orbital tiles. These show the position of each object at various fixed time steps from the object's zero tile, which in most cases corresponds to 1.0 January 2005. This start-date was chosen because 2005 is around the 300th anniversary of Graham's invention of the first orrery.

The tiles for the terrestrial planets, asteroid and comets have a diameter of 16 cm, while those for the gas giants (Jupiter and Saturn) have a diameter of 32 cm. The information on each orbital tile includes the astronomical symbol and name of the object, its tile number (starting with zero to represent the position at the object's start-date), the calendar date in the international standard format, the ecliptic longitude L (measured anticlockwise from the direction of the first point of Aries), the distance r from the Sun, and the true anomaly, f.

Time steps

One of the original ideas of the Human Orrery was to encourage friends or a family group to play the game of "walking the orrery". People walk around the orbits at a steady pace, moving from one tile to the next and demonstrating the different distances travelled by the different planets during a given, fixed time interval. The time steps can be called out by a group leader, and the steps on the ground should be such as to bring the "planet" back to its starting position after an integral number of steps, corresponding to the number of tiles for the given planet.

However, because no single time step is exactly commensurate with the number of days in every object's year, a planet's position as given by its tile number will eventually drift ahead of or behind its "true" position. Thus, in order to keep a planet's modelled position in line with its true position (i.e. as determined by its ecliptic longitude at that time), a person stepping forward at fixed time steps from one tile to the next must remember to take an extra step (a "leap step", analogous to a leap day in the calendar) or to skip a step (a "leap stop") after a certain number of revolutions.

The choice of time step, in this case 16 days, is a key factor in the accuracy of the Human Orrery. In order to avoid frequent leap steps (or leap stops) for the fastest moving planet, Mercury, it is necessary to choose a time step that is a simple fraction of Mercury's orbital period of 88 days. This suggests the possibility of 11 tiles at eight-day time steps, or 8 tiles at eleven-day steps. However, the former requires an excessive number of tiles for the other planets, whereas the latter provides a suboptimal solution to the leap-step problem.

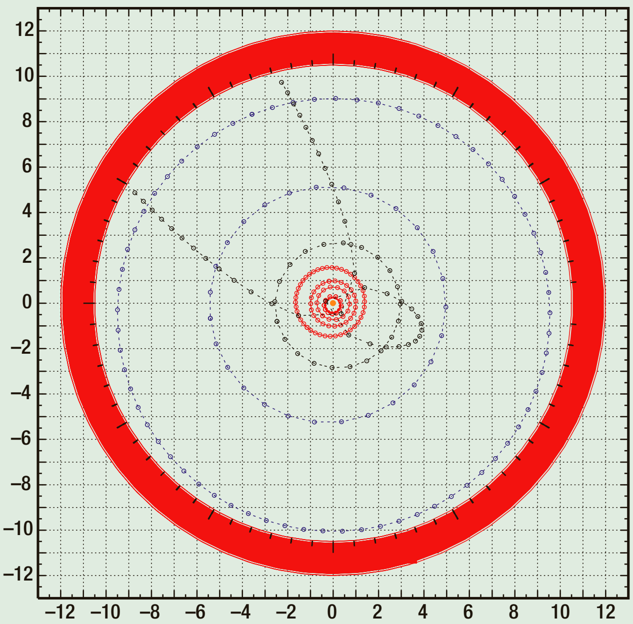
In the event, we chose 11 tiles to describe the orbit of Mercury, labelled 0, 1, 2, ... 10, but placed them at 16-day time steps to represent precisely two revolutions of the planet about the Sun. The adopted 16-day time step minimizes the accumulation of errors for this fastest moving object while also providing a suitable minimization of errors for the model as a whole.

For objects other than Mercury, returning to the zeroth tile indicates the completion of one revolution or "year" for that object. The orbits of Venus, Earth and Mars have 14, 23 and 43 tiles, while Jupiter and Saturn, marked at 160-day intervals, have 27 and 67 tiles respectively. Ceres has 21 tiles, spaced at 80-day intervals. The comets 1P/Halley and 2P/Encke are also marked every 80 days, but for these bodies the zeroth tile corresponds to their most recent perihelion passage, 9 February 1986 and 30 December 2003 respectively.

With these time steps, the least accurate example is the Earth, where one has to take a leap step every six revolutions, equivalent to six Earth years. By contrast, Mercury remains close to its true position for approximately 520 revolutions, or 125 Earth years, after which a leap step should be taken to maintain accuracy. Similarly, the longitudes of Venus and Mars are well determined for 14 and 30 Earth years respectively. Venus requires a leap stop once every 23 revolutions, while a leap step must be taken every 16 revolutions for Mars. The other objects all require leap stops, i.e. skip a step for Jupiter and Saturn once every 13 and 4 revolutions respectively, and for Ceres just once every 50 revolutions, or 230 years.

Thus the Human Orrery is remarkably accurate. A group "walking the orrery" in lockstep needs to introduce only very minor corrections to the positions of Earth and Venus over a timescale equivalent to the orbital period of Saturn (about 30 years). If further minor corrections are made (corresponding in calendrical terms to the change from the Julian to the modern Gregorian calendar), the orrery can be used to show the relative positions of the planets with precision for many centuries into the past or future.

7: The orbits of the six classical planets, two comets (1P/Halley and 2P/Encke) and the main-belt asteroid 1 Ceres. Tiles are placed on the ground at 16-day intervals for the terrestrial planets (Mercury, Venus, Earth and Mars), at 80-day intervals for Ceres and the comets, and 160-day intervals for Jupiter and Saturn.



Calendars

Although the Human Orrery is primarily a tool to explain astronomy, questions of distance-scales, timescales, and the dynamics and spatial relationships between solar system bodies lead naturally to considerations of the calendar, the seasons, the equation of time, and the precession of the equinoxes. In particular, the problem of identifying the positions of planets at times far removed from the present inevitably introduces questions concerning the reckoning of time and whether the date is recorded on the Julian or Gregorian system, or some other scheme. The Battle of the Boyne, for example, commemorated by Orangemen on 12 July, actually took place on Tuesday 1 July 1690 in the Julian calendar and on 11 July in the modern Gregorian system. The 12th is celebrated largely because of the more important Battle of Aughrim, Galway, which took place on 12 July 1691 on the Julian system, and the two are celebrated together. The excellent book *Marking Time*, by Duncan Steel, tells how societies have striven to develop an ever more perfect calendar.

Thus, rather than being just a two-dimensional map, the Human Orrery introduces the further dimension of time. It allows people to gain a deeper appreciation of issues ranging from the equation of time, to how historians and astronomers identify chronologically distant events and how modern calendars differ from their historical counterparts.

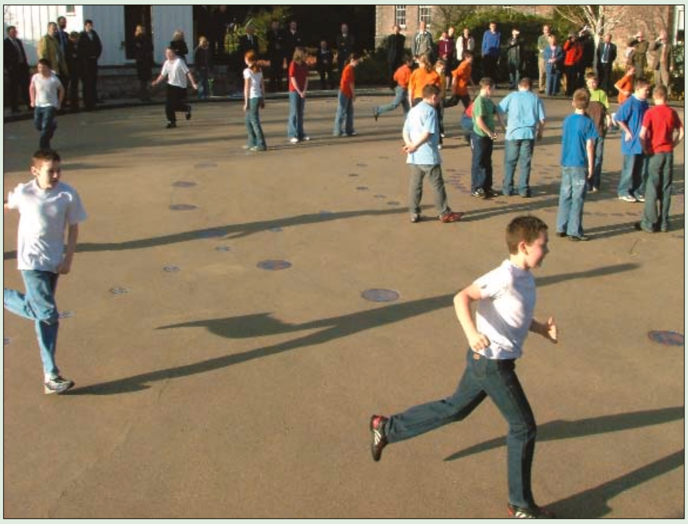
The wider universe

The region beyond Saturn is bounded by a circular path, shown red in figure 7, which is enclosed by two annuli. These are made from stainless-steel segments, each several metres long and 20 cm wide, fabricated similarly to the orbital tiles. The inner annulus contains a scale of ecliptic longitude, the First Point of Aries, and the names of the 13 ecliptic constellations traversed by the Sun in the course of a year. It also shows the constellation boundaries. Moving anticlockwise in the direction of increasing ecliptic longitude from the First Point of Aries ($L = 0$), which lies in Pisces, one first enters Aries at 28.687°, and then Taurus at 53.417°, Gemini at 90.140°, Cancer at 117.988°, Leo at 138.038°, Virgo at 173.851°, Libra at 217.810°, Scorpius at 241.047°, Ophiuchus at 247.638°, Sagittarius at 266.238°, Capricornus at 299.656°, Aquarius at 327.488°, and finally Pisces at 351.650°. It is obvious, but nonetheless instructive, to note that the First Point of Aries currently lies in Pisces, that the Sun passes through 13 "zodiacal" constellations, and that the traditional 12 zodiacal constellations are not uniformly spaced.

Similarly, the outer annulus contains pointers or "signposts" to the current positions of Uranus, Neptune, Pluto and the recently discovered outer solar system object 90377 Sedna. Also shown are directions to various stars, nebulae and other objects in the universe that happen to lie close to the ecliptic. These include a gravitational lens in Pisces; galaxies such as M74 (Pisces) and M87 (Virgo); the quasar 3C 273 (Virgo); the Sagittarius dwarf elliptical galaxy; stars such as Hamal (Aries), Castor and Pollux (Gemini), and 55 Cancri (Cancer); the exceptional X-ray source Sco X-1 (Scorpius); and the enigmatic Sgr A* (Sagittarius) found at the centre of our galaxy.

In this way the outer annulus can be used to explain which stars can be seen "tonight" (or indeed at any other time), or to open people's

THE OPENING OF THE HUMAN ORRERY



8: Children from the Armstrong Primary School performing the *Dance of the Planets* choreographed by Jennifer Rooney, at the opening of the Human Orrery on 26 November 2004. (Image by Miruna Popescu)

9: At the opening of the Human Orrery (left to right): Ignacio Ugarte Urra, Babulakshmanan Ramachandran, Timur Şahin, Apostolos Christou, John Campbell (Deputy Mayor, Armagh City and District Council), Mark Purver (University of Nottingham), Stephen Leighton (Observatory Architect), Miruna Popescu, Brendan Owens (Dublin City University), David Asher and Mark Bailey. (Image by Philip Wilson)

eyes to the diversity of objects in the universe. Similarly, the 13 ecliptic constellations provide opportunities to introduce concepts such as the historical development of modern astronomy and its divergence from horoscopic astrology, as well as the precession of the equinoxes and the heliocentric ecliptic coordinate system.

Activities

The Human Orrery lends itself to various games and activities. For example, the game of "walking the orrery" in lockstep immediately shows users that the planets move at different speeds, and that the fastest lies closest to the Sun. Similarly, the speeds of the planets in different parts of their orbits can be measured and compared with results from celestial mechanics, and the distances from one object to another can be readily determined. In fact, all of Kepler's laws can be rediscovered by direct measurement on the ground, while more advanced students may use the shapes of the orbits to investigate the properties of conic sections.

One simple activity is to locate the position of the planets at today's date. Standing on the Earth-tile, one can look towards the "Sun" in order to identify whether Mercury and Venus might be visible as morning or evening stars, to the right or left of the Sun respectively. Looking away from the Sun immediately shows which planets are visible in the night sky. It is instructive to check the result on the next clear night.

These activities encourage people to look upwards and observe the sky, and help to give a sense of direction in space. Once people have successfully made the connection between what is seen on the ground and what can be seen in the sky, they can develop a deeper understanding of the Earth's motion and position in space.

The orrery can be used to show the relative positions of the planets with precision for many centuries into the past or future

Finally, by choosing appropriate dates one can also explore phenomena such as planetary alignments and conjunctions, and show how these patterns change when seen from another vantage point, for example the Sun or another planet. Users can apply the model to investigate modular arithmetic and the cycles associated with different planetary orbits, for example the near 8:13 commensurability associated with the orbital periods of Venus and the Earth or the 2:5 ratio between Jupiter and Saturn. They can also identify or perhaps discover phenomena such as transits of Mercury or Venus across the Sun.

Extension

The Human Orrery is a novel educational tool, open to elaboration in many different ways. For example, suitably marked lengths of rope can be laid on the permanent exhibit to illustrate the motion of a newly discovered comet or the approach to Earth of a near-Earth asteroid, or even the trajectory of a spacecraft *en route* to a planet, comet or asteroid.

Similarly, versions of the Human Orrery can be constructed in the foyer of a museum or a school assembly hall, or as a piece of kinetic art in a municipal park or garden. In fact, the concept of the Human Orrery is as versatile as a sundial. Once materials have been chosen for its manufacture and the start-date and scale of the model have been determined, the only additional requirements are a table of planetary coordinates, a measuring tape and a means to measure angles. The rest is up to you.

A bonus is that many Human Orrery activities can be carried out as part of a team. For example, people can be encouraged to run the orrery rather than walk it (and how fast can you go?), and the open space and pattern of tiles provide a basis for creativity such as a novel *Dance of the Planets* (figure 8).

Thus the Human Orrery, opened on 26 November 2004 (figure 9), is a dynamic, interactive map of the solar system. It gives users the opportunity, through play, to gain a better understanding of the solar system – represented by the markers on the ground – and its place in the universe – represented by the directions to more distant objects. The Human Orrery helps people obtain a deeper intuitive feel for the relationships between the various celestial bodies, and so keeps science in the public eye, helping – quite literally – to bring astronomy "down to Earth". ●

Mark Bailey (Director), David Asher and Apostolos Christou are astronomers at Armagh Observatory; their main research field is solar system dynamics.

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