Observatory, 126, 236–241, 2006

THE ARMAGH OBSERVATORY HUMAN ORRERY

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Summary of talk presented at RAS Ordinary Meeting, London Friday 13 January 2006

These days everyone is taught the principles of the Earth's place in the Universe: that our planet is one of nine traditional planets orbiting the Sun in the solar system; that its nearly circular orbit lies in a plane (the 'ecliptic') that reflects the path of the Sun in the sky; that the orbits of the other planets lie very close to the same plane; and that the Earth takes a year of 365.25 days to revolve once about the Sun.

Contrast this with the results of casual observation: a planet that is very much at rest; stars and the Sun that appear to circle the Earth every day; and five classical planets that either stay close to the Sun in the sky (as with Mercury and Venus), or move slowly from west to east against the fixed stars, repeating their positions at intervals of several years or more.

The difficulty facing modern educators — one which resonates with one of the biggest paradigm shifts in science — may be described as the 'geocentric illusion'. Indeed, if one abandons the call to a higher authority or arguments by assertion, the points in question are among the hardest to explain in a simple way. As a result, there are many people, perhaps some among this audience, who really have *no idea* of the Earth's position and the positions of the other planets in 3-dimensional space.

The general problem can be illustrated by asking two very simple questions: (1) 'how far can you see on a clear day?'; and (2) 'why do January mornings, as now, remain dark for so long after the winter solstice?'. The answers depend on understanding the Earth's position and orientation in space and knowing a bit about its elliptical orbit around the Sun. Of course, a moment's thought will soon convince you that the Sun is the farthest object normally visible on a clear day, but people often argue whether the correct answer is a few miles — or even a few hundred miles — i.e. to most distant horizontal horizon. In turn, this is a lower limit to the radius of the celestial sphere. Similarly, the correct answer to the second question initially eludes most people, but once they start thinking they soon recall knowledge learned, but not understood, at school. In fact, most of us are natural Aristotelians, and we intuitively think of a geocentric model of the Universe, where the Earth is at rest and where the Sun, planets and other solar system objects move slowly against the fixed backdrop of a more distant 'celestial sphere'.

An orrery, which is a *dynamic* model of the solar system, is designed to help us avoid this mistake, and to explain, in an informative and entertaining way, the heliocentric solar system. The earliest such model was invented by the English clock-maker and inventor, George Graham (c.1674–1751), around (or soon after) 1700. Graham gave a copy of his first model, or its design, to the celebrated London instrument maker John Rowley (1674–1728), later Master of Mechanics to George I. Rowley then made a copy for Prince Eugène of Savoy, and another for his patron, Charles Boyle, the fourth Earl of Cork and Orrery (1674–1731), which he presented around 1712 to Boyle's first son, John (1706/1707–1762), later the fifth Earl of Cork and Orrery. In this way, the device to illustrate the heliocentric model of the solar system received the moniker 'orrery'. The idea was an immediate success, and many variants of the original model were soon under construction.

This brief history shows that there is much more to an orrery than meets the eye. Indeed, one of the more interesting parts of the story is the light that it sheds on the history of these islands and on the society of the day. The Boyle family, for example, has an extraordinarily rich heritage, with roots extending to the first, or 'Great' Earl of Cork (1566–1643). This remarkable individual, apparently a self-made man from Canterbury, Kent, rose from humble origins to become one of the richest men on the planet. Notwithstanding the orrery connection (and his many lifetime achievements), he is nowadays perhaps most widely known through the work of his seventh and youngest son, Robert 'the philosopher' Boyle (1626/1627–1691), the father of chemistry and one of the founding members of the Royal Society. Charles Boyle, although from a later generation, was himself a scholar, soldier and statesman, and grandson of the Great Earl's third son, Roger Boyle (1621–1679), the first Earl of Orrery.

It is interesting to note that Charles Boyle's son, the fifth Earl of Cork and Orrery, subsequently married Henrietta (Harriet) Hamilton of Caledon, daughter of the first Earl of Orkney. He later acquired the Caledon Estate, in 1738, by marriage to the heiress Margaret Hamilton, following Henrietta's death in 1732. Any one of these names could be the point of departure for a piece of historical research in its own right. For those who collect coincidences, Caledon — where I lived for several years — is just a few miles from Armagh; and Henrietta Hamilton is buried near Taplow, Buckinghamshire, close to where I was born!

What then are the distinguishing features of the Armagh Human Orrery? In the first place, it is the first large-scale model of the solar system to have been laid out with *precision,* so that 1 metre on the ground corresponds to 1 AU in space, i.e. to a scale-factor 1:150 billion. This allows you to see at a glance not just the division of the classical planetary system into its two principal components, but also that the orbits are not quite circular, but elliptical. It also allows distances to be measured on the ground and converted accurately to distances in space. The enormous scale-factor reinforces another simple point about the solar system — its size — and means that basic calculators simply run out of digits, forcing students to flex their mental muscles and practice the lost art of mental arithmetic.

Another feature of the Armagh Human Orrery is that the positions of the terrestrial planets are labelled on the ground every 16 days, starting from 2005 January 1. Those for the asteroid (1) Ceres are labelled every 80 days (i.e. every five time-steps); and those for the gas giants, Jupiter and Saturn, every 160 days. The fundamental 16-day time unit was chosen so as to minimize the gradual accumulation of errors in a planet's position over many revolutions. The two comets, 1P/Halley and 2P/Encke, are also shown every 80 days, but with a 'zero' or start-tile corresponding to the time of their most recent perihelion passage.

Even with this optimized 16-day time-step, the positions of the planets on the ground, i.e. as determined by moving from one tile to the next at regular 16-day time-steps, gradually get out of step with the corresponding ecliptic longitudes of the real objects in space. Such deviations can be accommodated by introducing occasional 'leap steps' (taking an extra step) or 'leap stops' (standing still for a step), analogous to the insertion of a leap day into the calendar every four years. With this device the Human Orrery is accurate for many decades either side of the present day. If required, much less frequent double leap steps or leap stops can be introduced for greater accuracy, analogous to the Gregorian reform of the original Julian calendar. However, if one requires the planetary positions at a time far removed from the present day, for example to investigate the triple-conjunction theory of the Star of Bethlehem, it is simpler to compute the exact planetary longitudes for the time in question and convert these to a table of tile positions around the given date. These details provide great scope for advanced algebraic investigations of the orrery, while also introducing some of the intricacies of our modern calendar.

The fixed time-steps also lend themselves to the game of 'walking the orrery', designed to illustrate Kepler's third law. Here, members of a group stand on different planetary tiles, and move forward one tile at a time on the call of the group leader. Mercury whizzes round, while

Venus, Earth and Mars each move more slowly than the one before. In the outer solar system, Jupiter and Saturn move hardly at all, there being 10 time-steps, or 160 days, between each tile on the ground. This entertaining activity brings home to people the speed with which Mercury moves compared to Earth, and shows how the planetary orbital periods vary with heliocentric distance.

The planetary tiles contain various pieces of information, not just the name of the object and the tile number (i.e. the number of 16-day time-steps from the object's zero or start-tile), but the heliocentric distance (in AU), the ecliptic longitude (measured in degrees anticlockwise from the First Point of Aries), and the true anomaly (measured in degrees from the direction of the object's perihelion). This angle facilitates quantitative investigations to confirm the accuracy of Kepler's second law, i.e. the law of equal areas.

Beyond the planetary tiles are two engraved stainless steel annuli. The first of these is marked with a scale of ecliptic longitude l, the direction of the First Point of Aries ($l = 0$), and the names and boundaries of the *thirteen* ecliptic constellations traversed by the Sun in the course of a year. From inspection, it is evident that the First Point of Aries currently lies in the constellation of Pisces and that the ecliptic constellations are of unequal length. This provides a jumping-off point to explain the concept of precession and why the twelve horoscopic constellations are invalid.

The outer ring provides direction pointers or 'signposts' to various objects lying close to the ecliptic in the wider Universe. These include the positions of Uranus, Neptune, Pluto and Sedna on 2005 January 1, several bright stars, the direction of the Galactic Centre, galaxies such as M87, and a distant gravitational lens in Pisces. The outer ring can be used to describe which objects are potentially visible in the sky 'tonight', or at any other time, and to introduce the whole gamut of objects in the modern astronomical 'zoo'.

The wide variety of activities made possible with the Human Orrery include: investigations into which planets are visible in the sky at any time, for example whether Mercury and Venus are morning or evening 'stars', to the right or left of the Sun respectively as seen from the Earth's northern hemisphere; studies of planetary alignments or of planetary positions at the times of particular historical events; investigations into the ratios of the orbital periods of the different planets; calculations of the *speeds* of the planets in different parts of their orbits; and mathematical projects such as testing Kepler's laws, or investigating the properties of ellipses on paper and by direct measurement on the ground.

In short, the Human Orrery is an innovative educational tool with wide-ranging applications for explaining the positions and motions of the planets and other solar system objects with respect to the Earth. 'Learning by doing' helps to instill in people's minds a picture of the heliocentric solar system, and facilitates a deeper understanding of our changing position in space. It helps people to engage with subjects such as astronomy, space science and mathematics, and encourages people to *observe* the sky in order to compare their observations with predictions made from the Human Orrery on the ground. Lastly, it opens the door to many interdisciplinary activities, is easy to make and use, and — like a sundial — can be realized in many different ways.

In conclusion, I should like to thank David Asher and Apostolos Christou for their contributions to bringing the Armagh Human Orrery concept to fruition; the PPARC for seed funding to develop outreach materials for the exhibit; and the Northern Ireland Department of Culture, Arts and Leisure for their continuing support for astronomy at Armagh. More information on the Human Orrery is available at http://star.arm.ac.uk/orrery/.