12. Multiple-planet mandalas

THE IDEA THAT THE Earth was at the centre of the Universe, and that the Sun and planets were all in orbit around it, was central to the views of the ancient Greeks. But in this framework, the motions of the planets (being the Greek for 'wanderers'), was impossible to fathom.

Only with the adoption of the Copernican view, that the Sun was at the centre of the solar system, and that the planets (including Earth) moved in orbit around it, did their motions become possible to comprehend.

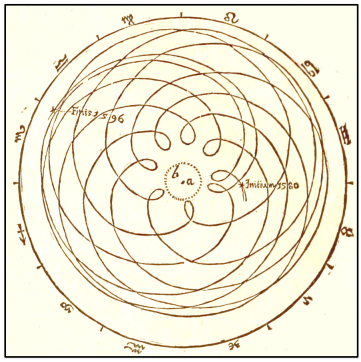
The very complex apparent motions of the planets, as seen from Earth, could eventually be explained by the combination of the Earth moving in an elliptical orbit around the Sun, and the other planets orbiting with slightly different eccentricities. This is because elliptical orbits, with the Sun at one focus, are 'permitted' types of orbit under Newton's inverse square law of gravity.

MORE PRECISELY, planets orbit the *centre of mass* of our solar system, rather than orbiting the centre of mass of the Sun itself. In many case, this (often very small) difference may have no obvious effect. But it will become relevant with high-accuracy measurements.

Let us first conisder an analogy to get a clear picture of what this might mean. Imagine two ice skaters, holding hands, and twirling around each other. If one is particularly bulky, and their partner very slight, it may almost appear that the latter is circling the former. But if our two skaters are of equal weight, it should be obvious that both circle around their common centre – their centre of mass (their 'barycentre', in scientific speak).

The same is true of a system of one or more planets orbiting a star. If the star is very massive and the planets are very small, it may seem that the latter are strictly orbiting the star. But imagine the planets becoming more and more massive, and it again might be more obvious that everything – the planets and the star itself – are orbiting their overall centre of mass.

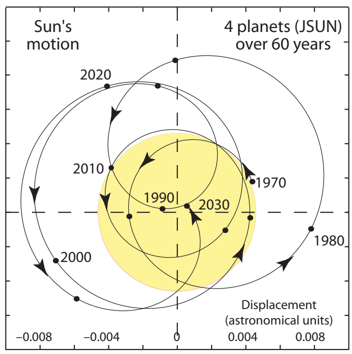
IN 1609 Johannes Kepler published his *Astronomia Nova* (A New Astronomy), including his analysis of the orbit of Mars from 10 years of observations.



Kepler's study of the orbit of Mars

In late 1604, and after various attempts at describing its orbit around the Sun, he at last hit upon the idea of an ellipse, which he had previously assumed to be too simple a solution for earlier astronomers to have overlooked. Finding that an elliptical orbit fitted the Mars data, Kepler concluded that all planets move in ellipses, with the Sun at one focus (his first law of planetary motion). His diagram of the orbit of Mars, seen from Earth, appeared in *Astronomia Nova*, and confirms the remarkable accuracy of his observations.

Our Sun's own path over decades reflects the combined gravitational effects of all solar system objects.

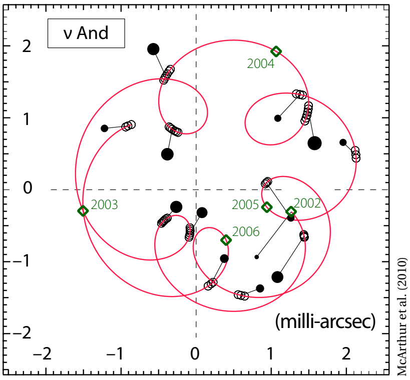


Perryman & Schulze-Hartung (2010)

Indeed, as already noted by Isaac Newton, the actual motion of the Sun about the solar system barycentre is rather complex *'since that centre of gravity is continually at rest, the Sun, according to the various positions of the planets, must continuously move every way, but will never recede far from that centre.'*

Looking down on the plane of the solar system, this figure shows the effect of the four most massive planets (Jupiter, Saturn, Uranus, and Neptune) over 60 years, from 1970–2030. The Sun itself is tugged continuously, smoothly but somewhat erratically due to the different planetary periods. We can see that the Sun often moves by more than its own radius over long periods of time.

THIS GRAVITATIONAL TUGGING on the motion of a host star will exist for any star orbited by planets. If the orbit is viewed edge-on, the effect will be most noticeable in the Doppler shift (radial velocity) of the star's spectrum. Viewed face-on to the orbital plane, the star will move in the same way as we have seen for the Sun.



The orbit of υ And, from Hubble Space Telescope

A single orbiting planet moving in an elliptical orbit will cause the host star to move in a scaled-down elliptical orbit, mirroring the planet's motion.

Multiple planets lead to a more complex star motion over time, dependent on the number of planets, their masses, and their orbital periods.

The bright star *υ* And was one of the first known multi-planet systems, discovered from long-term monitoring of it radial velocity, and now known to be orbited by at least three planets. Observed with the Hubble Space Telescope a number of times over four years, McArthur et al. (2010) were able to reconstruct the orbit of the host star (shown here as the red curve) from the various individual positional observations (solid dots).

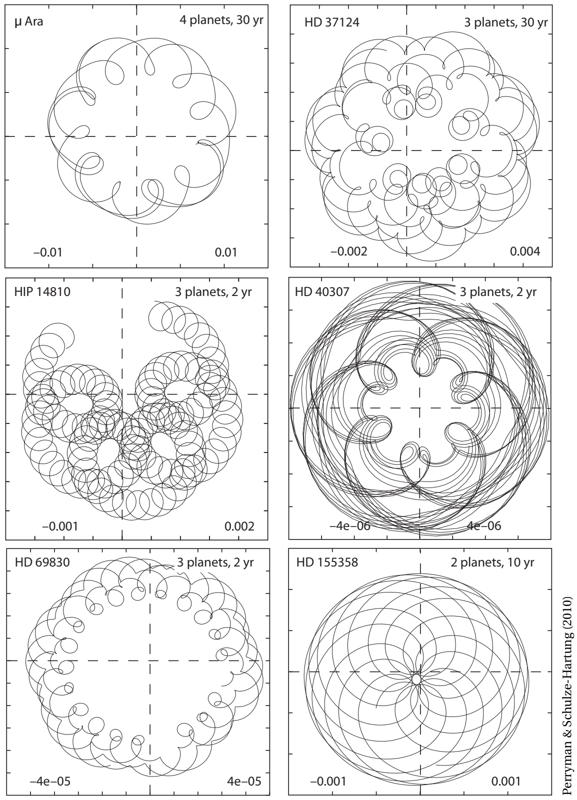
THE TYPE OF positional accuracy needed to make this kind of astrometric observation has not been routinely available so far. But this is the type of observation that is being made, in enormous numbers, by Gaia.

To give an indication of the expected yield, the orbits of just a handful of systems have been measured by the Hubble Space Telescope. By 2020, Gaia will have already acquired around 100 positional observations for perhaps 30 000 exoplanet systems. The results are not available for study, because much more work must be done to calibrate, validate, and interpret the results before they can be made available. Perhaps they will be available around 2025.

But meanwhile, we can predict what the results will look like. We can rather easily take the information that is known about each planetary system, in particular the mass of the host star, and the masses and orbits of the planets that have so far been discovered around them.

Together these will define the path on the sky that the host star will follow over time. Gaia will measure some 100–200 data points on these curves over a total interval of 5–10 years, and in many cases the smooth path of the star can then be reconstructed.

Some examples of the complex star paths predicted for real multi-planet systems are shown in the figure. These types of beautiful curve, drawn out by Nature, have been named *planet mandalas*, after the Sanskrit for circle.



Astrometric orbits expected for some known planetary systems

THIS KIND OF DIAGRAM allows us to visualise the motion of the host star in a multi-planet system. Viewed edge-on, we can see how the transit times of an orbiting planet will be not be regularly spaced at exactly the planet's orbital period, but instead modulated by the star's motion as affected by other planets in the system.

These sorts of 'transit timing variations' are seen frequently in the accurate Kepler transit data, and allow a wealth of new information about the system to be derived, including the mass and orbital periods of any non-transiting planets that might orbit the same system.