PLANETARY MOTION

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Within this use case you learn about Kepler's laws, a cornerstone of astronomy and a fundamental brick of both Newton's and Einstein's theories of gravitation. This use case is complemented by use cases 10 and 16 (at different levels of difficulty).

If used in the classroom this advanced use case requires mathematical skills. The geometry of ellipses has to be well understood and it is required to understand the fitting procedure of data points to a linear relation. The use case is therefore suggested for students at college level.

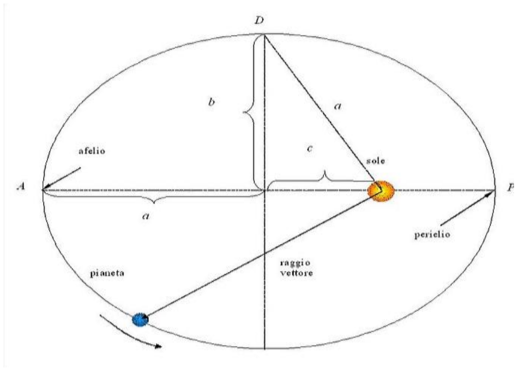
History

Planetary motion has been a mystery for a very long time.
By naked eye we can see five planets: Mercury, Venus, Mars, Jupiter and Saturn. These planets are visible in different periods of the night and of the year. Sometimes two ore more planets appear next to each other on the celestial sphere, while most of the times they are rather distant from each other.
During the night planets seem to move like stars: they rise eastwards and set westwards. Studying their position for a longer time, weeks or months, we notice they slowly move through the zodiac constellations. The Sun and the Moon move through constellations too, but planets move in a more complicated way.
In fact most of the time planets move eastwards, with respect to stars, but sometimes they move in the opposite direction (retrograde motion). After some weeks of retrograde motion, the direction changes again and the planets move eastwards again.
Ancient Greeks believed that the Earth was at the centre of the Universe and that stars belonged to a sphere rotating around it. This model, called “geocentric” (Ptolemy, 100 – 175 a.C.), explained very well the apparent motion of stars.

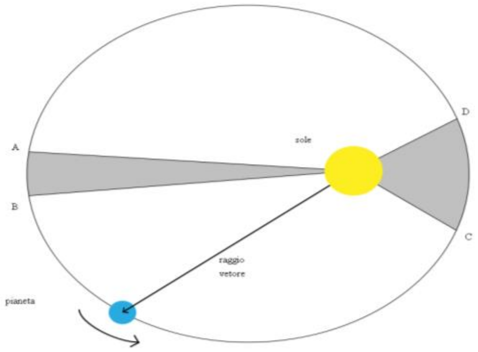
Planetary motion remained however a mystery.
According to the geocentric model, each planet moves around the Earth along a little circle that is itself orbiting on a larger circle. The little circle is called “epicycle”, the larger one “deferent”. A planet moving on epicycles and deferents, if observed form Earth, appears to have a forward and backward motion similar to the retrograde motion.
Ptolemy’s geocentric model could predict the planet positions (ephemerides) within few degrees and, since it worked sufficiently well, it was used for the next 500 years.
The motion of planets becomes relatively easy to explain in an “heliocentric” model where the Sun is at the centre and planets, including the Earth, orbit around it. The heliocentric system was proposed by the Dutch astronomer Nicolaus Copernicus (1473 - 1543) at the beginning of the XVI° century.
Working on the mathematical aspects of his model, Copernicus discovered basic geometrical laws that allowed him to calculate the planet orbital periods and their distance from the Sun.
The success of his model convinced Copernicus that the idea of an heliocentric model was correct. However the Copernican model didn’t improve substantially the computation of the ephemerides with respect to the Ptolemaic model. The main reason was that Copernicus was convinced that planetary orbits had to be circular.
In order to describe the planetary motions using circular orbits, Copernicus had to add epicycles and deferents, obtaining a model as inaccurate and complex as the Ptolemaic one, although with fewer assumptions.
In the 50 years following the publication of the “De revolutionibus orbium coelestium” (1543), in which Copernicus published the final version of his theory, the Copernican model found very few followers.
The main problem of astronomers trying to improve either the Copernican or Ptolemaic models, was the lack of accurate naked eye observations.
The first astronomer to concentrate on accurate and systematic observations of planetary positions on the sky was Tycho Brahe (1546 - 1601). At the end of XVI° century he and his students performed, in three decades, naked eye observations more accurate than 1 arcmin.
Since the telescope was invented few years later, these astronomical observations remain the most accurate ever made by naked eye.
Brahe asked his student Kepler to elaborate a model matching his observations. Kepler, as Copernicus, was convinced that the Earth and other planets were moving on circular orbits around the Sun.
Trying to match Tycho’s data on circular orbits, Kepler discovered that some observations were in disagreement with predictions by more than 8 arcmin. Because Kepler believed that the data of Tycho were precise, the discrepancy between them and observations made him change the shape of orbits from circular to elliptical.
Kepler’s heliocentric model allowed predictions of planetary positions with unprecedented accuracy and was universally adopted.

Kepler’s laws

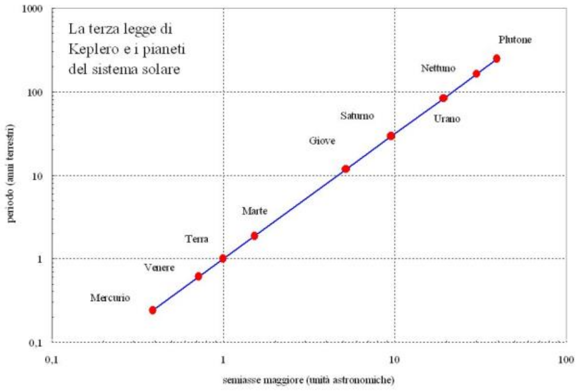
The orbits of planets and of their moons, of asteroids and of comets are governed by the gravitational force and described by the three Kepler’s laws (published between 1610 and 1618):
First law: the orbit described by a planet is an ellipse and the Sun occupies one of the two foci.



Second law: the vector joining the planet and the Sun describes equal areas in equal times.



Third law: the square of the revolution period of the planets is proportional to the cube of their orbit semi-major axes.



As a result of the Kepler's laws the angular velocity of a planet is not constant but varies along the orbit. Angular velocity is larger at the perihelion (the point of the orbit nearest to the Sun - where the radius vector is shorter) and lower at the aphelion (the point of the orbit more distant from the Sun - where the radius vector is longer).

Another result is that the revolution period is as long as the planet is distant from the Sun: this means that internal planets cover their orbits in a shorter time and appear to pass the external ones.

This difference of the relative velocities produces the retrograde motion of the planets observed on the celestial sphere. When the Earth passes the external planets (Mars, Jupiter, Saturn, Uranus and Neptune), or is passed by the internal ones (Mercury and Venus), they seems to move from East to West with respect to the stars.

Stellarium

Stellarium is a free software that transforms a home computer in a planetarium. It calculates the positions of Sun and Moon, planets and stars, and draws the sky how it would be seen from an observer anywhere on the Earth and at any epoch. Stellarium can also draw the constellations and simulate astronomical phenomena such as meteor showers and solar or lunar eclipses.

Stellarium may be used as an educational tool for kids of all ages, as an observational aid for amateur astronomers wishing to plan an observing night, or simply to explore the sky (it is fun!). Stellarium shows a realistic sky, very close to what you see with naked eye, binoculars or telescope. Stellarium gives astronomical data (coordinates, magnitude, distance, etc.) of most of the celestial objects visualized on the screen.

You can freely download Stellarium from our site http://vo-for-education.oats.inaf.it or from http://www.stellarium.org.

Planetary motion in Stellarium

We can easily visualize planetary motions and explore Kepler's laws using Stellarium.
Stellarium offers the possibility to observe the Solar System from different viewpoints: from one of the planets, from the Sun or from outside the Solar System.
We start positioning outside the Solar System: from this position we can see how planets are arranged, which are their orbits and their distances from the Sun.
Start Stellarium and open the *location window* - (left menu), in the menu *planet* select "Solar System Observer".
In order to obtain a better visualization, in the *sky and viewing option* window - , tab *sky*, turn off the atmosphere and dynamical eye adaption, set to the minimum value both the star relative scale (0.25) and the light pollution (1), check "show planets" and "show planet orbits". In the next tab, *markings*, deselect everything and in the *landscape* tab turn off horizon and fog.
Now find the Sun (write "Sun" in the search window -). Zoom on it until you see the planets. In order to have a better view of the Solar System turn off the stars (press "s" key).
In order to visualize the orbit of a planet select it with the mouse. If you select the Sun the orbits of all Solar System objects will be visualized.
From the *sky option window* - you can increase or decrease the number of objects of the Solar System to be visualized in Stellarium: move to the right or to the left the bar *planets* in the *labels and markers* section.
Now that we have set up Stellarium, we can observe how all planets move within our Solar System. For a better evaluation of the orbital motion of the planets, accelerate the time speed with the arrows on the right of the bottom menu ( ). The button *play* - brings back the flow of time to its standard rate.
In order to see the planet revolution, select each planet to see its orbit, zoom in or out from the Sun to see all the Solar System or only the internal planets.
Observe that planets more distant from the Sun have a longer revolution period with respect to the nearer ones, according to the third Kepler's law.
Now we change point of view: move on the Sun and observe from there the motion of the planets.
In the *location window* - , in the *planet* menu, select "Sun". Search the Earth and fix it at the centre of the screen by clicking the button *centre on selected object* - (bottom menu). Switch from azimuthal to equatorial mount, with the button *switch between mounts* - . From the *sky options window* - turn off the stars and decrease the number of their labels. Set the zoom level so that you have a field of view (FOV) of about 20°.
Accelerate the speed of time and observe how the Earth, along its orbit, passes the external planets (Mars, Jupiter, Saturn, Uranus and Neptune) and how it is passed by the internal ones (Mercury and Venus).
Finally, in order to visualize the retrograde motion, we observe the planets from the Earth. Proceed as follows: select the Earth in the *location window* - , then search Mars and fix it at the centre of the screen. Turn on the stars, accelerate the speed of time and observe the planet motion with respect to the stars: sometimes Mars seems to invert its motion following a curved path in the sky.
Retrograde motion can be observed for all other planets, but as distance of planets from the Sun increases, the time between occurrences becomes longer.