UNIT 5:

LAWS OF PLANETARY MOTION

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The origins of astronomy

The origins of astronomy lie in the times when near-human creatures looked at the moon and the stars and wondered what they were. Early humans fed on what they could gather from the earth and from hunting animals. At some point, they began to wonder when the harvesting season would come or when the migratory movements of large herds of animals would occur. Thus, little by little, in the search for answers to these questions, humans learned to relate the events of the world around them to the changes they observed in the sky. It was possibly then when the first calendars appeared, related to the movements of the sun, the moon and the stars. They observed that the sun rose and set in roughly the same places every day. But they realised that these points on the horizon changed according to the different seasons, so they found it more practical to use the stars for orientation.

Since then, thousands of generations of astronomers have lived and worked on this planet, leaving virtually no record of their achievements. By studying their archaeological sites and the ruins of their temples and observatories, we have been able to learn a little about them.

Other cultures, such as ancient Greece, have left us some written documents from which we have been able to reconstruct the sophisticated astronomy of the ancient world. Apart from studying the stars, they tried to understand the motion of the planets (which they called wandering bodies) and their situation in the Universe. Since then, for more than 1600 years, the most accepted theory was that the Earth was the centre of the Universe (geocentric model) and that everything revolved around us. Some astronomers in the Middle Ages, making more precise observations of these wandering bodies, suggested that there might be another model of the Universe in which everything did not revolve around the Earth and the Earth was not stationary. A revolution that began with Copernicus and that, thanks to the work and sacrifice of other scientists and astronomers after him, managed to take hold up to the present day.

The laws of planetary motion

Tycho Brahe

Undoubtedly one of the best observers before the discovery of the telescope was Tycho Brahe, who managed to achieve very high accuracies in his observations of the motion of the planets. Tycho's earliest observations date from his student days. In 1563, Jupiter and Saturn passed very close to each other in the sky, almost blending together as a single point on the night of 24 August. He realised that the Alphonsine Tables (which predicted this phenomenon) were in error by one month, which awakened his interest in the movements of the planets.

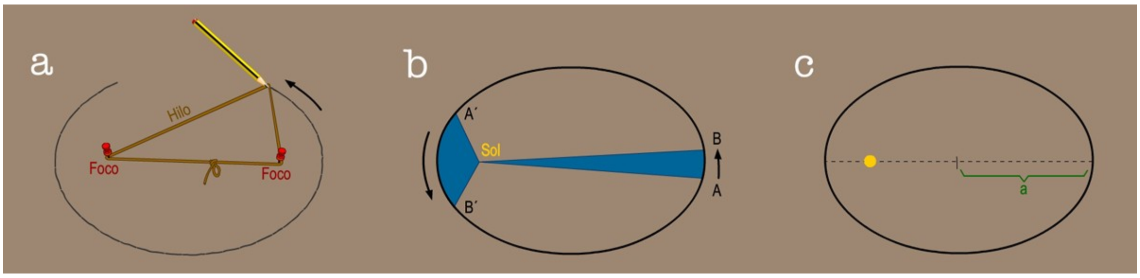
After observing in 1572 the position of a new star (a nova named after him), he received funds for the construction of an observatory. He built new and better instruments that allowed him to make the most accurate measurements to date of the positions of the stars, the Sun, the Moon and the planets. Tycho surrounded himself with a number of astronomers and mathematicians, among them Johannes Kepler, who was appointed imperial mathematician on his recommendation.

Johannes Kepler

After Tycho Brahe's death, Kepler ussed Tycho's observations to make mathematical calculations and to describe the motion of the planets. At first, he tried to fit the data from Tycho's observations of the motion of Mars into a circular orbit, but he encountered many difficulties, until he eventually came to the conclusion that the orbit could be elliptical. From the study of planetary positions, especially of the planet Mars, he deduced the three laws that bear his name.

Kepler's First Law states that the orbits of the planets around the Sun are ellipses, with the Sun at one of their foci. An ellipse can be defined as a plane figure drawn around two points called foci, so that the sum of the distances from each point of the ellipse to the two foci is constant and equal to the major axis of the ellipse. So, if we want to draw an ellipse, we can do it easily with two drawing pins and a piece of string. Stick the two pins into a piece of cardboard and pass the knotted string around them as shown in **figure a**. We move a pencil so that the thread is kept taut at all times and we obtain an ellipse whose foci are the two pins. Although the orbits of the planets are ellipses, we must take into account that most of them have an orbit that is practically circular (the foci are very close to each other).

Kepler's Second Law says that the line joining the Sun to the planet sweeps over equal areas at equal intervals of time. This means that when a planet is in the part of the orbit closest to the Sun, it must move faster than when it is further away from the Sun, where it moves more slowly (see **figure b**).



Kepler's Third Law states that the time it takes for a planet to complete its orbit (what we call the orbital period), squared, is proportional to the cube of the semi-major axis of that orbit, figure c. If we measure this distance (*a*) in astronomical units and the orbital period (*P*) in years, Kepler's third law is summarised in the following expression:

$$P_{years}^2 = a_{UA}^3$$

For example, Jupiter has a nearly circular orbit, so its major axis nearly coincides with the planet's mean distance from the Sun, which is about 5 A.U. This quantity cubed gives us 125, so Jupiter's orbital period will be the square root of 125, or about 11 years.

Kepler's three laws are empirical, i.e. they describe the phenomenon without explaining why it occurs, but they work perfectly.

Although Kepler discovered the three laws of motion of the planets, he never knew why they moved in those orbits. Some writings of the time suggested that they are pushed by magnetic forces emanating from the Sun, while others speculated that they are pushed by angels flapping their wings. They had no clue about the physical principles behind the movements.

Galileo Galilei

A great friend of Kepler studied the free motion of bodies, performing experiments on his own. His name was Galileo Galilei. Galileo began by studying the falling motion of bodies, but soon realized that the velocities were so great and the times so short that he could not measure them accurately. He therefore proceeded to study the behavior of balls on sloping planes, in which case the velocities were smaller and the times longer. He came to the conclusion that they were proportional to those required for free fall. He realized that when falling the bodies did not fall with uniform velocity, but accelerated, i.e., they moved faster with each passing second. In addition, he discovered that the acceleration was independent of the weight of the object, something that could be verified on the Moon (where there is no air) when the astronauts who stepped on it dropped a steel hammer and a feather at the same time, verifying they reached the ground at the same time.

Galileo revealed that an object falling down an inclined plane is accelerated towards the ground while an object going up the same plane is slowed down. He concluded that if the surface were perfectly horizontal and in the absence of friction, there could be neither acceleration nor braking that would change the velocity of the object and it would continue to move indefinitely. In his own words, “any body in motion maintains its velocity indefinitely unless external causes force it to change its velocity”. Galileo published his work on motion in 1638, four years before his death.

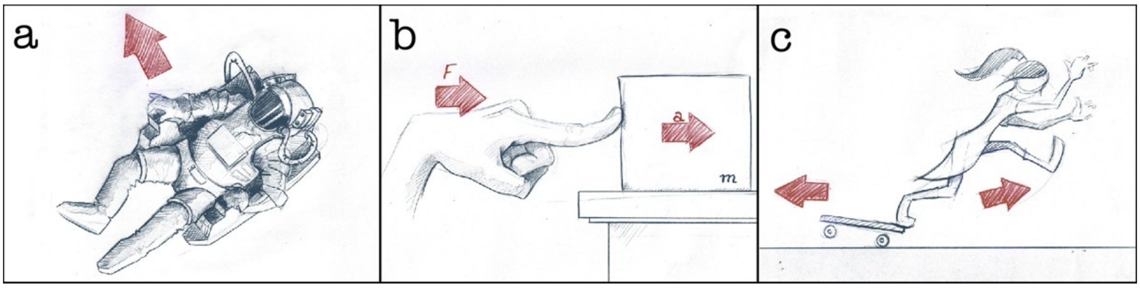
Another of Galileo's great achievements was the improvement of the telescope, which allowed him to make astronomical observations of higher quality and, thanks to them, to make important discoveries that made it possible to discard the old geocentric model of Ptolemy: the Moon is not a perfect sphere but has mountains and craters; Jupiter has several satellites that revolve around it (he discovered 4 of them, the largest ones); the size of the planets and the Moon increased when observed through the telescope, but not that of the stars (which are much farther away); Venus presents phases and changes in size that are compatible with the planet's rotation around the Sun; the Sun is not a perfect and immutable sphere either because spots are observed on its surface and it rotates.

Isaac Newton.

In the same year that Galileo died, another great scientist was born, Isaac Newton, who would take the definitive step in the study of the motion of bodies in the Universe. Newton based his own work on the studies of Galileo and some others. Throughout his life he studied optics, invented calculus systems, built new models of telescopes, developed three laws of motion and discovered the principle of universal gravitation.

Newton's three laws of motion are fundamental to the study of the motion of any body in the Universe. They apply to any celestial object, from the smallest asteroids to colliding galaxies. They can be stated as follows:

I. A body remains at rest or with uniform rectilinear motion, unless acted upon by some force.
II. The acceleration of a body is inversely proportional to its mass, directly proportional to the force that produces it and has the same direction as it
III. To every action corresponds an equal and opposite reaction, that is to say, the mutual actions of two bodies are always equal and directed in opposite directions.



The first law is actually a restatement of Galileo's principle of inertia. This law explains, for example, why an astronaut continues to move in space after the force that has propelled him or her (the propulsion nozzles of his or her suit, see **figure a**) has ceased.

The second law is important because it establishes a relationship between cause and effect. Objects subjected to a force not only move, but also accelerate as long as this force remains (**figure b**). A clear example is space rockets. From the moment the rocket starts the engines, it begins to accelerate, constantly increasing its speed until, once in space, it turns them off and continues at the same speed, since there is no friction with the air or any other force that slows it down.

Newton's third law specifies that for every action there is an equal and opposite reaction. For example, if we are on a skateboard that is standing still and we jump forward, the skateboard will shoot backward (**figure c**).

From the first and second laws, Newton deduced that bodies in free fall accelerate downward because some force pushes them in that direction. Together with the third law, which indicated that if there was a downward force there must be an upward force, he deduced that if the Earth pulls down on an object, it should do the same by pulling the Earth toward it. Thus, for example, the Moon should pull the Earth toward it, only with less intensity, since its mass is smaller.

He also deduced that the intensity of that force decreased with distance, just as the brightness of a candle decreases as we move away from it.

Newton combined these deductions in the **Law of universal gravitation** which describes the gravitational interaction between various bodies with mass. The law can be stated as: the force exerted between two bodies of masses M and m separated by a distance r is proportional to the product of the masses and inversely proportional to the square of the distance.

$$F = -G\frac{Mm}{r^2}$$

where G is the universal gravitational constant and the negative sign indicates the force is attractive.

For further information, visit our website: **www.iac.es/peter**

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