# DSE
# Space Satellite Physics

## Europe in Space

Since its foundation in 1975, the *European Space Agency (ESA)* has led many major space projects and has cooperated with Russian and US space agencies. At present the ESA has eighteen member countries including Ireland and many Irish companies provide components for satellites and other space craft. At present, there are over 3,000 operating *satellites* orbiting the Earth. The largest of these is the *International Space Station (ISS)*. None of this would have been possible without a thorough understanding of the laws of motion and gravitation. In this lesson we look at the mathematics behind these laws.

## Revolutionary Ideas

In the 1630s *Galileo* published two major works in which he contrasted a new scientific world view with the traditional view. For example, from the time of *Aristotle* it was generally believed that motion required a force. This seems like a reasonable idea which is consistent with our everyday experience. However, it could not explain, for example, why an arrow would keep moving long after it had been fired from a bow.

Galileo carried out many experiments and showed that a *force* causes *acceleration* — not a steady speed. He also realised that *friction* caused moving bodies to slow down and eventually stop, and proposed that if there were no friction then, once a body was set in motion, it would move forever without the need for further force. This was (and still is) a *counter-intuitive* idea that many people could not accept. However, we now know that as we reduce friction in machines, less force is needed to keep things moving.

*The Space Shuttle, Endeavour, docked with the International Space Station (ISS) (NASA image)*

## Newton

Building on the ideas of Galileo and others, Isaac Newton devised three simple propositions ('laws') to describe how things move. He also proposed an *inverse-square law* of gravitational attraction, that is the force of attraction between two bodies (such as the Earth and the Moon or the Earth and an apple) was inversely proportional to the square of the distance between their centres; for example, if the distance is doubled then the force is reduced to a quarter of what it was. These revolutionary propositions were published in 1687.

## Newton's Laws

- No force, no acceleration (If no force acts on a body it remains at rest or in constant motion in a straight line).
- A force causes acceleration. Large masses are harder to accelerate. So $a = F/m$ or $F = m \times a$, where $a$ is the acceleration, where $F$ is the force and m the mass.
- Action and reaction: This is usually stated as 'for every action there is an equal and opposite reaction' or 'when a force acts on a body an equal and opposite force acts on another body'. More precisely, forces exist only between bodies. For example, the Earth attracts the Moon and the Moon attracts the Earth — there is just one force involved, but it pulls one body in one direction and the other body in the opposite direction.
- The Law of Gravitation: $F \;\; m_1 \times m_2 / r^2$.
  The gravitational constant, $G$, was measured by Cavendish in 1798. The law of gravitation can now be written as: $F = G \times m_1 \times m_2 / r^2$.

## Circular Motion

If you use a piece of thread to swing a ball of paper at a steady speed in a circle then the thread provides the force necessary to keep the ball on the circular path. This 'centripetal force' causes the direction of motion to change continuously. The following equation relates the *'centripetal force'* ($F$), the mass ($m$), the *linear velocity* ($v$) and the radius of the circular path ($r$): $F = m\,v^2/r$.

It is often easier to consider the time (or *period*) for a revolution or *orbit* rather than the actual speed. The *speed* is the distance divided by the time. For a body in circular motion, one orbit is $2\pi r$ and so the speed is $2\pi r/T$, where $T$ is the time for one revolution. The quantity $2\pi/T$ is called the *angular velocity* (ω, lower case omega); it is related to the linear velocity as follows: $v = r\omega$. The centripetal force can therefore be written as: $F = m\,r\omega^2$.

## Satellites in Orbit

Every month the Moon orbits the Earth on a roughly circular path. Since gravitation provides the required *centripetal force* we can equate the two expressions for force, given above:

$G \times M \times m/r^2 = m\,r\omega^2$, where $M$ is the mass of the Earth, and $m$ the mass of the Moon.

Simplifying this we get: $G \times M = r^3\,\omega^2 = r^3(2\pi/T)^2$.

This shows that for a given large mass, such as the Earth, orbital time depends on the radius of the orbit; it does not depend on the mass of the satellite.

If a satellite is in orbit around the Earth at a height of 300 km above the surface then the radius of its orbit must include the radius of the Earth, (6,400 km or 6,400,000 m).

Using $T^2 = r^3(2\pi)^2/GM$ we get

$T^2 = (6{,}400{,}000 + 300{,}000)^3 \times (2\pi)^2 / (6.67\times10^{-11} \times 5.97\times10^{24})$.

This gives $T$ = 5458 seconds or about 1.5 hours.

Using the same equation we can show that the height above the surface of the Earth of a satellite that orbits in 24 hours is 35,786 km. If this orbit is directly over the *equator* then the satellite's position in the sky appears fixed even though its linear speed is more than 3 km per second. Such *geostationary orbits* are much used for telecommunications.

As another example, we can use the same equation to find the orbital period of the Moon:

The average radius of the Moon's orbit is 384000 km ($= 3.84 \times 10^8$ m).

$T^2 = (3.84 \times 10^8)^3 \times (2\pi)^2/(6.67\times10^{-11} \times 5.97\times10^{24}) = 5.614\times10^{12}$.

$T$ = 2,358,648 s or 27.3 days.

## Early Space Science

The launch in 1957 of the first artificial satellite (*Sputnik*) marked the beginning of the so-called *Space Race* whose high point was the first moon landing by *Apollo* in 1969. However, it is important to understand that, by that time, space science was already well developed. The following are some important historical milestones and the names of the scientists associated with them.

- Astronomical observations (by Chinese, Greek and Arabic scholars; later by Brahe, Copernicus, Kepler and many more)
- Astrophotography: Draper (1840), Whipple (1850), (mapping the sky, *spectra* of stars; improved sensitivity)
- Astronomical telescopes: Galileo (1610), Newton (1668), Birr (1845), Mount Wilson (from 1908)
- *Cosmic ray* studies (Hess, from 1911)
- *Radio telescopes*: Jansky (1911), Reber (1937)
- Solar observatories: Kodaikanal, India (1901), McMath-Hulbert (from 1931).

## Space Science Today

Scientific instruments in space, whether in Earth orbit in satellites or on long range missions in space craft, continuously gather images and other data that enhance our understanding of the Earth, the Sun, the solar system and the cosmos. Many satellites provided telecommunications services allowing us to make global calls, connect to the internet and receive radio and TV signals. Space science is truly a multidisciplinary area, involving physicists, biologists, chemists, engineers, mathematicians and technicians across a wide range of disciplines.

# European Space Education Resource Office (ESERO) Ireland

**European Space Education Resource Office (ESERO) Ireland** promotes space as a theme to inspire and engage young people with STEM subjects (science, technology, engineering and mathematics). Space is fascinating to people of all ages; it is all around us and inspires us in many different ways. Space is the ultimate cross-curricular theme cutting across history, geography, science, maths, literature and religion. ESERO Ireland makes space-themed resources accessible to teachers as a tool to engage their pupils.

ESERO Ireland is co-funded by the European Space Agency (ESA) and Discover Science and Engineering (DSE). *For more information go to www.esero.ie.*

# Discover Science & Engineering (DSE)

**Discover Science & Engineering (DSE)** is Ireland's national science promotion programme, managed by Forfás. DSE aims to increase interest in science, technology, engineering and mathematics (STEM) among students, teachers and members of the public. DSE's mission is to contribute to Ireland's continued growth and development as a society – one that has an active and informed interest and involvement in STEM. DSE has many target audiences. These include students at all levels (with a particular focus on those in primary and secondary education), their parents and teachers, and the wider public.

To reach these varied audiences, DSE runs many events, and supports and participates in initiatives which help to raise the general awareness of science, technology, engineering and mathematics (STEM) across Ireland.

*For more information on DSE go to www.discover-science.ie.*

# The European Space Agency (ESA)

**The European Space Agency (ESA)** is Europe's gateway to space. Its mission is to shape the development of Europe's space capability and ensure that investment in space continues to deliver benefits to the citizens of Europe and the world. By coordinating the financial and intellectual resources of its members, it can undertake programmes and activities far beyond the scope of any single European country.

ESA is an international organisation with 18 Member States, including Ireland.

You can find out more about the work of The European Space Agency on www.esa.int.

# Teaching Notes

## Syllabus References

### Leaving Certificate Physics

- Force and linear motion; Newton's laws of motion.
- Circular motion; gravity.
- Centripetal force required to maintain uniform motion in a circle.
- Definition of angular velocity ω.
- Derivation of $v = r\omega$. Use of $a = r\omega^2$, $F = m\,r\omega^2$.
- Circular satellite orbits; derivation of the relationship between the period, the mass of the central body and the radius of the orbit.

### Leaving Certificate Applied Mathematics

- Newton's laws. Mass, momentum.
- Motion in a straight line under uniform acceleration e.g. motion under gravity.
- Angular velocity.
- Uniform motion in a circle without gravitational forces.
- Circular orbits.

## Learning Outcomes

On completion of this lesson, students should be able to:

- Describe Newton's Laws.
- Explain why a mass would keep moving in the absence of friction.
- Compute the orbital time of a satellite, given the orbital radius (or vice versa).
- Identify some early milestones in the evolution of space science.
- Discuss some practical applications of space science.
- Describe the missions of Discover Science and Engineering and the European Space Agency.

## General Learning Points

The following information can be used to revise the lesson's main learning points and inform discussion.

- The sidereal month is the time the Moon takes to complete one full revolution around the Earth with respect to the background stars. However, because the Earth is travelling in its orbit around the Sun, the Moon must travel more than 360° to get from one new moon position to the next, which is called the synodic or lunar month. Hence the synodic month (29.531 days) is longer than the sidereal month (27.322 days).
- In space science a satellite is an artificial object which is put into orbit. There are also natural satellites such as the moon.
- A rocket is a jet engine that uses only propellant material that produces pressurised gas to create the high speed propulsive jet which provides thrust in accordance with Newton's third law.
- The first two ATVs are called Jules Verne and Johannes Kepler.
- As well as delivering supplies such as food, fuel and water to the ISS, an ATV can also reboost the station into a higher orbit.
- Satellites are tracked by United States Space Surveillance Network (SSN), which has been tracking every object in orbit over 10 cm in diameter since it was founded in 1957.
- The Iridium satellite phone system has over 60 satellites in fast low-altitude orbits to give good reception even in remote areas of the world.

# Student Exercises

## Student Activities

- The International Space Station is 380 km and the Hubble space telescope is 600 km from Earth. Calculate the speed of these two satellites.
- A satellite in orbit around the earth has kinetic energy ($E_k = ½\, m\, v^2$) and potential energy ($E_p = m\, g\, h$) because of its height above the surface of the earth.
  A calculation in the lesson showed that a satellite at a height of 300 km above the earth would orbit the earth in about 1.5 hours. Calculate the following:
  - The radius of the orbit of the satellite.
  - The distance travelled by the satellite in one orbit.
  - The distance travelled by the satellite in one hour (i.e. its speed in m/s and km/h).
  - Assuming the satellite has a mass of 1000 kg (1 tonne) calculate:
  - The potential energy of the satellite.
  - The kinetic energy of the satellite.
  - The minimum energy required to put the satellite into that orbit, assuming a rocket efficiency of 50%.

## True/False Questions

(1) A satellite that appears to move is said to be in a geostationary orbit.

(2) The force of attraction between two bodies is proportional to the cube of the distance between their centres.

(3) A force causes a mass to accelerate.

(4) A centripetal force keeps a body moving in a straight line.

(5) The International Space Station is the largest artificial satellite in orbit.

(6) Sputnik was the first satellite to be launched into orbit.

(7) Ireland is a member of the European Space Agency.

(8) In the absence of any friction, a moving mass would keep moving forever.

*Check your answers to these questions on www.sta.ie.*

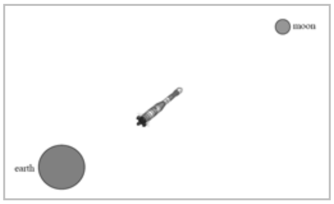
## Examination Questions

### Leaving Certificate Physics (HL) 2010, Q. 6

State Newton's law of universal gravitation.

Use this law to calculate the acceleration due to gravity at a height above the surface of the earth, which is twice the radius of the earth.

A spacecraft carrying astronauts is on a straight line flight from the earth to the moon and after a while its engines are turned off.




Explain why the spacecraft continues on its journey to the moon, even though the engines are turned off.

Describe the variation in the weight of the astronauts as they travel to the moon.

At what height above the earth's surface will the astronauts experience weightlessness?

The moon orbits the earth every 27.3 days. What is its velocity, expressed in metres per second?

Why is there no atmosphere on the moon?

*(Radius of the earth = 6.36 × $10^6$ m); Acceleration due to gravity at the earth's surface = 9.81 m $s^{-2}$.*

*Distance from the centre of the earth to the centre of the moon = 3.84 × $10^8$m (Assume the mass of the earth is 81 times the mass of the moon.)*

### Leaving Certificate Physics (HL) 2008, Q. 6

- State Newton's law of universal gravitation.
- The International Space Station (ISS) moves in a circular orbit around the equator at a height of 400 km.
- What type of force is required to keep the ISS in orbit?
- What is the direction of this force?
- Calculate the acceleration due to gravity at a point 400 km above the surface of the earth.
- An astronaut in the ISS appears weightless. Explain why.
- Derive the relationship between the period of the ISS, the radius of its orbit and the mass of the earth. Calculate the period of an orbit of the ISS.
- After an orbit, the ISS will be above a different point on the earth's surface. Explain why.
- How many times does an astronaut on the ISS see the sun rise in a 24 hour period?

(gravitational constant = $6.6 \times 10^{-11}$ N m$^2$ kg$^{-2}$;

mass of the earth = $6.0 \times 10^{24}$ kg; radius of the earth = $6.4 \times 10^{6}$ m)

## Did You Know?

In November 2011, six astronauts completed a record 17 months in a spacecraft simulating a trip to Mars. The project, called Mars500, is the first simulation of its kind at took place in the Institute of Biomedical Problems in Moscow. The crew carried out over 100 experiments related to the problems of long-duration space missions. You can watch a video of the hatch opening at www.esa.int.

The ESA offers students a wide range of work placement options. One is the one year programme for Young Graduate Trainees which enables participants to gain experience in the development and operation of space missions. Information is available at www.esa.int.

Among the programmes DSE operates are:

- Discover Sensors www.discoversensors.ie
- SciFest www.scifest.ie
- Science Week Ireland www.scienceweek.ie
- My Science Career www.mysciencecareer.ie

## Biographical Notes

### Galileo Galilei (1564-1642)

Galileo Galilei was an Italian mathematician who became famous at the age of twenty when evolving the law of the pendulum. In a famous incident he proved Aristotle wrong when he demonstrated that objects of various weights, dropped from the top of the Tower of Pisa, all reached the ground at the same time. He later developed a telescope which led him to suggest that the sun does not move around the Earth. He was tried for heresy and put under house arrest until he died.

### Robert Hutchings Goddard (1882-1945)

He was an American physicist and engineer who built the first liquid-fuelled rocket launched in1926. His theories for rocket design are seen as milestones in the progress of spaceflight. Many scientists did not believe that rockets would work in the vacuum of space until he proved that they do.

### Yuri Gagarin (1934-1968)

Yuri Gagarin was the first human to journey into outer space. His Russian spacecraft, Vostok 1, completed an orbit of the Earth on April 12, 1961. Gagarin died when his MiG 15 jet crashed.

## Revise The Terms

*Can you recall the meaning of the following terms? Reviewing terminology is a powerful aid to recall and retention.*

Acceleration, angular velocity, Apollo, ATV, centripetal force, cosmic ray, European Space Agency (ESA), force, friction, gravitational constant, International Space Station (ISS), inverse-square law, linear velocity, radio telescope, satellite, Space Race; Space Shuttle, spectra, Sputnik, the Law of Gravitation.

*Check the Glossary of Terms for this lesson on www.sta.ie.*