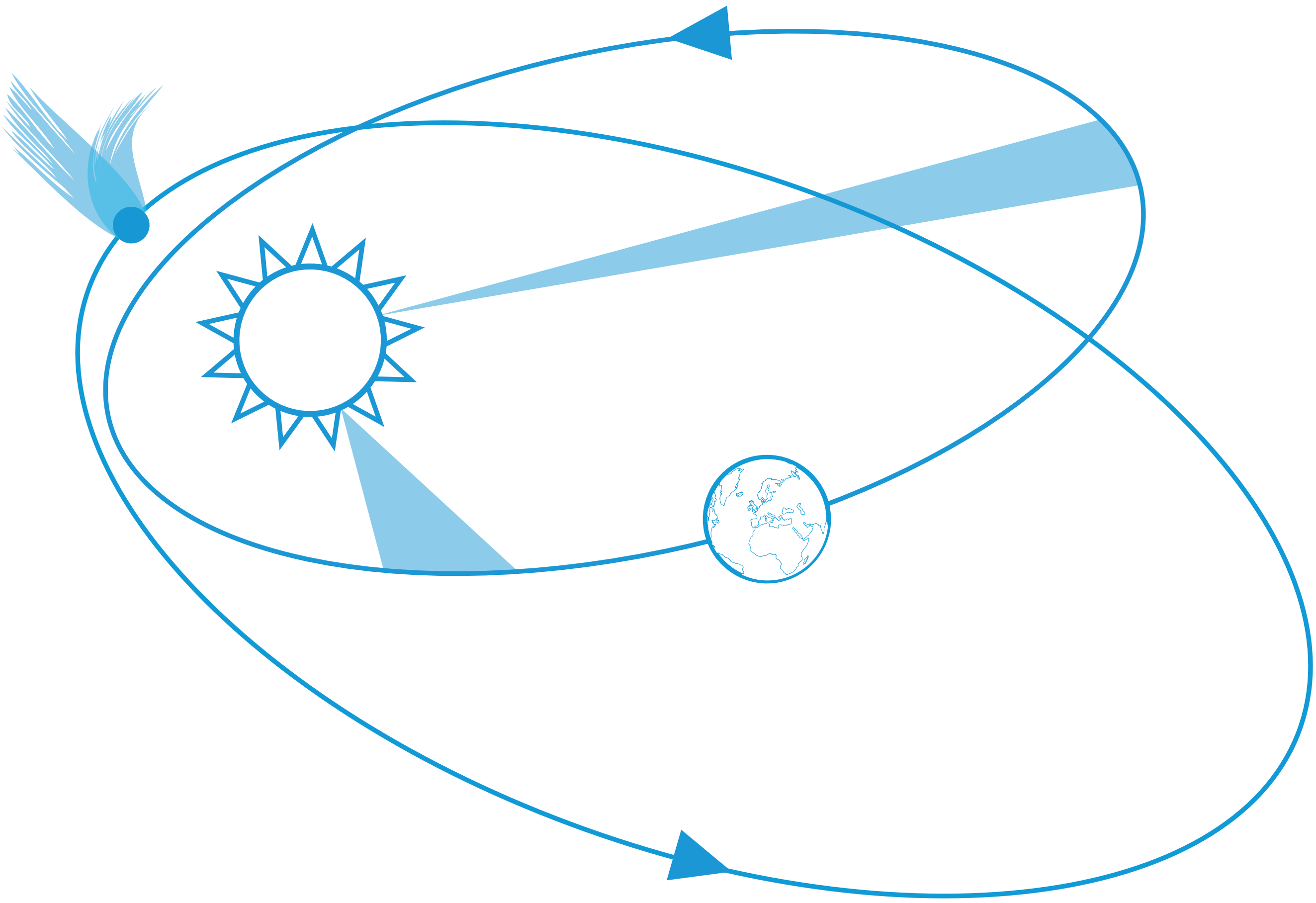
teach with space

→ MARBLE-OUS ELLIPSES

Speed and time of orbiting bodies



→ INTRODUCTION

In order to understand the orbits of planets, comets and other celestial bodies, it is necessary to examine the principles of how gravity, and the velocity of an object, interact to produce an orbit. It is a common misconception among students that planetary orbits are circular. This practical activity gives a space setting to speed-time graphs. It shows how the speed of objects in elliptical orbits change as they orbit the Sun. An extension activity, looking at the geometry of ellipses and their relation to physical parameters in the Solar System, is included.

→ MARBLE-OUS ELLIPSES

Speed and time of orbiting bodies

FAST FACTS

Age range: 14-16 years old

Type: student activity

Complexity: medium

Teacher preparation time: 1 hour

Lesson time required: 15 minutes to 1 hour

Cost: low (less than 10 euro)

Location: indoor (any classroom)

Includes use of: marbles, rulers, no hazardous materials

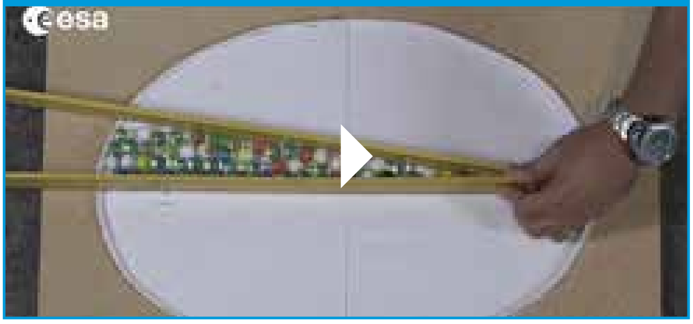
Students should already know

1. The concept of kinetic energy and gravitational potential energy.
2. The concept of velocity vector.

Learning outcomes

1. Students should be able to construct a graph of speed against time and link this to ideas of acceleration and distance to understand the principles of orbital mechanics.
2. Students should understand how the strength of gravity varies with distance from a planet or star.
3. Students should relate this to how a planet or satellite accelerates and decelerates in an elliptical orbit.

You also need



↑ Marble-ous ellipses video. See Links section.

Curriculum links

Physics
- Orbits
- Satellites
- Comets
- Planets
- Stars
- Gravitation (variation of gravitational strength with distance)
- Kepler's laws

Mathematics
- Graphs of speed against time
- Area under graph equal to distance
- Gradient at a point equal to acceleration
- Drawing graphs and their interpretations
- Geometry: ellipses, eccentricity, major and minor axes

Outline

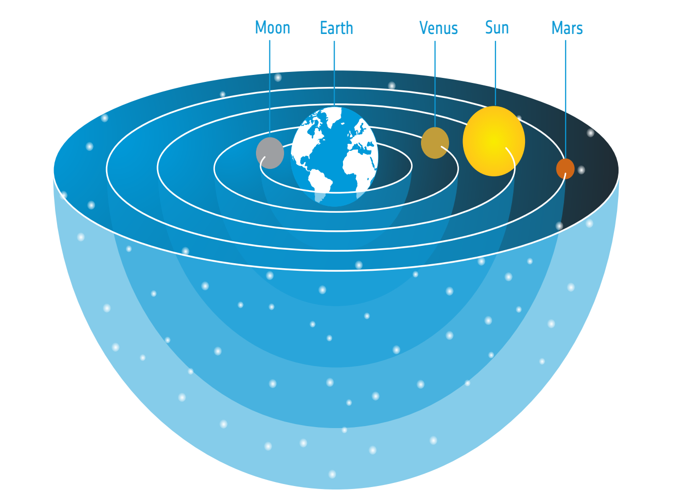
In this activity, students will use an elliptical board to obtain speed and distance measurements for an object in an elliptical orbit. The results are then plotted on a graph of speed against time in order to understand how gravity effects (or changes) the speed of a planet or a satellite in an elliptical orbit.

→ BACKGROUND

A short history of geocentricism

For thousands of years, philosophers and astronomers argued about the nature of the structure of the Solar System and beyond. Two conflicting models for our Solar System emerged: geocentric (or Earth-centred) and heliocentric (or Sun-centred).

Figure 1

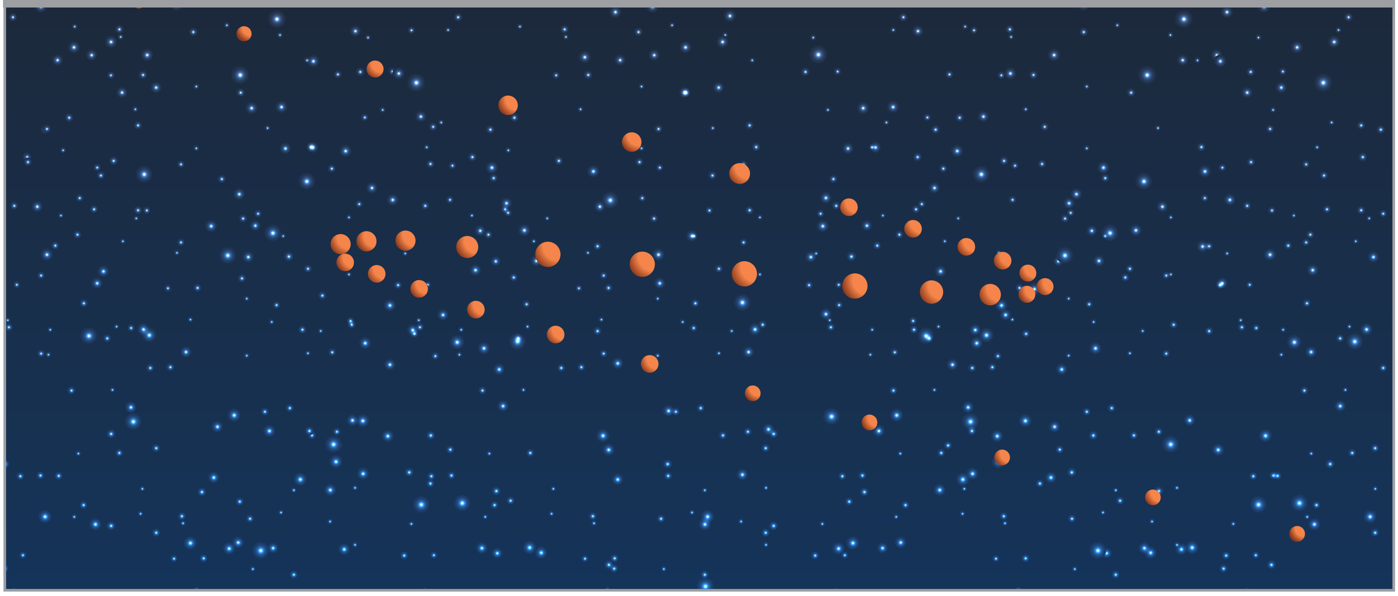


↑ Geocentric model – the Earth lies at the centre of the Universe.

Around 200 BC, the ancient Greek astronomer Aristotle was a supporter of the geocentric model (Figure 1). He proposed that the planets (and the Sun) moved at uniform speeds along circular paths around the Earth, which was at the centre of the Universe.

There were however problems with this model. At certain times, when viewing Mars, it seemed to move across the sky in an odd way (Figure 2). Instead of continuing on its path, Mars would double back on itself for a short while before continuing along in the sky. This effect could not be explained with a purely geocentric model.

Figure 2

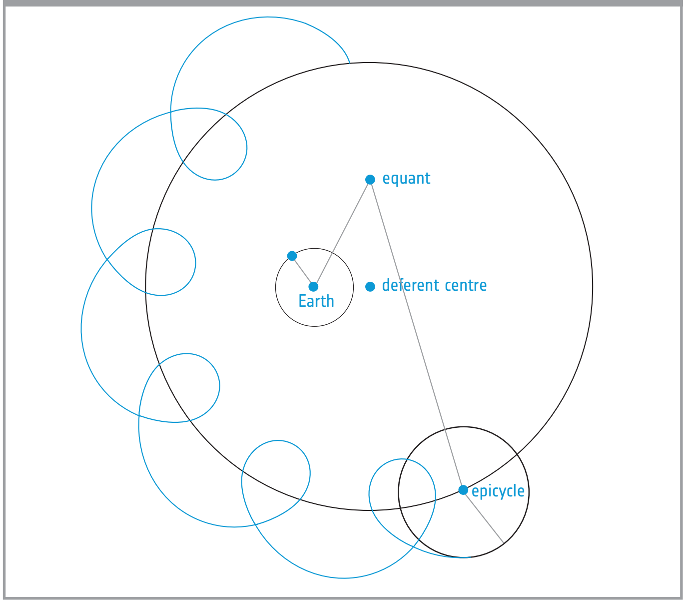


↑ The apparent motion of Mars in the sky during retrograde motion. For an animation showing the motion of Mars in the night sky, see the Links section.

Nearly 400 years later, Ptolemy put forward his solution to this problem. The Earth was still placed at the centre of the Universe, but the planets moved with secondary orbits called epicycles along their main orbital path (Figure 3). This could then partially explain and predict the observed **retrograde motion*.**

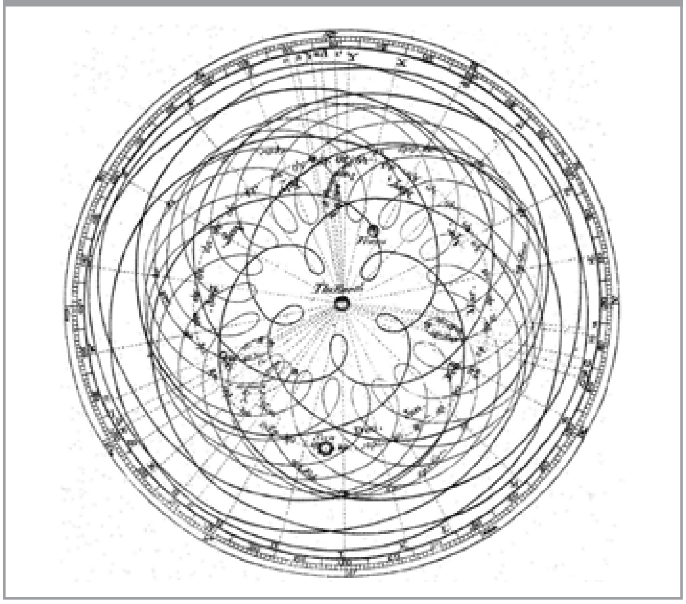
However, in order for this system to work, Ptolemy had to construct a range of complicated epicycles (Figure 4). It was really more of a 'fix' to make the evidence fit a geocentric model.

Figure 3



↑ Epicycles can be used to explain retrograde motion. For animations on epicycles see the Links section.

Figure 4



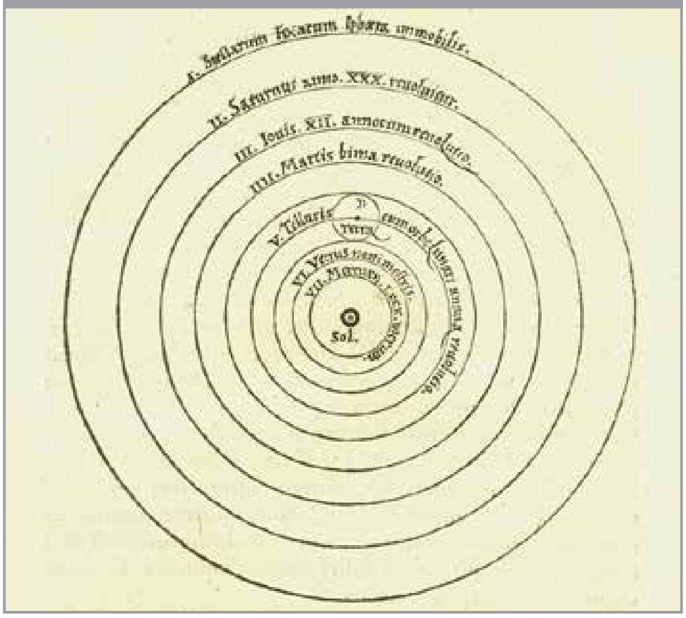
↑ Ptolemy's full solution was incredibly complicated.

A short history of heliocentricism

In 1543, Nicolaus Copernicus published 'De revolutionibus orbium coelestium' (On the Revolutions of the Celestial Spheres) whereby he argued that the Universe actually followed a heliocentric model (Figure 5). This started the Copernican revolution. Great thinkers slowly began to adopt this revolutionary model.

However, one problem remained. All orbiting bodies were still thought to have circular orbits and so the heliocentric model could also not explain all observations of the planetary movement. In particular, the orbit of Mars still did not fit the constraints of a circular orbit.

Figure 5



↑ Copernicus' heliocentric model of the Solar System.

***Retrograde motion of a planet:** Apparent motion of a planet in the night sky in the direction opposite to what is normally observed (prograde motion).

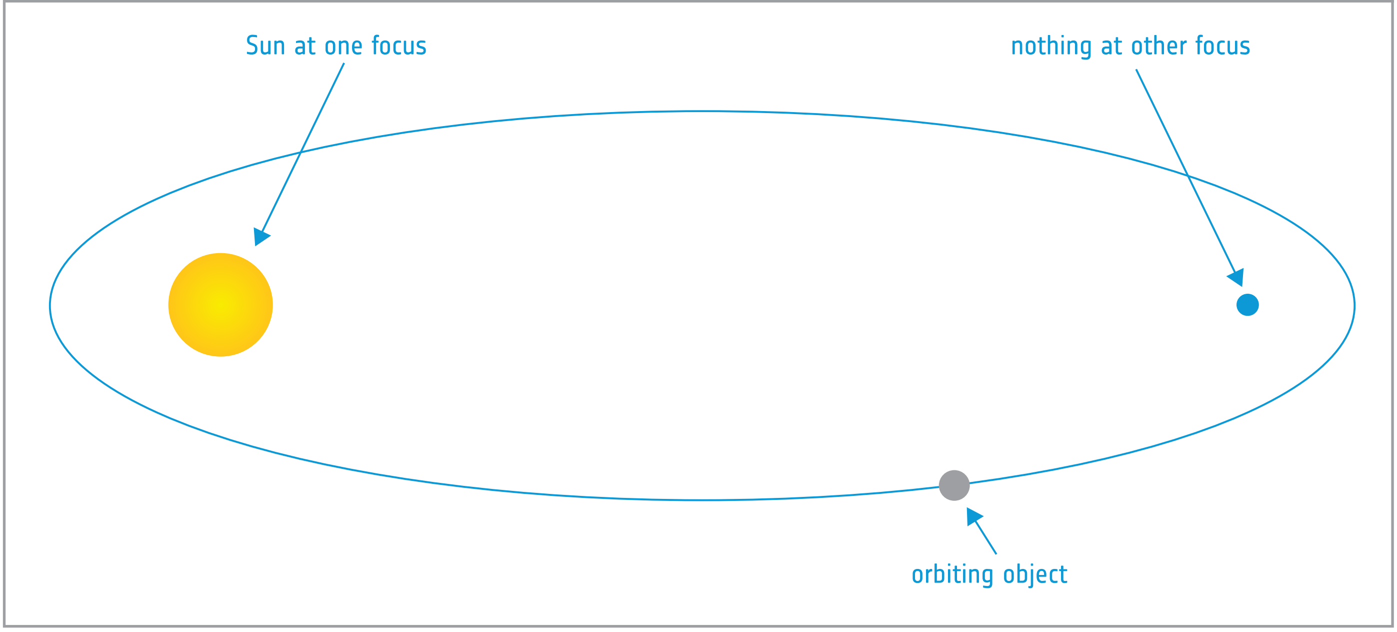
Kepler’s revelation on the nature of orbits

In the early 1600s, astronomer Johannes Kepler revolutionised our view of the Solar System and the nature of orbits. After meticulous analysis of data of the planet Mars’ observed motion in the night sky, Kepler concluded that the orbits of the planets must be elliptical rather than circular. With further study and calculation, Kepler was able to derive three laws that applied to all objects in an orbit.

Kepler’s laws of planetary motion

Kepler’s first law: A planet orbiting the Sun follows an elliptical path with the Sun at one focus (Figure 6).
Kepler’s second law: A line joining a planet and the Sun sweeps out equal areas in equal intervals of time.
Kepler’s third law: The square of a planet’s **orbital period*** is directly proportional to the cube of the semi-major axis of the orbit.

Figure 6



↑ Kepler made the revolutionary discovery that planetary orbits were elliptical.

For further information see the animations of Kepler’s first, second and third laws, as well as the ESA ATV-2 educational video 'Johannes Kepler' in the Links section.

The significance of these laws to planetary orbits and Solar System exploration are discussed later in the guide.

* **Orbital period**: time taken to complete one orbit.

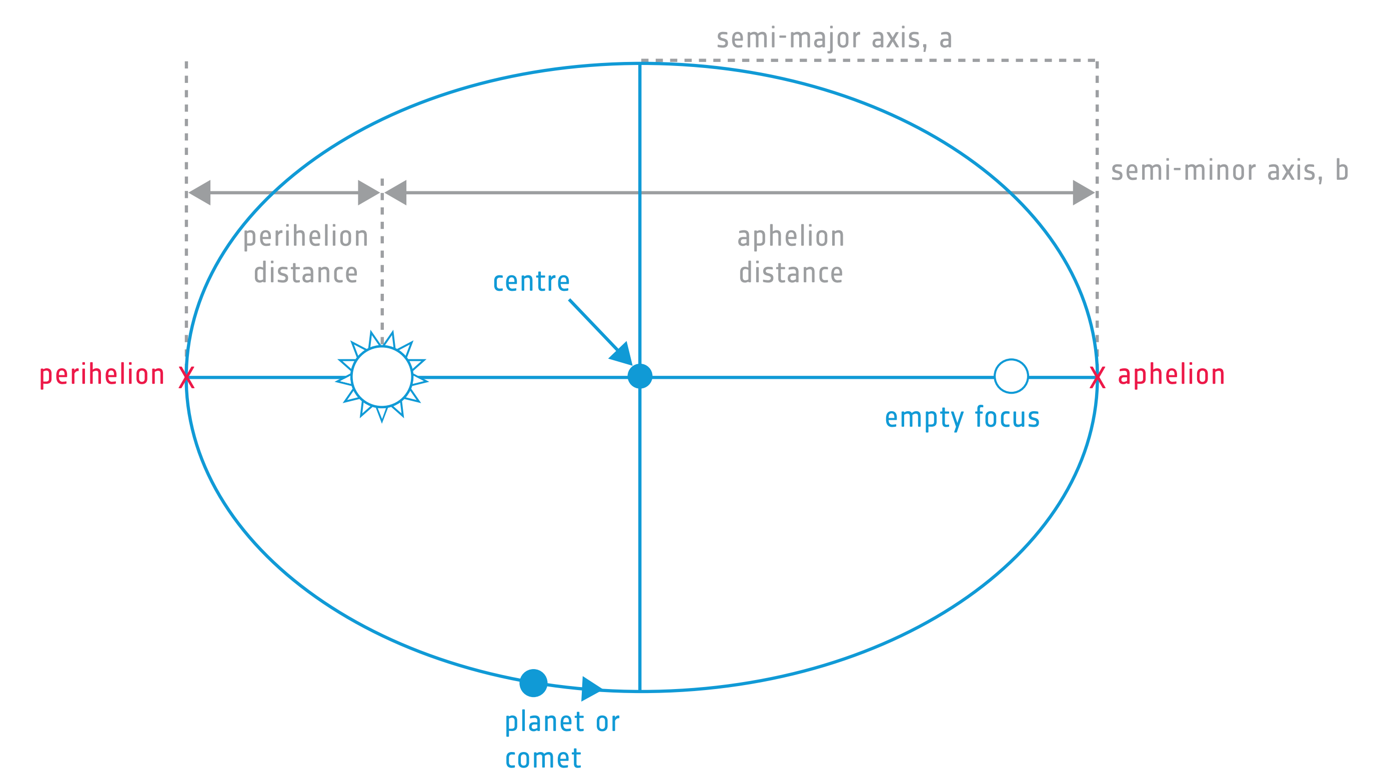
Properties of elliptical orbits

In order to effectively analyse the properties of an object in orbit, and apply Kepler's laws in a meaningful way, we need to define some key terms:

Axes

An ellipse is a curve on a plane that surrounds two foci. The sum of the distance from any point on the ellipse to the two foci always stays the same. This can be demonstrated with a piece of string (see Figure A1 in the Activity section).

Figure 7



↑ Properties of an elliptical orbit, including the (semi-) major and (semi-) minor axes, and the locations of perihelion and aphelion.

To understand orbits we need to define two properties – the major axis and the minor axis (Figure 7). The major axis is the longest diameter of an ellipse that passes through the two foci and the centre. The minor axis is the line that bisects the major axis. Both of these lines, and the corresponding locations of an orbital object on the ellipse play important roles in analysing the speed and energy of the orbital object.

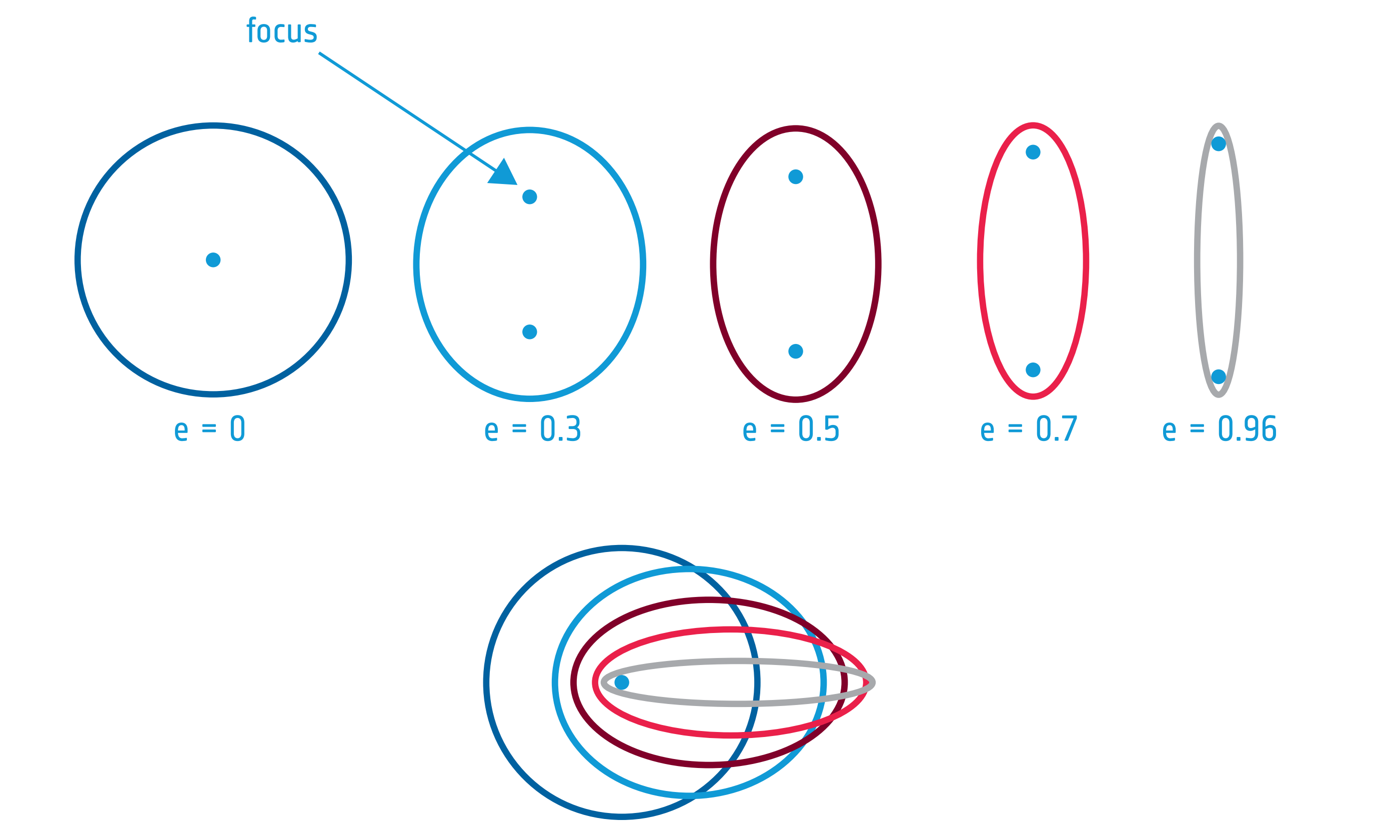
Another useful term for calculating the properties of an orbit is the semi-major axis and the semi-minor axis (Figure 7). The semi-major axis is half the length of the major axis, and the semi-minor axis is half the length of the minor axis. For a circle, both of these axes are the same, effectively the radius of the circle.

Eccentricity
Eccentricity is a measure of how far an ellipse is from being perfectly circular (Figure 8). In Figure 8 eccentricity is denoted by 'e'.

A circle is a special ellipse where the two foci overlap, creating a single focus. Perfect circles have an eccentricity of 0.

As the ellipse becomes more eccentric, the value of 'e' increases. The range for elliptical eccentricity is: $0 < e < 1$. A parabola has an eccentricity of 1. When $e > 1$, the curve is a hyperbola.

Figure 8



↑ The eccentricity of different ellipses. As eccentricity increases, an ellipse appears to be more 'squashed'.

Orbital locations
When considering the energy and velocity of an orbital object, we need to think about where an object will have maximum kinetic energy (and therefore minimum gravitational potential energy), and where an object will have minimum kinetic energy (and therefore maximum gravitational potential energy). This point is expanded further in the Discussion extension and Figure A5.

The point at which the major axis intersects the orbital path closest to the Sun is known as perihelion (Figure 7). The point at which the major axis intersects the orbital path furthest from the Sun is known as aphelion.

Comets

One group of objects that can orbit the Sun with highly elliptical (highly eccentric) orbits are comets (Figure 9). These small, icy worlds, originate primarily from two regions of the Solar System. Short period comets (those with an orbital period of less than 200 years) originate from the Kuiper Belt, a disc-like collection of frozen remnants from the formation of the Solar System just beyond the orbit of Neptune.

Long period comets (those with orbital periods of up to tens of thousands of years) are thought to originate from a spherical halo of icy material towards the edge of our Solar System known as the Oort Cloud. Reaching out to a distance of many thousands of **astronomical units (AU)***, the Oort Cloud is too far away to be imaged directly. Instead we must track a long period comet orbit back to determine its origin (Figure 10).

Figure 9

↑ Photo of comet Hale-Bopp taken in Croatia.

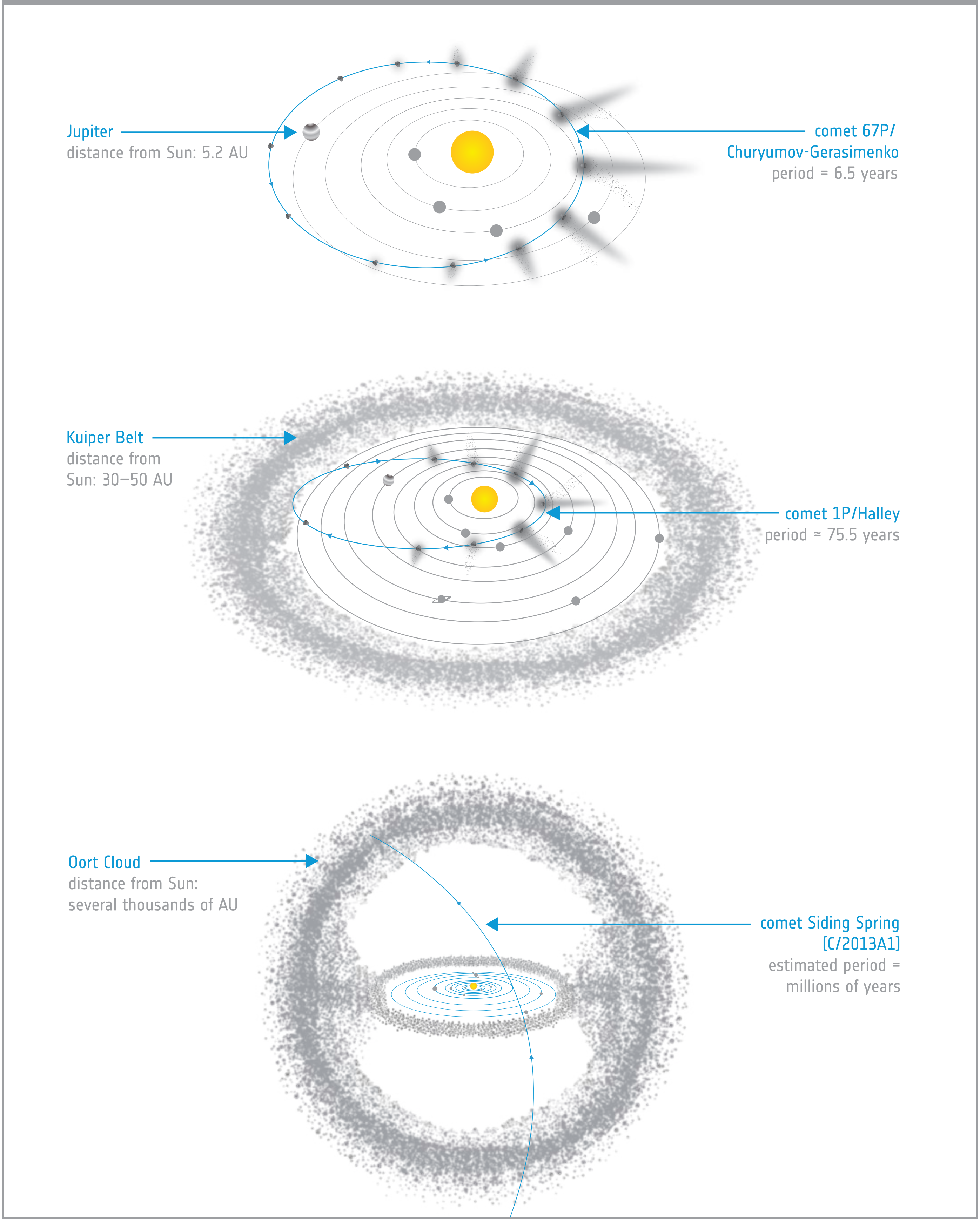
Comets will, for the most part, orbit the Sun in stable orbits. However, Kuiper Belt objects can be influenced by the gravitational fields of the giant planets (Jupiter, Saturn, Uranus and Neptune), and Oort Cloud objects by **gravitational perturbations*** caused by the motions of other stars. These perturbations can occasionally change the orbits of these small, cold worlds, sending them racing towards the inner Solar System.

As these objects approach the Sun they begin to heat up and the ice within them **sublimates***. The original structure is now referred to as a 'nucleus'. As the nucleus heats up it gives off gas and dust forming a thin, but vast, 'atmosphere' known as the coma (Figure 11).

As the comet gets even closer to the Sun, the interaction of the coma with increasing levels of solar radiation and the solar wind produce the spectacular 'tails' with which comets are most often associated. Very occasionally the tails are bright enough to be seen by an observer on Earth in daylight.

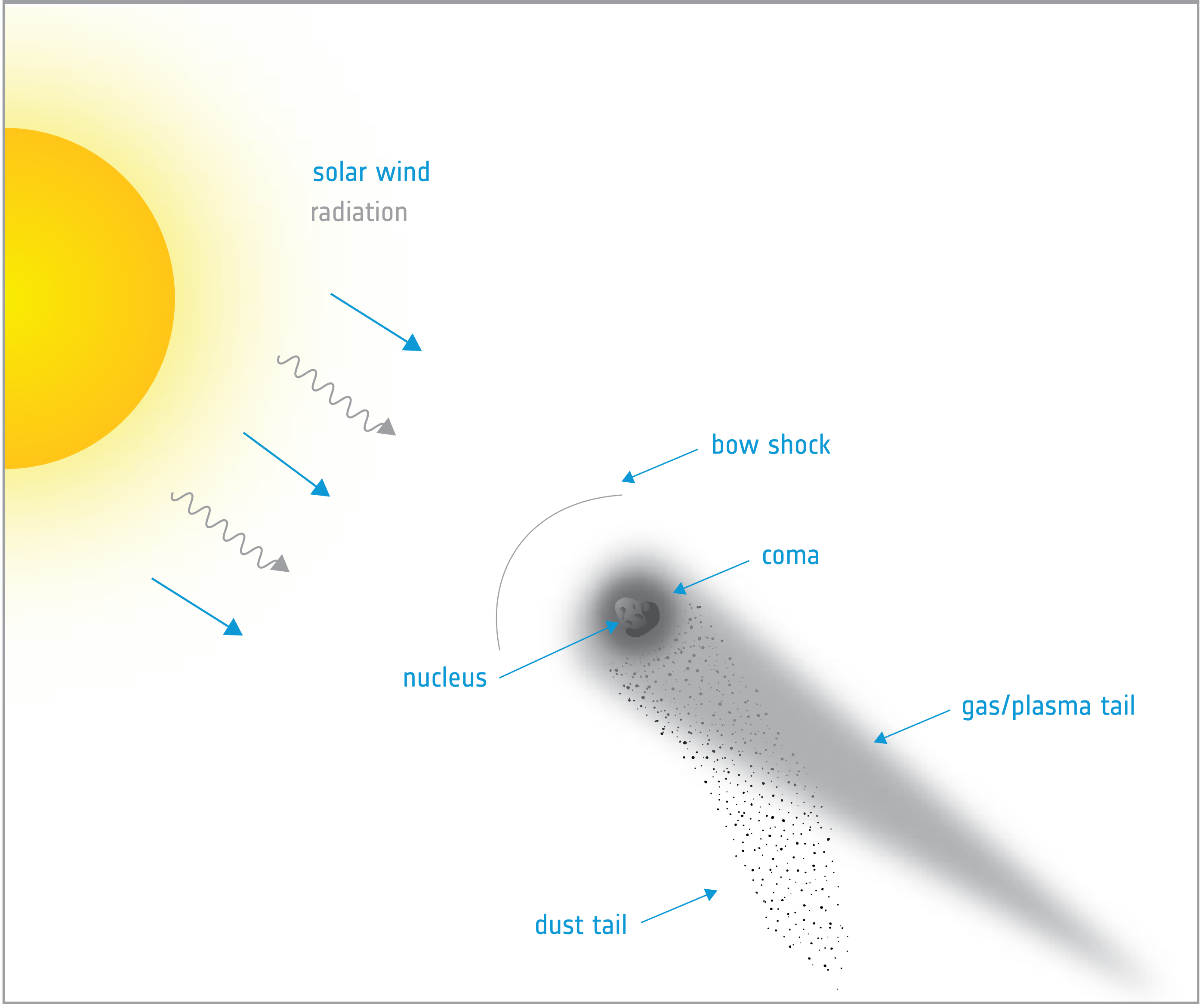
***Astronomical unit (AU)**: 1 AU is the average distance between the Earth and the Sun, or the Earth's orbital radius, which is approximately 150 million km.
***Gravitational perturbations**: changes to the orbit of a celestial body (e.g. planet, comet) due to interactions with the gravitational fields of other celestial bodies (e.g. giant planets, other stars).
***Solar wind**: a stream of high energy particles (plasma) being emitted by the upper atmosphere of the Sun in all directions. It contains mostly electrons and protons.
***Sublimate (sublimation)**: when heating causes a substance to change directly from the solid phase to the gas phase, bypassing the liquid state. When the gas is re-cooled, it typically forms a solid deposit.

Figure 10



↑ Comet orbits in the Solar System.

Figure 11



↑ The anatomy of a comet.

More details about comet orbits can be found in the Discussion section.

For more information on the structure, composition and significance of comets please refer to the ESA teach with space - cooking a comet | P06 classroom resource (see the Links section).

***Bow shock (comet)**: surface of interaction between the ions in the comet coma and the solar wind. The bow shock forms because the relative orbital velocity of the comet and the solar wind are supersonic. The bow shock forms upstream of the comet in the flow direction of the solar wind. In the bow shock, large concentrations of cometary ions build up and load the solar magnetic field with plasma. The result is that the field lines bend around the comet, entraining the cometary ions, and forming the gas/plasma/ion tail.

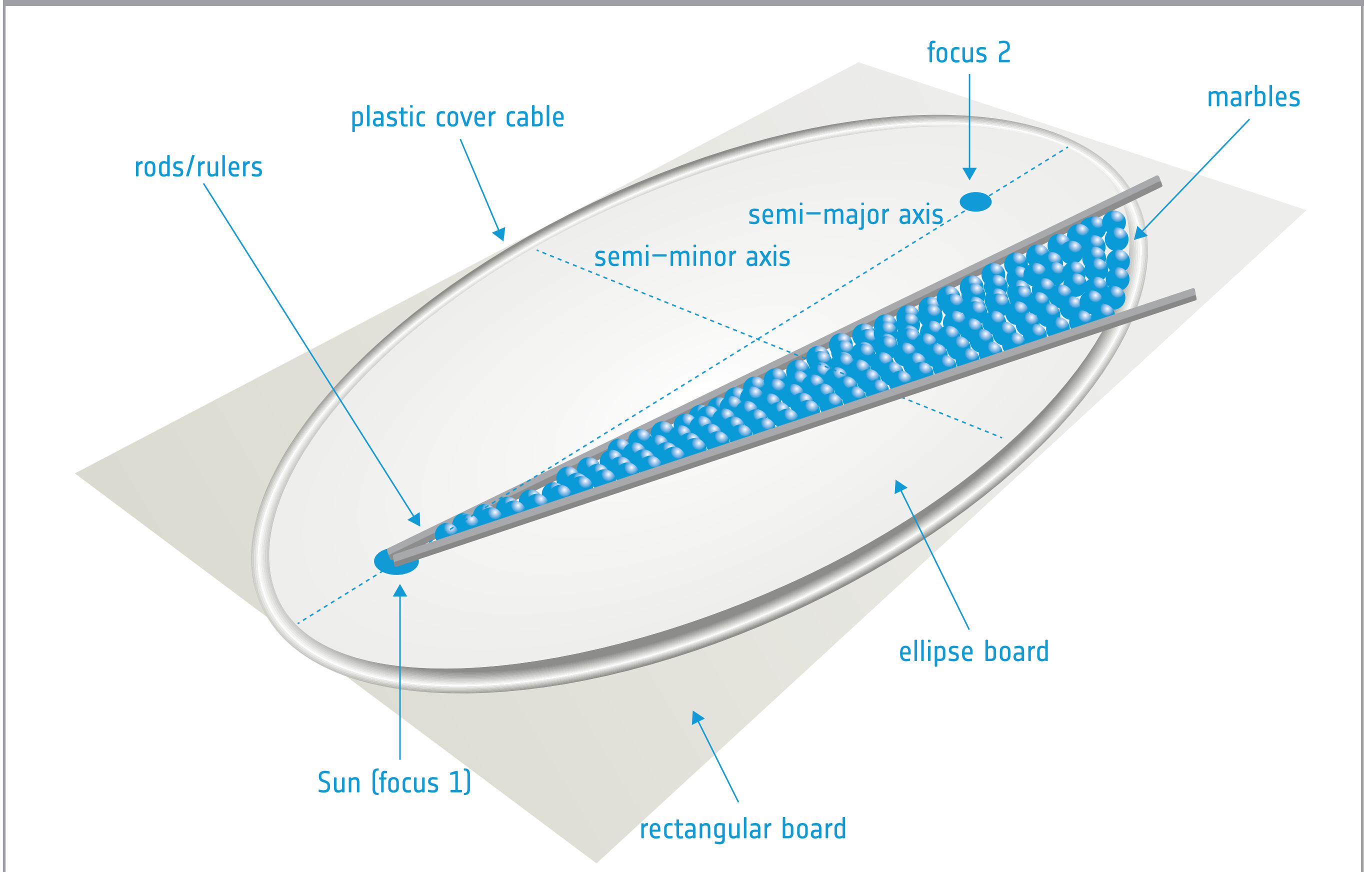
Measuring speed and distance on an elliptical board

In this activity, students will use an elliptical board to obtain speed and distance measurements for an object in an elliptical orbit. The results are then plotted on a graph of speed against time in order to understand how gravity affects (or changes) the speed of a satellite in an elliptical orbit. Student worksheets and instructions are provided later in the document.

Equipment

- Ellipse board – made in advance, for instructions see Appendix: Elliptical board template instructions
- About 75 small marbles (a few small ones are useful to fill in the sharp end of the wedge)
- 2 x metre rulers or rods
- 50 cm of string
- Non-permanent marker

Figure A1



↑ Experiment setup. For instructions on how to construct the board, see Appendix: Elliptical board template instructions.

Health & Safety

This is a very low risk activity. No extra precautions need to be taken.

Instructions

Note: the elliptical board represents the path of a comet in orbit around the Sun. Please also refer to the accompanying video: ESA teach with space – marble-ous ellipses | VP02.

1. Using a non-permanent pen, mark a point on the ellipse as far from the Sun (focus 1) as possible – at aphelion. A metre ruler or rod is placed across this point, to the Sun (focus 1). This ruler will pivot about the Sun (focus 1) throughout the experiment. Refer to Figure A1.

2. Place a second ruler/rod to one side, with one end at the Sun (focus 1). This ruler will also pivot about the Sun (focus 1) throughout the experiment. Place the marbles into the space between the two rulers. Move the second ruler/rod until the marbles just fit into the space. Make a second mark on the ellipse on the inside of where the second ruler crosses it. Note, the number of marbles used will determine the number of measurements to be made – fewer marbles will give more data points.

3. Move both rulers around the ellipse until the first ruler is where the second ruler was originally (the second ruler is further along the ellipse). Then move the second ruler until the marbles just fit into the space between the two rulers as in step 2 (Figure A1). Again, make a mark on the inside of where the second ruler crosses the ellipse.

4. Repeat step 3 until the full ellipse has been covered.

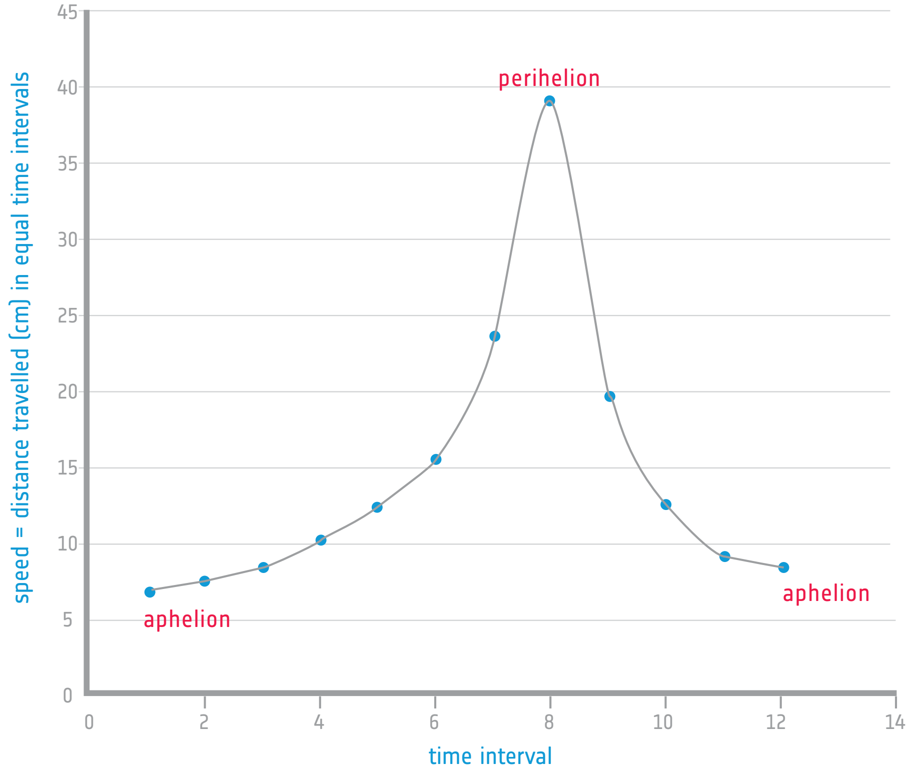
5. Use string to measure the distances around the outer edge of the ellipse between the marks. Record these values in a table along with the time intervals (number of the area measured – the first area is interval 1, the second area is interval 2 etc.). The measured distances are speeds as they are the distance travelled over equal time intervals.

6. Plot a graph of speed (the measured distances) against time (interval number) for each section. Figure A2 shows an example table and graph. The gradient of the curve/line in the graph will depend on the eccentricity of the ellipse – a more eccentric ellipse will give a steeper gradient whilst a less eccentric (more circular) ellipse will give a less defined peak.

7. Note that, the more elliptical the board, the steeper the gradient of the speed vs time graph.

Figure A2

area number	distance
time interval	speed
1	6.7
2	7.5
3	8.4
4	10.1
5	12.2
6	15.5
7	23.6
8	39.2
9	19.8
10	12.5
11	9.2
12	8.4



↑ Example table and graph.

Discussion

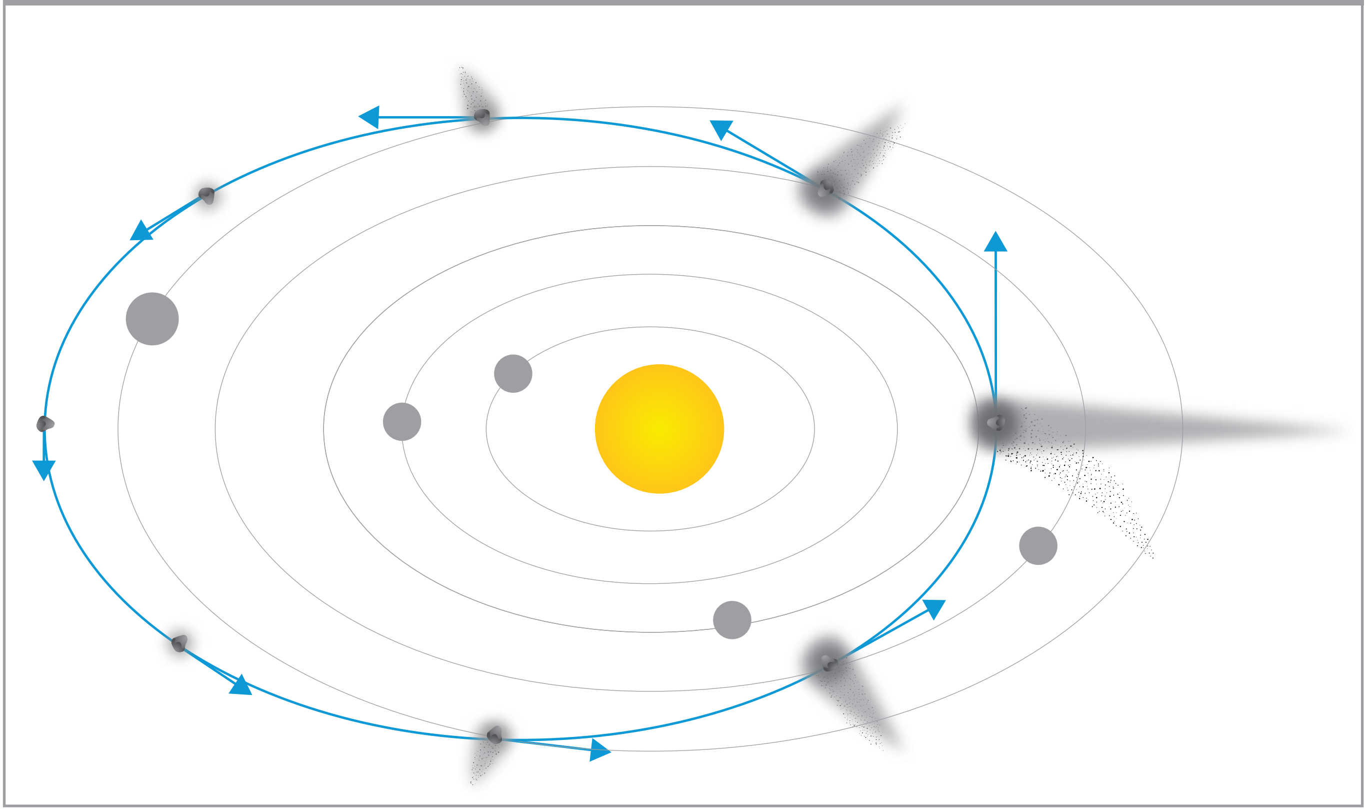
Comet observations and explanations

A comet has a force of attraction due to gravity pulling its mass towards the Sun.

The track that a comet follows depends upon two factors - its speed and initial direction. For one object to orbit another, a centripetal force (a force acting towards the focus that is the Sun) is required, to constantly change the path of motion, accelerating or decelerating the orbiting body in the process (Figure A3).

In a stable orbit the gravitational pull of the Sun accelerates the comet, causing the speed to increase until it reaches perihelion. Once it has passed perihelion, the gravitational pull from the Sun now opposes the motion of the comet, causing it to decelerate and lose speed.

Figure A3



↑ How the velocity vector (blue arrows) of a comet in orbit around the Sun changes with orbital position. The variation is due to the centripetal acceleration provided by the gravitational attraction of the Sun. The change in the comet tail is also shown.

If a comet was in a circular orbit the centripetal acceleration would always be perpendicular (at 90°) to the velocity of the comet. In an elliptical orbit, the angle between the centripetal acceleration and the velocity varies. It is this variation in the centripetal acceleration that leads to the changing speed of a body in an elliptical orbit.

What does the gradient of the line (Figure A2) at any point tell us?

Since the gradient of a speed-time graph gives the rate of change of speed, the gradient of the line is a measure of the acceleration of the comet at that point. The maximum acceleration (gradient) will occur as the comet approaches perihelion, the point at which the comet will be travelling at its fastest speed in the orbit. After passing perihelion, the comet will experience the maximum deceleration, and will continue to decelerate until it reaches aphelion, the point in its orbit where it travels with the lowest speed.

What does the area under the graph tell us?

The area under the graph shows the distance travelled by the comet. It is easy to see that as the comet approaches perihelion, the distance covered by the comet per time section, increases due to its increasing speed. Similarly, as the comet approaches aphelion, it is travelling at a lower speed and covers a shorter distance per unit time.

Discussion extension

The activity can be extended by discussing what parameters would affect the orbit such as the original speed and direction of orbiting body and the masses of the orbiting body and the central star.

For more information see the ATV-4 'Albert Einstein' educational video (refer to the Links section).

Students can also use Kepler's third law to analyse the effect of the semi-major axis (r) on the orbital period of a comet.

Kepler's third law

$$T^2 = \left(\frac{4\pi^2}{GM}\right) a^3$$

T = time period for one revolution
a = average radius of orbit
G = universal gravitational constant
M = mass of the Sun

The larger the semi-major axis, the longer the orbital period. This is also observed with planets in the Solar System – the further away from the Sun a planet is, the longer its period.

Energy considerations and Near Earth Objects

As a comet travels on its elliptical path it experiences a continual cycle of gravitational potential energy being transferred into kinetic energy (as it heads in towards the Sun), and the reverse (as it heads away from the Sun). Figure A5 shows how the kinetic and gravitational potential energy of an orbiting body varies along its orbital path.

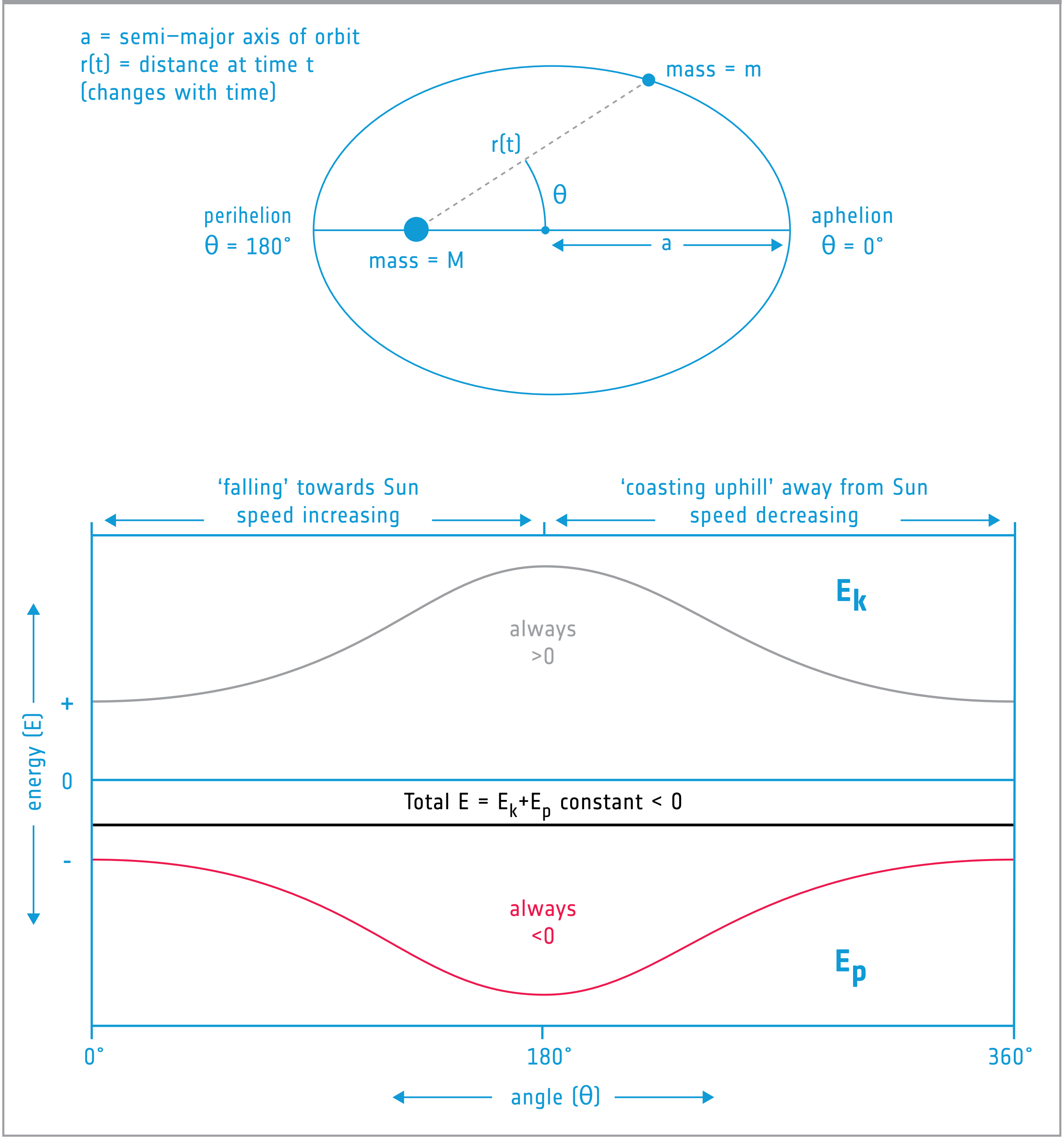
Since the total energy that the comet has must remain constant, this means that:

$$\text{Kinetic energy } (E_K) + \text{Gravitational potential energy } (E_P) = \text{constant}$$

Using this information, and the ability to calculate the orbital parameters from Kepler's laws, scientists at ESA's Near Earth Objects Coordination Centre, near Rome, Italy, can calculate the kinetic energy of a comet or asteroid at any point in its orbit.

This is important because occasionally, the elliptical orbit of a comet or asteroid will overlap with the orbit of the Earth leading to the potential for a collision. By extending Kepler's laws and using the equations of gravitational potential energy and kinetic energy, the potential impact of a collision can be assessed.

Figure A4



↑ How the kinetic and potential energy of an orbiting body change with orbital position. The total energy will always remain constant.

→ CONCLUSION

Understanding the nature of orbits is a critical skill for explaining the observations of celestial bodies. By linking Kepler's laws with ideas of kinetic and gravitational potential energy, not only can we interpret a comets orbit and any potential effects a collision may have, we can also model the complex orbital dance that spacecraft like Rosetta must undergo in order to enhance our knowledge of space. This activity also allows a skilful teacher to discuss and develop practical skills including precision and accuracy in measurement, planning tables, drawing good graphs, lines of best fit and the meaning of gradients.

Measuring speed and distance on an elliptical board

In this activity, you will use an elliptical board to obtain speed and distance measurements for a comet in an elliptical orbit.

According to Kepler's second law of planetary motion: a line joining a planet and the Sun sweeps out equal areas in equal intervals of time.

The area covered will be represented using a large number of marbles.

You need to record the distance around the orbit for each time period.

The distance you will measure actually represents the average speed of a comet. Take into account that **$v=d/t$**, where: d is distance in metres (m), t is time in seconds (s), and v is speed in m s^{-1}.

Record your results in the table below. You will have to choose your units of measurement depending on the actual size of your orbit. For example, in this experiment, we shall say that the time period is measured in seconds and the average speed in cm s^{-1}. The number of recorded measurements may vary depending upon the number of marbles, so be prepared for about ten measurements.

Time	Speed (cm s^{-1})

Plot a graph of speed (y axis) against time (x axis) - you can do this with graph paper or by using a spreadsheet. Label the aphelion and perihelion.

Make sure that the graph is large and fills the paper.

Draw in a curved line of best fit that represents the motion of the comet.
Read the following questions and then write a conclusion explaining the shape of the graph trying to answer as many of the questions as you can.

Questions

1. The gradient of the line is a measure of the acceleration of the comet. A downward slope shows a deceleration. How does the gradient change during the orbit?

2. The area under the graph represents the distance that the comet has travelled. How does this distance change?

3. Where is the comet travelling fastest? Where is it travelling slowest? Why?

4. Gravity is stronger closer to the Sun and weaker further away. How does gravity affect the speed of the comet?

5. What energy changes are taking place during an orbit?

6. What would the difference be for a comet in an orbit with a larger eccentricity?

7. The planets are also orbiting the Sun and have their own gravitational fields. How might they effect the path of a comet?

→ SPACE CONTEXT @ ESA

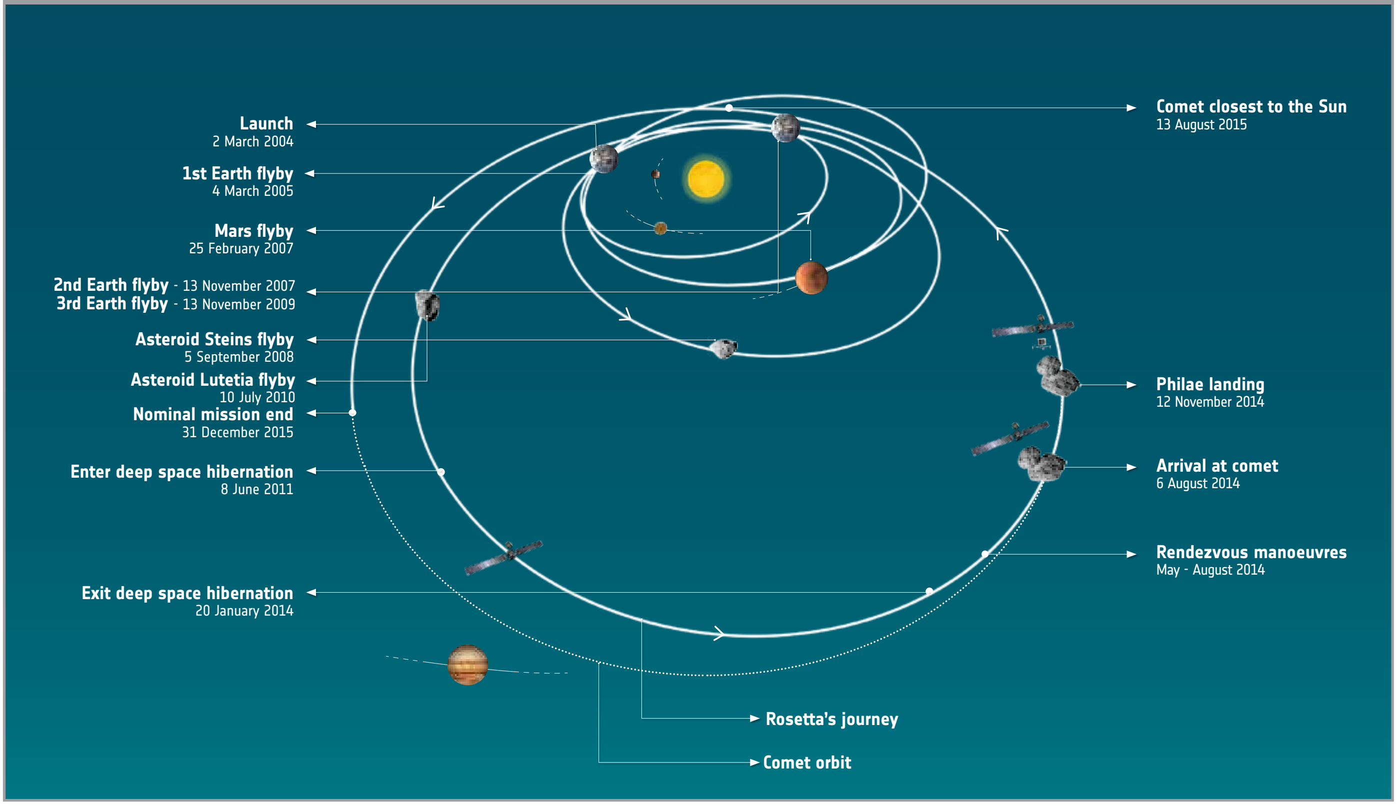
Rosetta

The ESA Rosetta mission to comet 67P/Churyumov-Gerasimeko was launched in 2004 on a 10 year journey to rendezvous with, and land on, the nucleus of a comet.

Rosetta's prime objective is to help understand the origin and evolution of the Solar System. A comet's composition reflects that of the pre-solar nebula out of which the Sun and the planets of the Solar System formed, more than 4.6 billion years ago. An in-depth analysis of comet 67P/Churyumov-Gerasimenko, by Rosetta and its lander, will provide essential information to understand how the Solar System formed.

There is convincing evidence that comets played a key role in the evolution of the planets, because cometary impacts are known to have been much more common in the early Solar System than today. Comets, for example, might have brought water to Earth. The chemistry of the water in comet 67P/Churyumov-Gerasimenko will be analysed to see if it is the same as that of Earth's oceans. In addition to ice and dust, comets contain many complex molecules, including organic materials that may have played a crucial role in the evolution of life on Earth.

Figure 12



↑ ESA's Rosetta spacecraft performed a series of planetary 'slingshots' in order to reach its destination.

***Flyby:** close passage of a spacecraft around a planet or other celestial body. If the spacecraft uses the gravitational field of a celestial body to boost the spacecraft's velocity and change its trajectory, this is called a swing by or gravity assist manoeuvre.

In order to get to the comet, Rosetta had to perform a series of gravitational 'slingshots', where the gravity of a celestial body is used to help accelerate the spacecraft (Figure 12). To fly deeper into space, Rosetta needed to make four slingshot manoeuvres including three close **fly-bys*** of the Earth, and one with Mars. Each slingshot altered the kinetic energy of Rosetta, and therefore changed the velocity of the spacecraft, altering the dimensions of the elliptical orbit.

With such a long journey to make, Rosetta was placed into hibernation mode in June 2011 to limit its consumption of power and fuel, and to minimise operating costs. Almost all of Rosetta's electrical systems were switched off, with the exception of the computer and several heaters.

In January 2014, Rosetta's pre-programmed internal 'alarm clock' carefully woke up the spacecraft in preparation for its rendezvous with comet 67P/Churyumov-Gerasimeko. Following wake-up, the orbiter's 11 science instruments and the 10 lander instruments were reactivated and readied for science observations. Then a series of ten critical orbital correction manoeuvres were carried out to reduce the spacecraft's velocity relative to the comet, and therefore match its elliptical orbit.

After Rosetta arrived at comet 67P/Churyumov-Gerasimeko, on 6 August 2014, it began further manoeuvres to place it into an 'orbit' around the comet nucleus. From this vantage point, Rosetta's suite of instruments are providing a detailed scientific study of the comet scrutinising and mapping the surface in unprecedented detail (Figure 13).

Figure 13

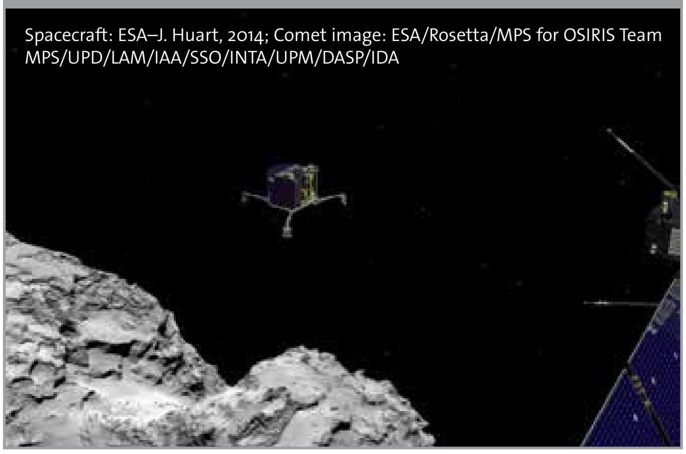
↑Four-image NAVCAM mosaic of comet 67P/Churyumov Gerasimenko, using images taken on 19 September 2014 when Rosetta was 28.6 km from the comet.

After the landing Rosetta will continue to accompany the comet on its elliptical journey. Rosetta will accelerate back towards the inner Solar System with the comet and will continue to study and watch from close quarters as the icy comet nucleus heats up as it approaches the Sun.

In November 2014, after mapping and analysing the comet nucleus for several months, Rosetta will deploy its lander Philae to attempt the first ever landing on a comet nucleus. As the comet has such low gravity, Philae will use harpoons and ice screws to attach itself to the surface. Figure 14 shows an artist's impression of Philae deploying onto the surface.

The Philae lander will use 10 instruments, including a drill, to collect samples of the surface and **spectrometers***, to directly analyse the structure and composition of the comet.

Figure 14



↑ The Philae lander will deliver unprecedented information about the surface and internal structure of a comet.

The International Space Station & the Automated Transfer Vehicle

In partnership with the United States, Russia, Japan and Canada, Europe is sharing in the greatest international project of all time - the International Space Station. The 360 tonne International Space Station (ISS, Figure 15) has more than 820 m^3 of pressurised space - enough room for its crew of six persons and a vast array of scientific experiments. Station construction began in November 1998 with the launch of Russia's Zarya module. The last major part of the Space Station delivered by a Space Shuttle was the AMS-02 instrument in May 2011.

With the assembly of the Space Station complete, and permanently crewed by six astronauts, more time than ever is being spent on experiments that cannot be done on Earth.

Europe's main contribution is the Columbus module, the primary research facility for European payloads aboard the ISS. Columbus provides a generic laboratory as well as facilities specifically designed for biology, biomedical research and fluid physics.

The areas of scientific study are many and diverse: from fundamental physics to human physiology, from new alloys to plant roots. The programme involves some 1500 scientists in hundreds of experiments, as well as a large and diverse group of industrial research and development users. The ISS thus provides the necessary conduit for researchers and the medical community to conduct multi-year investigations in a consistent microgravity environment.

Figure 15

↑ Automated Transfer Vehicle docked with The International Space Station.

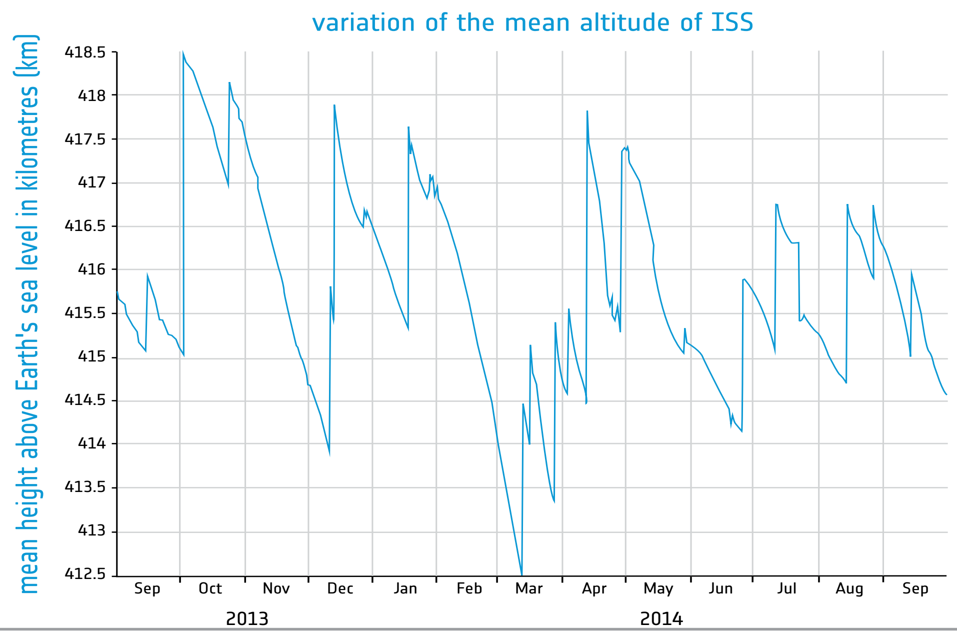
From its specific orbit **inclination***, the ISS also provides coverage of 90% of the world's populated area (75% Earth's surface), making it a valuable outpost for Earth and climate monitoring. Solar activity and cosmic radiation are also subjects of investigation from the ISS thanks to the external experiment capabilities.

Although each Space Station partner has distinct agency goals for research, everyone shares a unified goal to improve scientific and engineering knowledge for the improvement of quality of life on Earth and beyond.

Europe's second biggest contribution to the ISS after the Columbus module, is the Automated Transfer Vehicle (ATV), a supply ship lifted into orbit on an Ariane-5 launcher. ATV carries up to 7 tonnes of cargo, including provisions, scientific payloads and propellant. Once docked, the craft can use its engines to boost the Station to a higher orbit, counteracting the faint drag of Earth's atmosphere. The first spacecraft, ATV Jules Verne was launched in 2008 followed by ATV Johannes Kepler which was launched in 2011. The third, ATV Edoardo Amaldi was launched in 2012 whereas the fourth in the series, ATV Albert Einstein, was launched in 2013. The fifth and last, ATV Georges Lemaître was launched in July 2014.

The International Space Station orbits at a set **altitude***, at a particular inclination to Earth's equator, and at a certain **attitude***. ATV is capable of assisting ISS by making changes to its altitude and attitude, the first being relevant to this resource.

Figure 16



↑ The altitude range of the ISS over this period was higher than normal due to the enhanced re-boost capability of the ATV.

***Altitude:** height of ISS relative to Earth's sea level.
***Attitude**: the orientation of ISS relative to its orbital path.
***Inclination:** the angle of the plane of the orbit of ISS relative to Earth's equator.

The altitude of the ISS is determined primarily by safety and logistics considerations. It needs to be low enough to optimise transportation flights but also needs to be kept above 278 km (the so-called Minimum Recoverable Altitude) to avoid the danger of atmospheric re-entry. The ISS altitude profile is also managed to conserve propellant and minimise crew radiation exposure.

At its altitude of approximately 400 km, atmospheric drag causes the ISS to lower by about 100 - 200 m per day. The variation in decent rate is caused by changes in the density of the outer atmosphere, a consequence of solar activity.

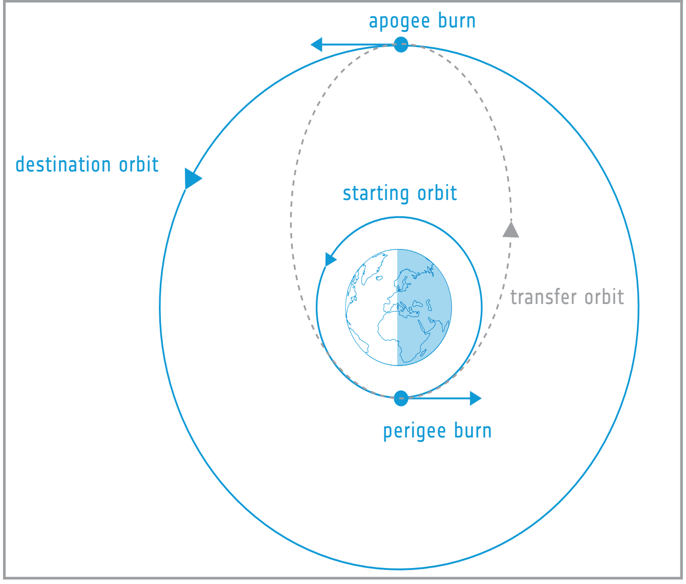
Visiting spacecraft, such as, ATV, Progress or Soyuz, are used to re-boost the altitude to counteract this degradation, or sometimes to avoid space debris. The Russian segment of the ISS also has thrusters allowing it to make small changes to the altitude of the ISS when no visiting vehicles are present. The re-boosts occur every 10 to 80 days.

The variation in altitude of the ISS between September 2013 and September 2014 is shown in Figure 16.

Each orbital reboost is a multi-step processes with 2 successive burns diametrically opposed to one another (see Figure 17).

The first burn increases eccentricity of the orbit while the second decreases it but at a higher altitude, with a net result in increased altitude and reduced velocity following Kepler's third law. Similar procedures are used for collision avoidance manoeuvres, whereby boosts are performed well ahead of time to increase altitude of the station, thus maximizing the distance between the foreign object and the Station.

Figure 17



↑Orbital reboost is a multi-step processes with 2 successive burns diametrically opposed to one another. The transition orbit is known as the Hohmann transfer orbit.

→ APPENDIX

Elliptical board template instructions

This section provides instructions to make the elliptical board required for the activity.

Equipment

- Stiff cardboard or wooden board
  - if the elliptical board template is used, the board should be approximately 75 cm by 60 cm
  - any size board can be used if drawing the ellipse using the method shown in Figure X1
- Plain paper or printed/photocopied elliptical track template
- Strong glue
- Pen or pencil
- String (if using the method in Figure X1)
- 2 pins
- Cord or plastic covered electrical cable (around 8 mm thickness works well)
  - 2 m (if using the template)

Instructions 1

This method uses the provided elliptical board template.

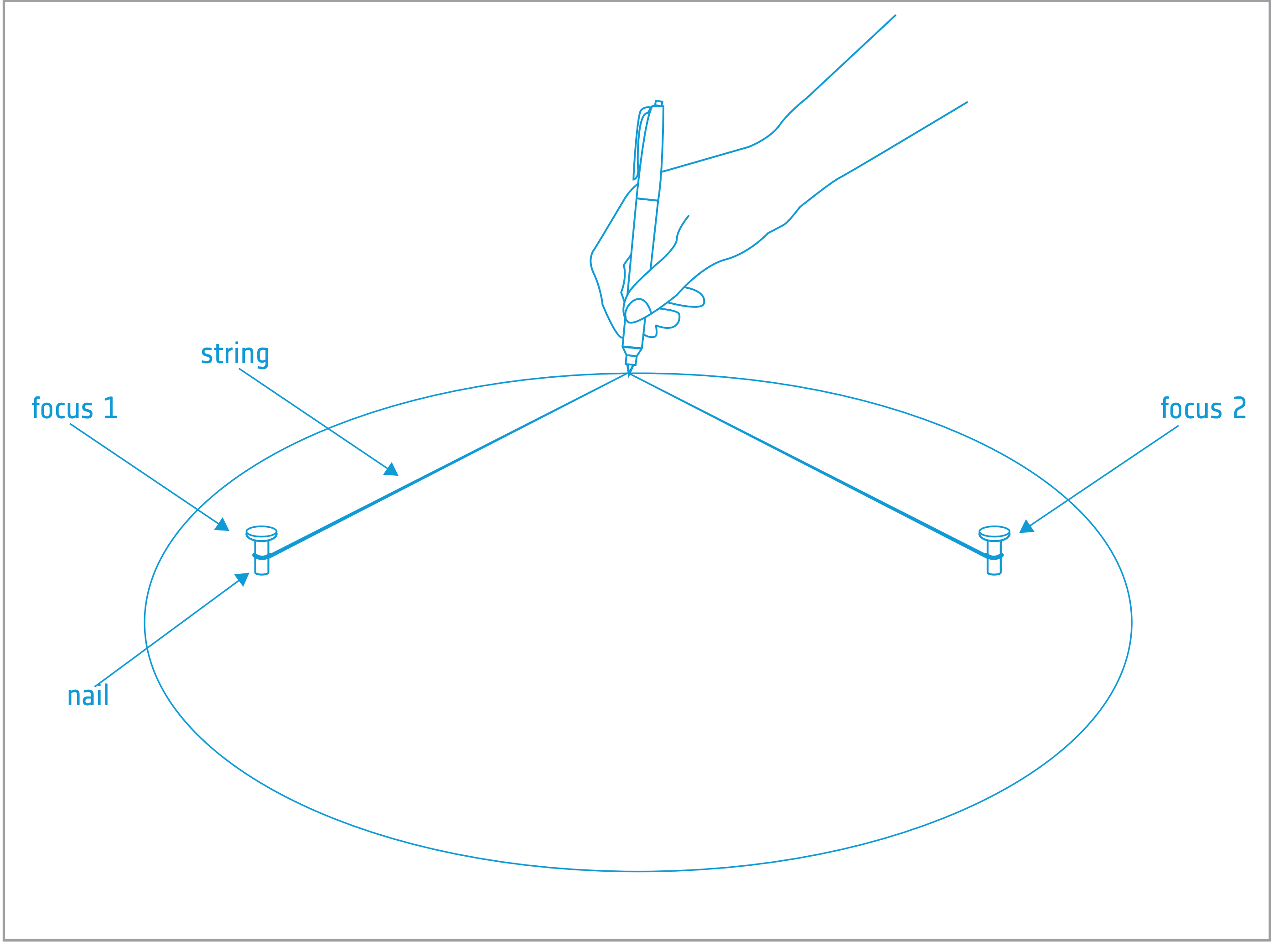
1. Print (or copy and scale) pages 29-32 to A3 size.
2. Carefully glue the pieces of paper together to form an ellipse.
3. Glue the cord or plastic covered cable onto the board following the line of the ellipse.

Instructions 2

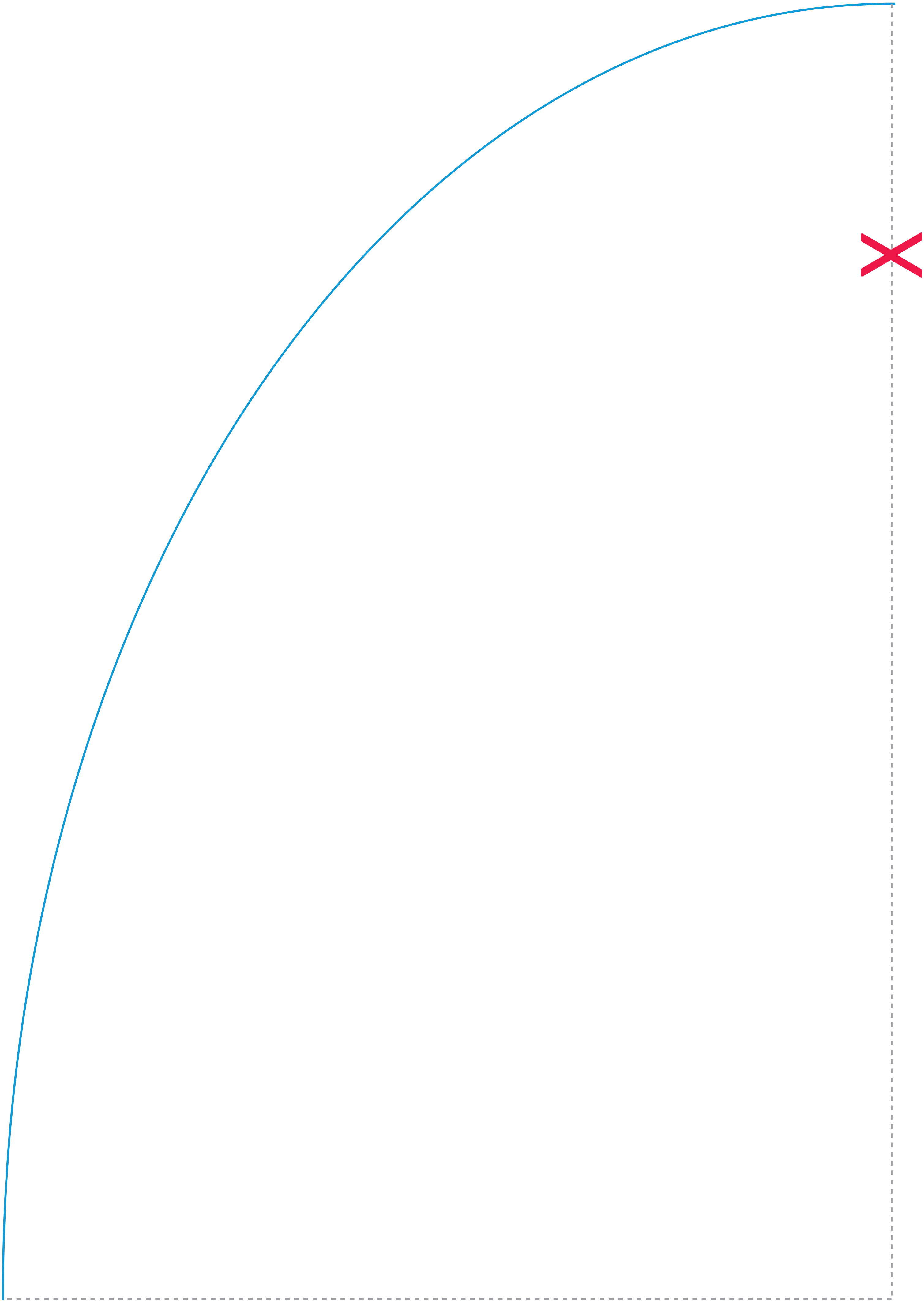
This method uses string to draw the ellipse.

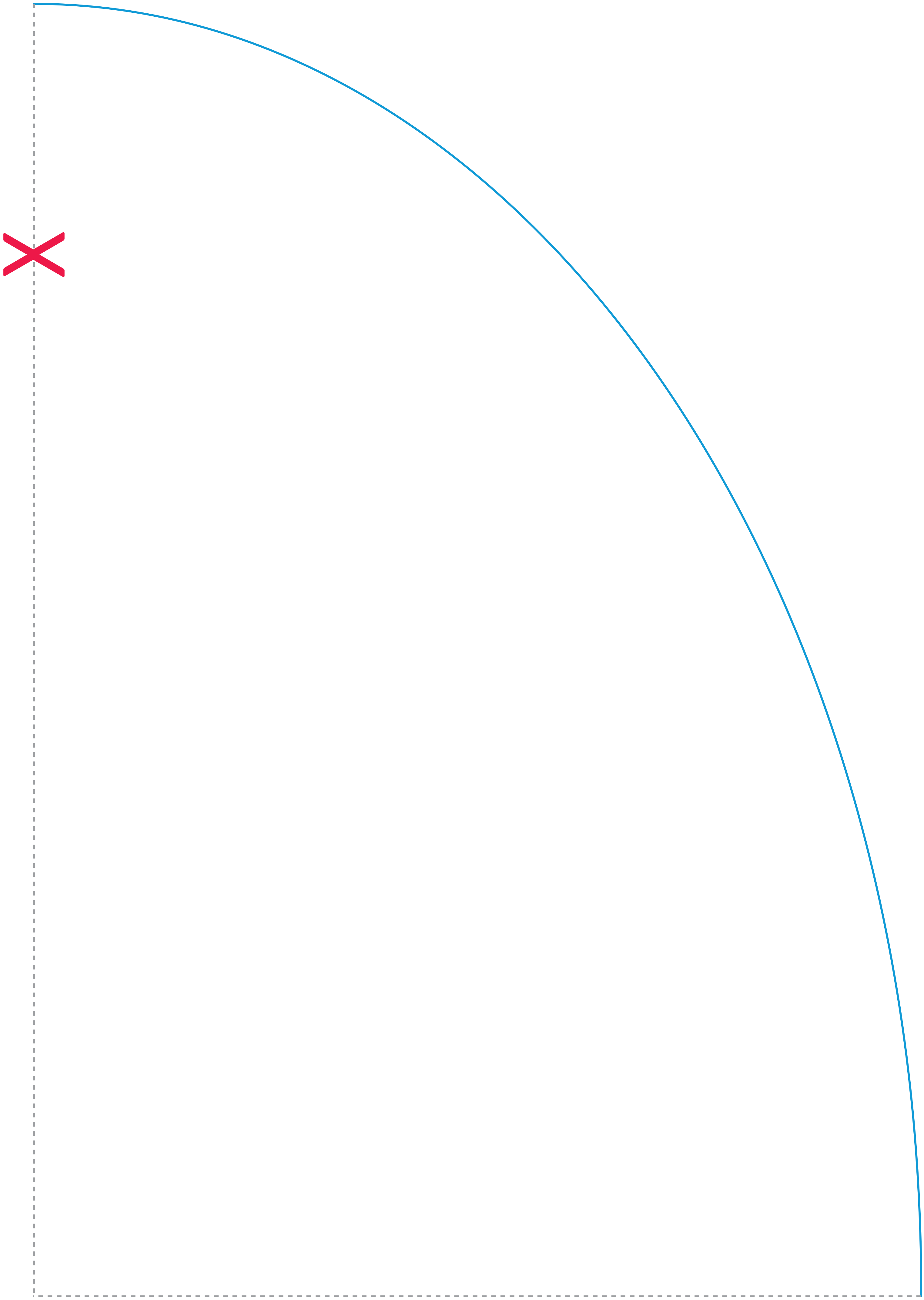
1. Cover the board with plain white paper.
2. Take a length of string. Attach the string to the central line of the board in two places using pins (as shown in Figure X1).
3. Place a pen or pencil approximately half way along the string and pull gently until the string is tight.
4. Move the pen to draw the ellipse. The string should remain tight.
5. Glue the cord or plastic covered cable onto the board following the line of the ellipse.

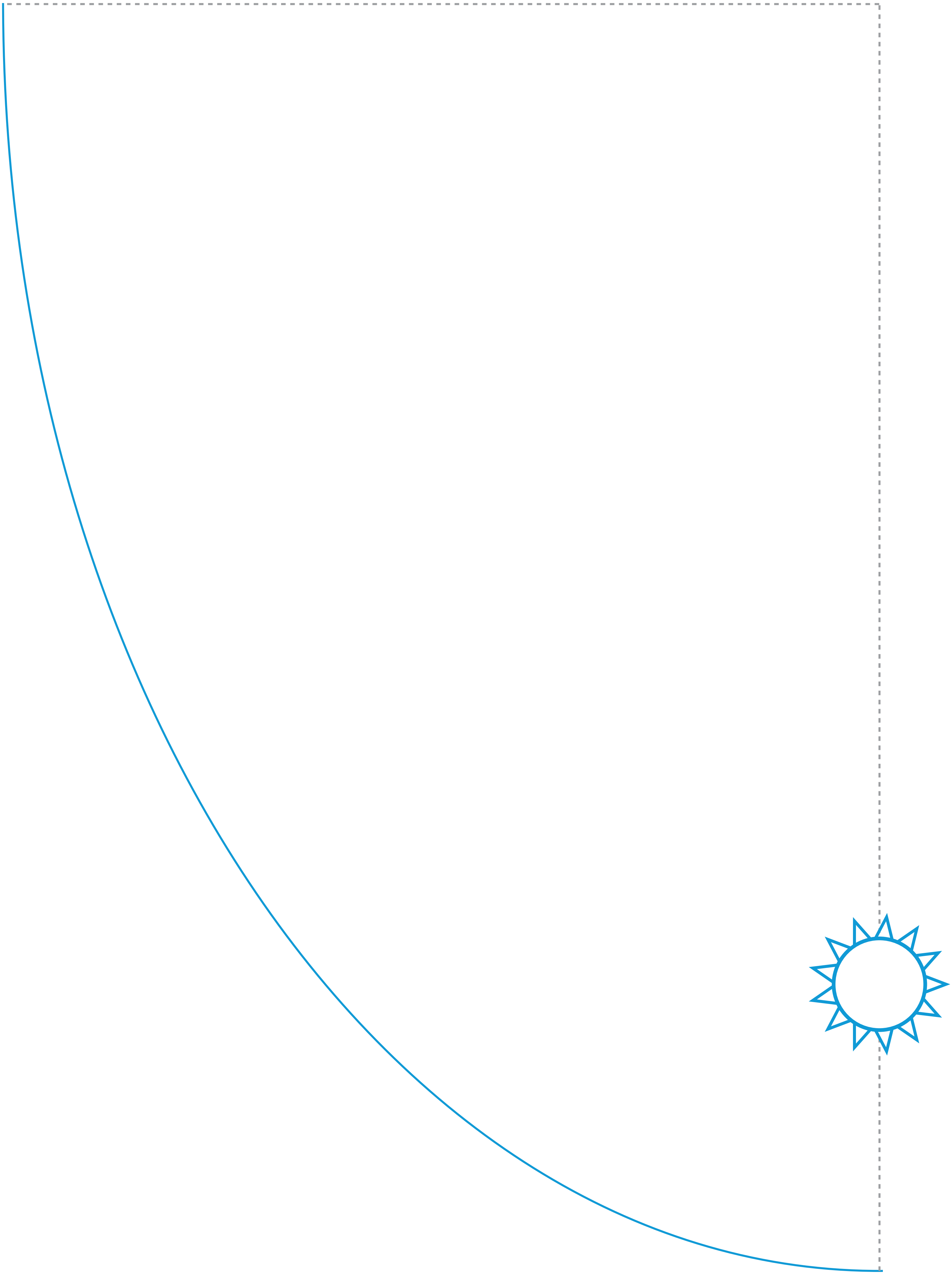
Figure X1

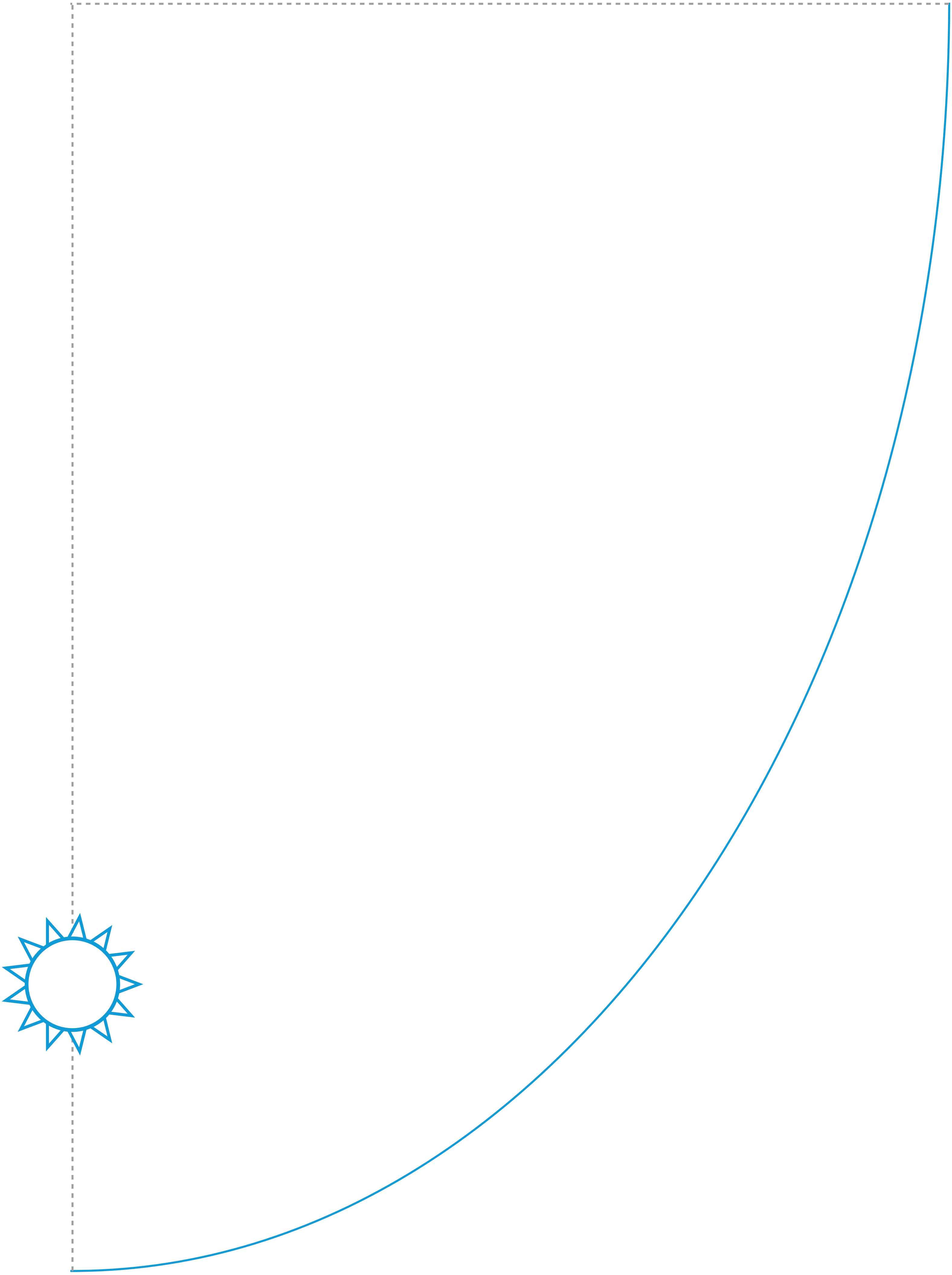


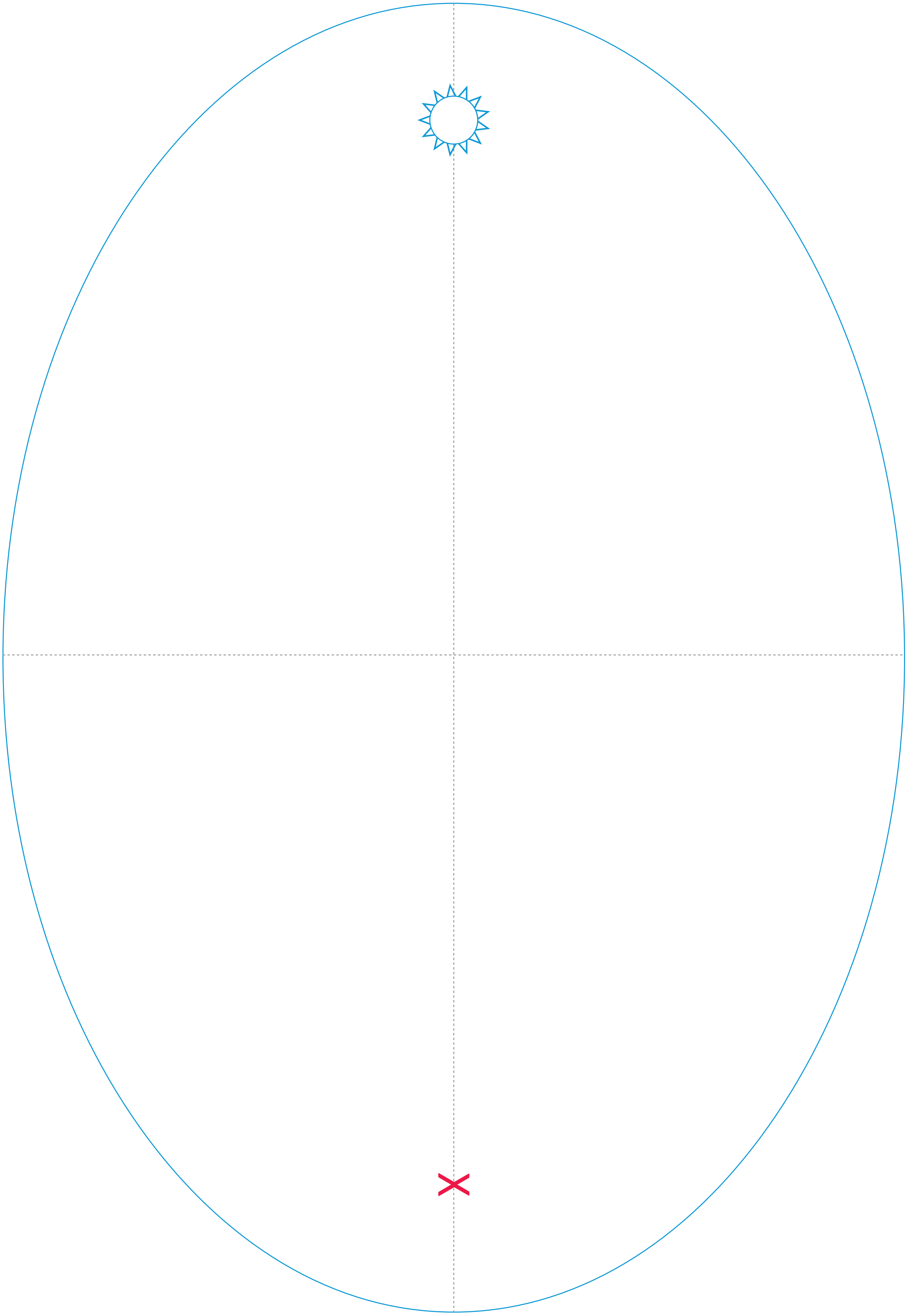
↑ How to construct an ellipse.











Glossary

Altitude: height of ISS relative to Earth's sea level.

Attitude: the orientation of ISS relative to its orbital path.

Astronomical unit (AU): 1 AU is the average distance between the Earth and the Sun, or the Earth's orbital radius, which is approximately 150 million km.

Bow shock (comet): surface of interaction between the ions in the comet coma and the solar wind. The bow shock forms because the relative orbital velocity of the comet and the solar wind are supersonic. The bow shock forms upstream of the comet in the flow direction of the solar wind. In the bow shock, large concentrations of cometary ions build up and load the solar magnetic field with plasma. The result is that the field lines bend around the comet, entrailing the cometary ions, and forming the gas/plasma/ion tail.

Flyby: close passage of a spacecraft around a planet or other celestial body. If the spacecraft uses the gravitational field of a celestial body to boost the spacecraft's velocity and change its trajectory, this is called a swing by or gravity assist manoeuvre.

Gravitational perturbations: changes to the orbit of a celestial body (e.g. planet, comet) due to interactions with the gravitational fields of other celestial bodies (e.g. giant planets, other stars).

Inclination: the angle of the plane of the orbit of ISS relative to Earth's equator.

Orbital period: time taken to complete one orbit.

Retrograde motion of a planet: Apparent motion of a planet in the night sky in the direction opposite to what is normally observed (prograde motion).

Solar wind: a stream of high energy particles (plasma) being emitted by the upper atmosphere of the Sun in all directions. It contains mostly electrons and protons.

Spectrometer: instrument to split light into its constituent wavelengths so that the properties of the light source can be measured.
Sublimate (sublimation): when heating causes a substance to change directly from the solid phase to the gas phase, bypassing the liquid state. When the gas is re-cooled, it typically forms a solid deposit.

Links

Rosetta

ESA Rosetta website: www.esa.int/rosetta
ESA Rosetta blog: blogs.esa.int/rosetta/
Rosetta videos and animations: www.esa.int/spaceinvideos/Missions/Rosetta
Rosetta images: www.esa.int/spaceinimages/Missions/Rosetta/(class)/image
Rosetta factsheet, including mission timeline: www.esa.int/Our_Activities/Space_Science/Rosetta/Rosetta_factsheet
The story so far: www.esa.int/spaceinvideos/Videos/2014/01/Rosetta_the_story_so_far
Chasing a comet: www.esa.int/spaceinvideos/Videos/2014/01/Chasing_a_comet
A 12 year journey through space: www.esa.int/spaceinvideos/Videos/2013/10/Rosetta_s_twelve-year_journey_in_space
Rosetta's orbit around a the comet: www.esa.int/spaceinvideos/Videos/2014/01/Rosetta_s_orbit_around_the_comet
How to orbit a comet: www.esa.int/spaceinvideos/Videos/2014/08/How_to_orbit_a_comet

Comets

ESA Kids article on comets: www.esa.int/esaKIDSen/SEMWK7THKHF_OurUniverse_0.html
ESA Rosetta website (technical): www.esa.int/Our_Activities/Space_Science/Rosetta
ESA Giotto website: sci.esa.int/giotto/
ESA Kids article on our Universe: www.esa.int/esaKIDSen/SEMYC9WJD1E_OurUniverse_0.html

Orbits

An animation showing the motion of Mars in the night sky: www.esa.int/spaceinvideos/Videos/2014/01/Rosetta_s_orbit_around_the_comet
Animation on epicycles: ESA Studio Epicycles: www.esa.int/ESA_Multimedia/Videos/2014/09/Studio_Epicicles
Animation on epicycles: ESA Studio Retrograde Motion Explanation: www.esa.int/ESA_Multimedia/Videos/2014/09/ESA_Studio_Retrograde_Motion_Explanation
Rosetta's orbit around the comet: www.esa.int/spaceinvideos/Videos/2014/01/Rosetta_s_orbit_around_the_comet
ESA Kids quiz on orbits: www.esa.int/esaKIDSen/SEMZPCMVGJE_q.html
Kepler's first law: ESA Studio Law 1: www.esa.int/ESA_Multimedia/Videos/2014/09/Law_1
Kepler's second law: ESA Studio Law 2: www.esa.int/ESA_Multimedia/Videos/2014/09/Law_2
Kepler's third law: ESA Studio Law 3: www.esa.int/ESA_Multimedia/Videos/2014/09/Law_3
Planetary system simulator game: phet.colorado.edu/sims/my-solar-system/my-solar-system_en.html
Super planet crash simulator game: www.stefanom.org/spc/

The International Space Station and the Automated Transfer Vehicle

ESA ATV-2 educational video 'Johannes Kepler': www.esa.int/spaceinvideos/Videos/2014/07/ATV_Johannes_Kepler_-_Orbits_and_body_motion_in_space
ESA ATV-4 educational video 'Albert Einstein': www.esa.int/spaceinvideos/Videos/2014/07/ATV_Albert_Einstein_-_Relativity_of_space_and_time

Teach with space collection

ESA teach with space - gravity wells video | VP04: www.esa.int/spaceinvideos/Videos/2014/07/Gravity_wells_-_classroom_demonstration_video_VP04
ESA teach with space - cooking a comet teacher's guide and student activities | P06:
ESA teach with space - cooking a comet video | VP06: www.esa.int/spaceinvideos/Videos/2014/10/Cooking_a_comet_ingredients_for_life_-_classroom_demonstration_video_VP06
ESA teach with space - marble-ous ellipses video | VP02: www.esa.int/spaceinvideos/Videos/2014/07/Marble-ous_ellipses_-_classroom_demonstration_video_VP02

teach with space – marble-ous ellipses | P02
www.esa.int/education

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