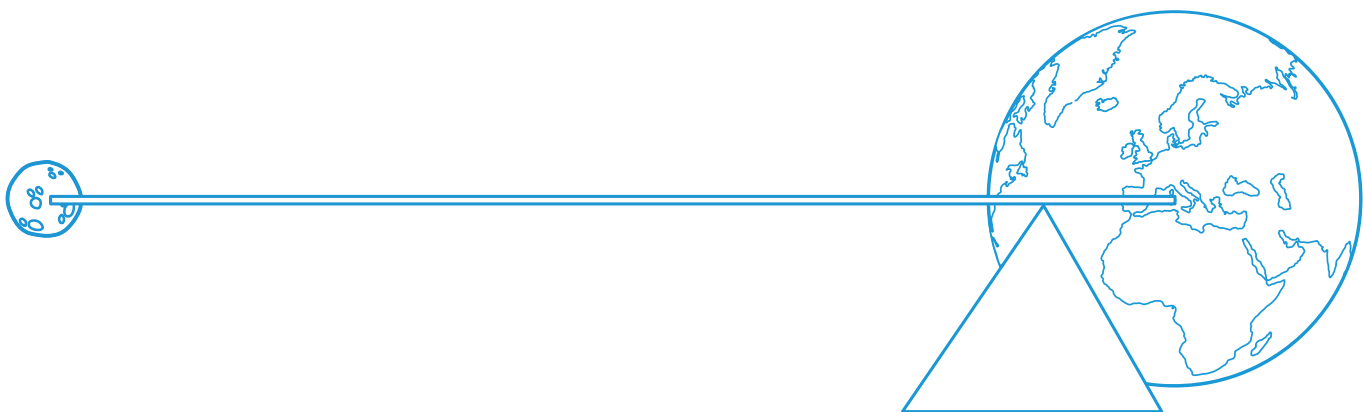


teach with space

→ BARYCENTRIC BALLS

Orbits and the centre of mass





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→ BARYCENTRIC BALLS

Orbits and the centre of mass

FAST FACTS

Age range: 14-18 years old

Type: teacher demonstration

Complexity: easy

Teacher preparation time: 1 hour to prepare equipment

Lesson time required: 10 to 30 minutes

Cost per kit: medium (5-25 euro)

Location: outdoors or large indoor space (i.e. school hall/gym)

Includes use of: tennis balls, ball bearings

Curriculum links

Physics

- Principle of moments/torque
- Centre of mass
- Planetary/satellite orbits
- Doppler effect
- Rotational mechanics

Mathematics

- Principle of moments/torque
- Centre of mass
- Rotational mechanics

Astronomy

- Planetary/satellite orbits
- Doppler effect
- Binary stars
- Detecting exoplanets

Outline

In this activity, the principle of moments is applied to rotating systems to demonstrate the concept of a barycentre, or centre of mass, and how objects in orbit around each other move. Students then consolidate this concept by calculating the centre of mass in a number of astronomical contexts.

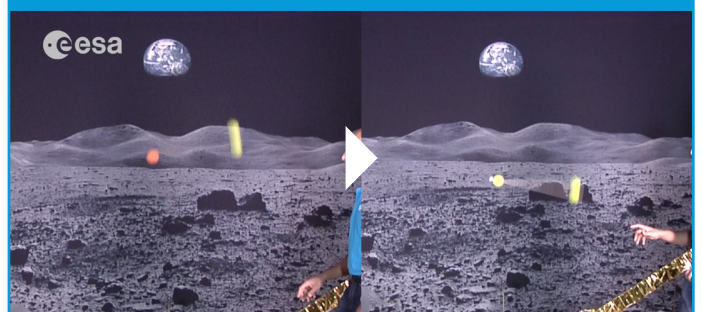
Students should already know

1. The concept of the principle of moments/torque.
2. The concept of the Doppler effect applied to the electromagnetic spectrum.

Learning outcomes

1. Students will learn about the centre of mass and understand that for a gravitationally bound system with two or more bodies, all objects orbit about a common centre of mass.
2. Students will learn how to apply the principle of moments in order to calculate the centre of mass of a two body system.
3. Students will apply the physical concepts to several astronomical situations, learning about binary star systems, planet-moon systems and extrasolar planets.

You also need



↑ [Barycentric balls video \(VP07a\)](#).

[Barycentric balls in space video \(VP07b\)](#). See Links section.

Barycentric balls

When considering the orbits of planets around the Sun, moons orbiting their parent planet, or spacecraft orbiting the Earth or another celestial body, it might be tempting to assume that one object (the least massive object) is moving whilst the other remains stationary. However, from Newton's Third Law,

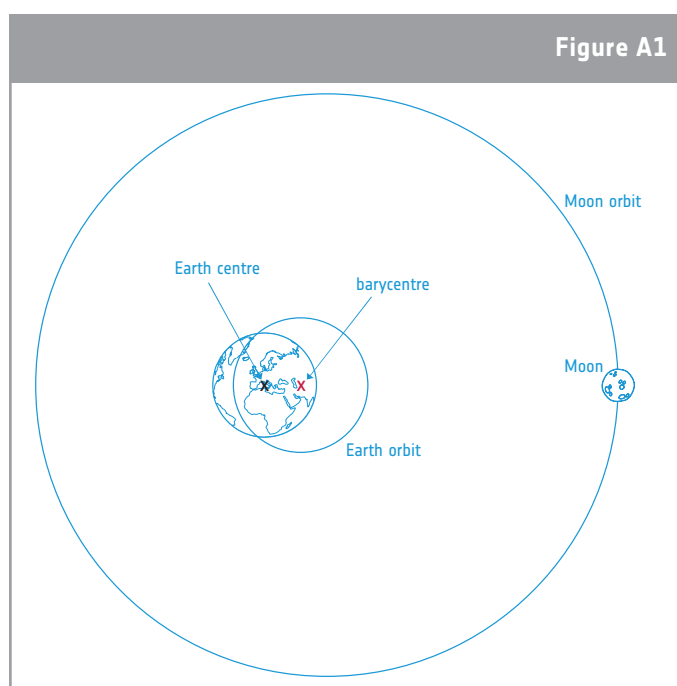
If body A exerts a force on body B, then in that process body B will exert an equal and opposite force back on body A.

often described as 'every action has an equal and opposite reaction', it is clear that both objects will exert the same gravitational force of attraction on each other, and both of their trajectories will be affected by this gravitational force.

This means that if we are considering a system of two bodies, for example the Earth and the Moon, it is not the Moon that orbits the Earth – both the Earth and the Moon orbit a common point in space. The point about which they both orbit, the common **centre of mass*** of the system, is called the **barycentre***

When one object is much more massive than the other, as is the case with the Earth and the Moon (or an artificial satellite orbiting the Earth), the orbital motion of the more massive object (the Earth), may not be so clearly visible. This is because the barycentre, or centre of mass, is much closer to the centre of the Earth than it is to the centre of the Moon or satellite. Figure A1 shows a representation of the Earth-Moon system.

The same applies to the Solar System as a whole. The Sun contains approximately 99.85% of the mass of the Solar System. The barycentre of the Solar System is therefore close to the centre of the Sun and, as a result, the orbit of the Sun around the barycentre is only detectable with high precision observations.



↑ A schematic diagram of the Earth-Moon system (not to scale), highlighting the position of the barycentre and the orbits of the Earth and Moon about this point. The barycentre is located around 4 650 km from the centre of the Earth – the radius of the Earth is just under 6 400 km. The barycentre is approximately 80 times further from the centre of the Moon than from the centre of the Earth.

* **Barycentre:** the centre of mass of a system.

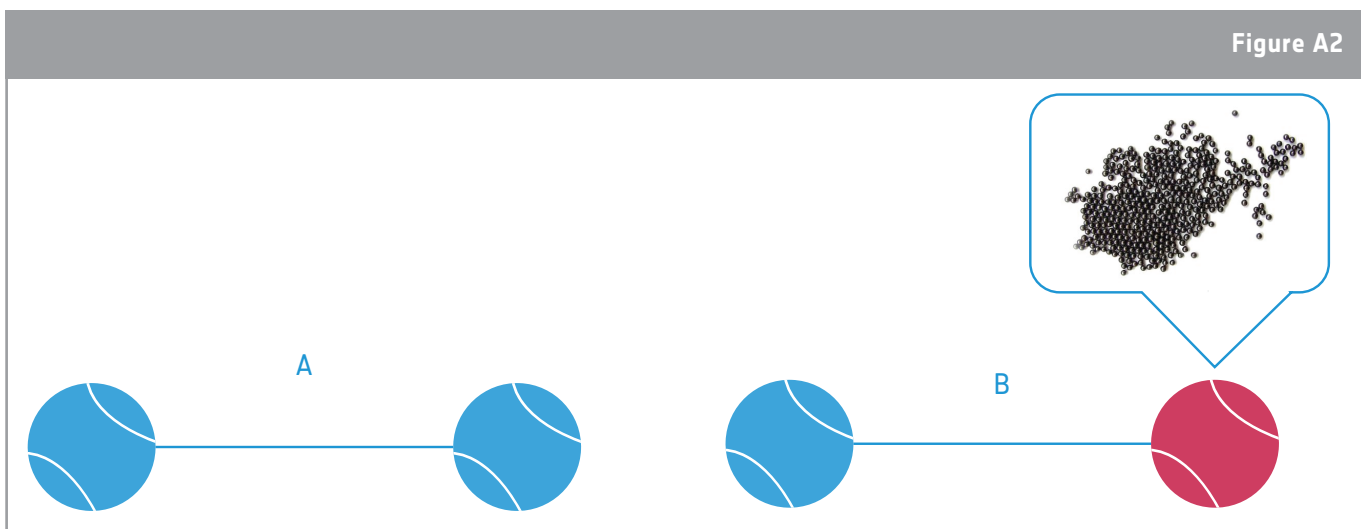
Centre of mass: the unique point in an object or system where the components of weight for each point have a resultant of zero. An object will balance if suspended on a point at this location.

In this demonstration, two pre-assembled pairs of tennis balls are used to show how the position of the barycentre of a two-body system changes with the mass of the two bodies. The balls in the first pair have the same mass. In the second pair, one of the tennis balls is filled with coins or ball bearings to increase its mass.

Equipment

Instructions on how to prepare the tennis balls can be found in the Appendix.

- Pair of equal-mass tennis balls, connected with string
- Pair of unequal-mass tennis balls, connected with string



↑ A) Set of equal-mass (empty) tennis balls.

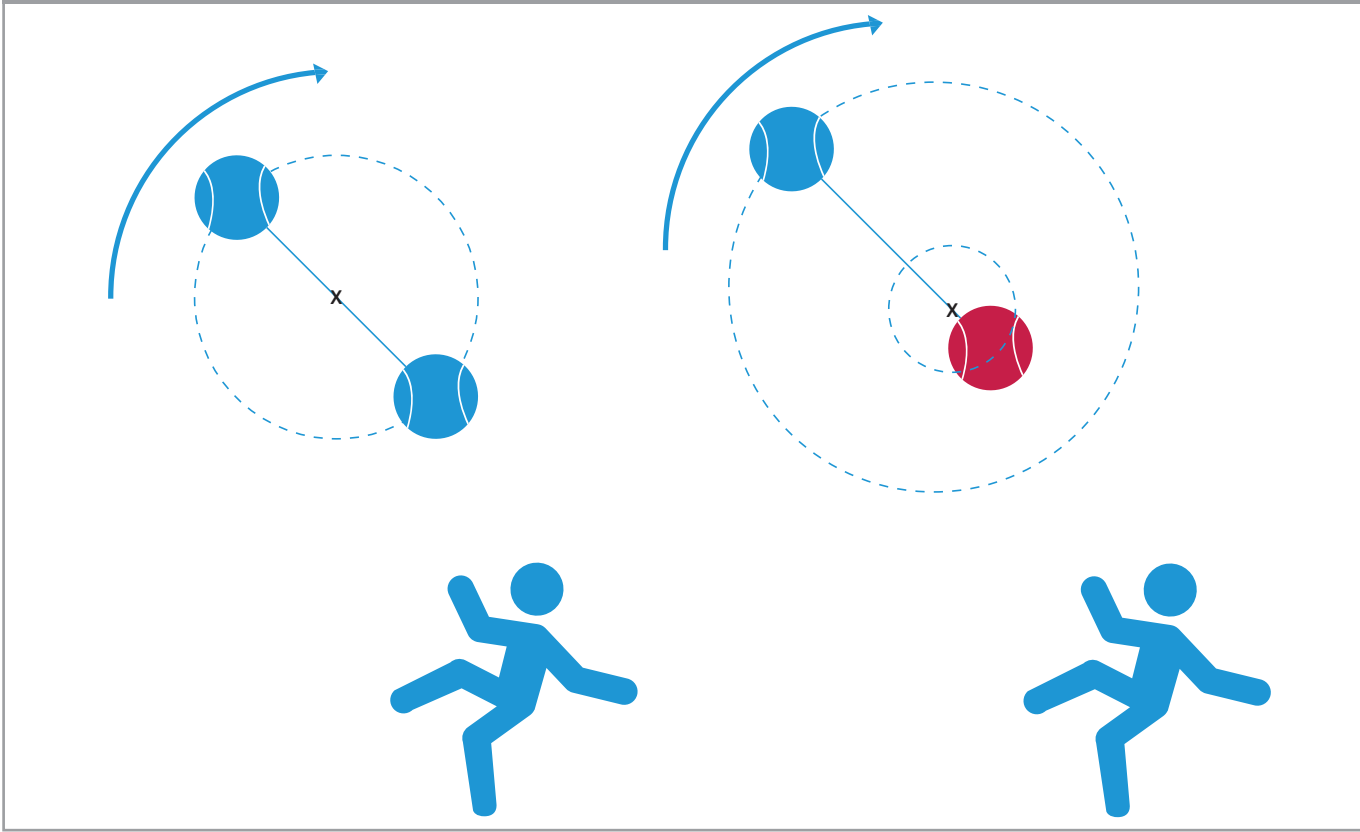
B) Set of tennis balls with unequal masses: one of the tennis balls has been filled with ball bearings, lead pellets or coins and is coloured to identify it as the more massive ball.

Instructions

Please refer to the accompanying video: Teach with space – barycentric balls | VPO7a.

1. Hold the pair of tennis balls of equal mass with one ball hanging below the other.
2. Swing a few times to gather momentum and then release the ball being held.
3. As the balls follow their trajectory, they will both rotate around the centre of mass of the system. For the case of equal-mass balls, this is the centre of the string (Figure A3).
4. Repeat with the pair of unequal-mass balls. It is down to personal preference as to whether the demonstrator holds the heavier or lighter ball. When the unequal-mass balls are released, the heavier ball clearly follows a small orbit around the centre of mass (i.e. close to the heavy ball) whilst the lighter ball describes a much larger orbit (Figure A3). The greater the difference between the masses, the closer the barycentre will be to the heavier tennis ball.

Figure A3



↑ Left: For the pair of equal-mass tennis balls, the centre of mass or barycentre is located at the centre of the system in the middle of the length of the string, marked by the X. Both tennis balls describe the same orbital path (dashed line). Right: For the pair of unequal-mass tennis balls, the centre of mass or barycentre is located much closer to the more massive, filled ball (coloured red) – marked by the X. This is observed as the more massive ball following a much smaller orbital path/circle whilst the lighter ball follows a much larger orbit/circle.

Health & Safety

- This demonstration should be done outdoors, or in a large indoor space such as a school hall or gym.
- Students should stand well back.
- The demonstrator should practise throwing the balls before demonstrating in front of a class.
- Before each demonstration, carefully check that all knots are secure and that the hole used to fill the more massive ball is sealed well.

Discussion

After performing the demonstration, discuss with the students what they have observed. Some suggested discussion questions are listed below.

A led discussion based on these questions, focussing on the link to space is provided in the Appendix. A student worksheet with calculations in a space context is also provided and can be used if required.

The aim of the discussion is for students to take away the following key points:

- In a system of two or more objects, there is a shared barycentre or centre of mass about which all objects orbit.
- The location of the barycentre is dependent on the masses of the objects. For two objects of equal mass, the barycentre lies at the geometric centre of the system. When the masses are unequal, the barycentre will lie closer to the centre of mass of the more massive object.
- For a simple two-body case, students should be able to apply the principle of moments to calculate the location of the barycentre.
- Understanding barycentres is important in a space context, from applying the barycentre principle to detect otherwise unseen planets around other stars, to the classification of celestial bodies in our Solar System distinguishing between planets with moons or double-planet systems.

Suggested questions:

- How can we find the barycentre of a system?
- How do astronomers find the barycentres of distant orbital systems in space, such as binary star systems or planets orbiting around other stars?
- How is the barycentre concept used to tell the difference between a planet with a natural satellite (Moon) and two planets in a mutual orbit about a barycentre (a double-planet system)?
- Is Pluto actually part of a 'double-dwarf planet' system?
- What happens in binary star systems when two very massive objects orbit each other closely?

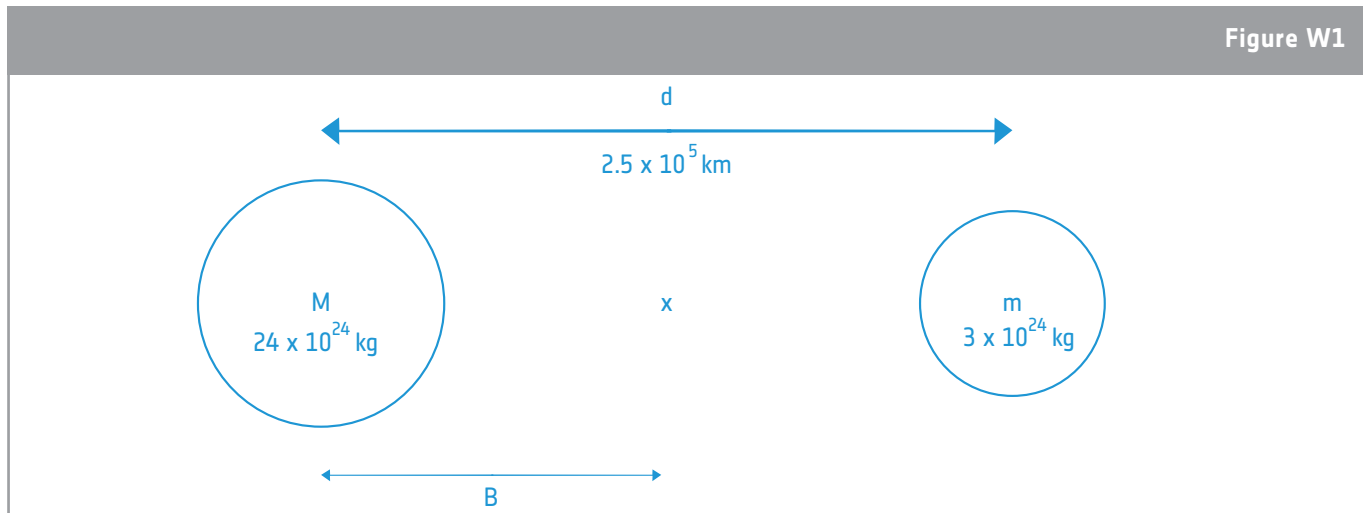
→ CONCLUSION

This activity explores two key concepts in physics and mechanics – the barycentre or centre of mass and the principle of moments – through a simple but effective demonstration. The activity places these concepts in the context of orbits in space, moons, binary planets and stars to engage and trigger students' imaginations.

Barycentres in space

Questions

- For the objects shown in Figure W1, find the distance of the barycentre from the centre of object M and then from the centre of object m.



- The moon has a mass of $0.0123 M_E$ (where M_E is the mass of the Earth) and the separation from the centre of the Earth to the centre of the Moon is 384 000 km. If the radius of the Earth is $6.37 \times 10^3 \text{ km}$, show that the Earth and Moon are a planet-moon system.
 - Some data for Pluto and its largest moon Charon, taken from the NASA Lunar and Planetary Science factsheets, are shown below:

Mass of Pluto	$1.31 \times 10^{22} \text{ kg}$
Radius of Pluto	1 195 km
Mass of Charon	$1.62 \times 10^{21} \text{ kg}$
Separation of centres	19 600 km

Show whether Pluto and Charon are a planet-moon or a double-planet system.

- The Sun has a diameter of 1.4 million km and Jupiter has a radius of 140 000 km. The mean Sun-Jupiter distance is 778 million km. The Sun's mass is approximately 1 000 times that of Jupiter. Calculate the position of the barycentre of the Sun-Jupiter system and comment on its location.

4. In the Teach with space – barycentric balls in space | VP07b video, ESA astronaut Samantha Cristoforetti demonstrates the barycentric principle in microgravity on board the International Space Station (ISS).

In the first scenario, Samantha connects two baseball balls with a knitting needle. The two balls have equal mass and so the barycentre lies in the geometric centre of the system, the centre of the knitting needle. When Samantha applies a force to one of the balls, the system rotates about the barycentre. The second time Samantha applies a force, this time to the position of the barycentre, the whole system translates (moves) through space, but does not rotate.

In the second scenario, Samantha replaces one of the baseballs with another ball of similar size but different mass. When Samantha applies a force to the new ball, the system rotates around the barycentre which is no longer in the geometrical centre of the system. As before, when Samantha applies a force to the location of the barycentre, the system no longer rotates and only translates.

Given that the mass of a baseball is 0.145 kg, the length of the knitting needle is 0.3 m and the location of the barycentre is a quarter of the distance between the centre of the baseball and the centre of the other ball, what is the mass of the second ball? Which object is more massive?

→ APPENDIX

How to prepare the two sets of tennis balls

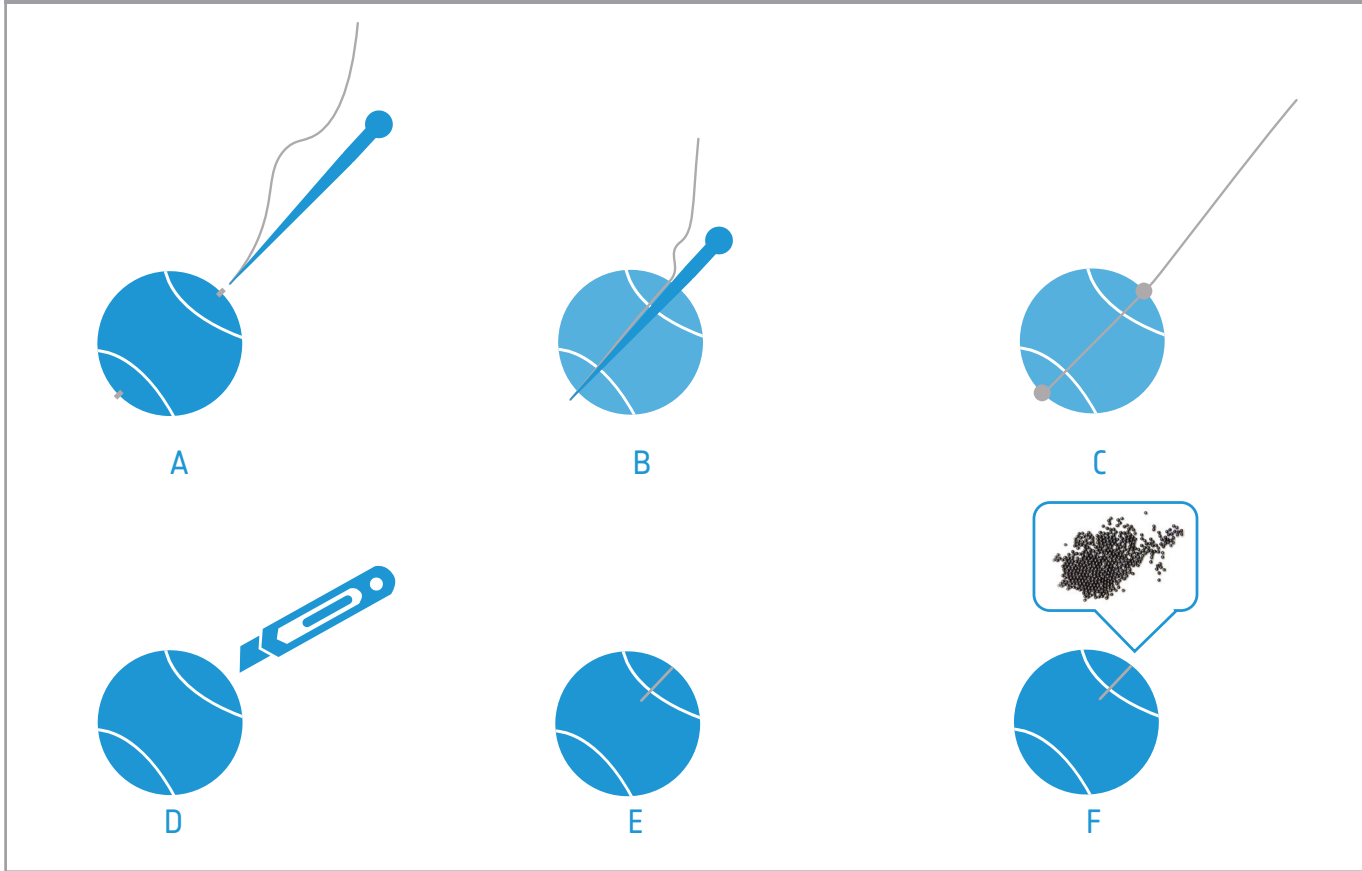
In each case, two tennis balls are connected with a strong piece of string. The balls in the first pair are of equal mass. In the second pair of tennis balls, one ball is filled with ball bearings or coins to make a pair of unequal-mass objects.

Equipment

- 4 tennis balls
- Strong string
- Scissors
- Marker pen
- Knitting needle (or screwdriver)
- Ball bearings/lead pellets/small coins – enough to fill one tennis ball
- Strong glue or strong sticky tape
- Sticky tape
- Craft knife

Instructions

1. Cut a length of string approximately 60 cm long.
2. Attach one end of the string to the knitting needle with sticky tape.
3. Push the knitting needle into the tennis ball so that it makes a small hole. The tip of the knitting needle should exit on the opposite side of the ball, making another hole – it may be easiest to draw two dots on the outside of the tennis ball to guide you. Once the tip of the knitting needle exits the ball on the opposite side, remove the sticky tape and tie a double knot to secure the string (see Figure AX1 A-B).
4. Pull the knitting needle back through the original hole and tie a second double knot in the string. The string will now be securely through the ball, secured by knots on either side. If necessary, increase the strength around the holes with glue or strong sticky tape (see Figure AX1 C).
5. Repeat steps 1-4 using a second tennis ball and the opposite end of the length of string. Approximately 40-50 cm of string should be separating the two tennis balls.
6. Repeat steps 1-5 on a second set of tennis balls. Ensure that the length of string between the tennis balls is approximately the same for both sets.
7. Choose one set of tennis balls. Cut a small slit into one of the balls using a craft knife. Insert ball bearings/lead pellets/small coins until the ball is full. Re-seal the slit with glue or strong tape. (see Figure AX1 D-F)
8. Colour/mark the filled tennis ball with the marker pen.



↑ How to assemble the two sets of tennis balls.

Led discussion

How can we find the barycentre of a system?

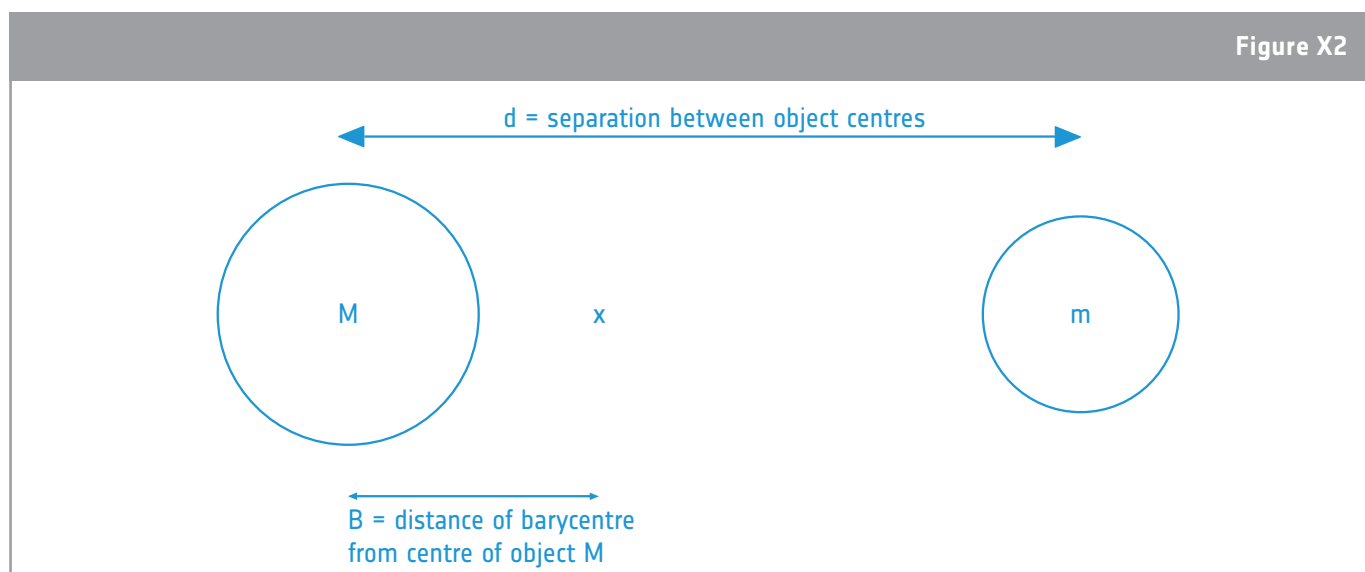
For any system in space where two or more objects are orbiting each other, the system will have a centre of mass, or barycentre, about which all bodies orbit.

The simple case: a two-body system

For the simple case of a two-body system, the centre of mass or barycentre is the point around which both of the objects orbit. The barycentre can be thought as the 'balance point' of the system.

If we know the masses of two objects and the distance between them, then we can calculate the position of the barycentre using the principle of **moments***. Let's start by visualising the system as balancing on a pivot point, like two people sitting on a see-saw. If the pivot were located at the barycentre, then the moments on each side would cancel out if the system was placed in an imaginary external gravitational field.

Consider the system of two objects as shown in Figure X2. The objects have a mass M and m respectively and their centres are separated by a distance d . The barycentre is located between the objects. The distance between the centre of the most massive object and the barycentre is B .



↑ Two objects (mass M and m) in orbit about a common centre of mass or barycentre. The objects are separated by a distance d and the distance between the centre of the most massive object M and the barycentre is B .

If we apply the principle of moments around the centre of mass (the barycentre) then we get:

$$\text{Sum of clockwise moments around barycentre} = \text{Sum of anti-clockwise moments around the barycentre}$$

i.e. the moments will cancel each other out. Therefore, for the system in Figure X2:

* **Moment**: a tendency to produce motion, especially a rotation about a point or axis.

B = distance from the barycentre to the centre of the object with mass M (in meters)

d = separation between the centres of mass of the two objects (in meters)

m = mass of smaller object (in kilograms)

M = mass of larger object (in kilograms)

Therefore:

$$M \times B = m \times (d - B)$$

$$MB = md - mB$$

$$MB + mB = md$$

$$B \times (M + m) = md$$

This gives the distance to the barycentre from the centre of the object with mass M as:

$$B = md/(M+m)$$

How do astronomers find the barycentres of distant orbital systems in space, such as binary star systems or planets orbiting around other stars?

At astronomical distance scales, the motion of the stars in a **binary star*** system about their barycentre is difficult to detect. Whilst the physical distance between the stars may be many millions of kilometres, from our view point on or close to the Earth, the motion of the stars on the sky is tiny – it may be just a thousandth of a degree or even less.

Even more difficult to observe than the movements of binary stars are the tiny 'wobbles' of a parent star caused by the motion of an orbiting planet (**exoplanet***) about their shared centre of mass – in a planet-star system, the barycentre will be located within the parent star. In order to detect these tiny movements, the positions of stars must be measured very accurately, and many times over, to discern the 'wobble'.

Did you know?

In December 2013, the European Space Agency launched the Gaia observatory (Figure X3) whose mission is to accurately map the positions and characteristics of about 1.2 billion stars within our own Milky Way Galaxy. Gaia is following in the footsteps of ESA's earlier Hipparcos mission – Hipparcos was launched in 1989 (Figure X4). Over a period of four years, Hipparcos carried out a detailed survey of the positions of around 120 000 stars in the sky. Measurements made by Hipparcos allowed the barycentres of many binary star systems to be determined. For some systems, the results did not match with expectations suggesting the possibility of companions, some of which have been later confirmed by other observations. Studying the positions and motions of stars in the plane of the sky, also known as the science of **astrometry***, is just one technique astronomers use to detect the presence of companion stars or planets. Another complimentary technique, called the **radial velocity*** technique, uses the Doppler effect to look for a 'wobble' in the observed light spectrum of a star. For a discussion on these techniques, plus other methods for detecting exoplanets, see the link 'How to find an extrasolar planet' in the Links section.

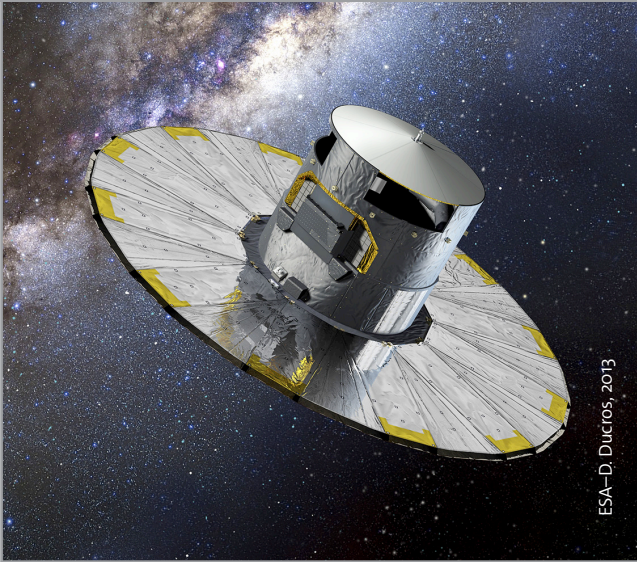
* **Astrometry**: a branch of astronomy involving precise measurements of the positions and movements of celestial objects.

Binary star: two stars in orbit about their common barycentre.

Exoplanet/extrasolar planet: a planet that orbits a star other than the Sun.

Radial velocity: the velocity of an object along the line-of-sight between two objects.

Figure X3



↑ An artist's impression of ESA's Gaia spacecraft.

Figure X4



↑ The Hipparcos spacecraft produced a positional survey of two million stars.

How is the barycentre concept used to tell the difference between a planet with a natural satellite (moon) and two planets in a mutual orbit about a barycentre (a double-planet system)?

In a system where two objects orbit each other, the barycentre will always be closer to the centre of mass of the more massive object. The larger the difference in mass between the two objects, the closer the barycentre will be to the centre of mass of the more massive object.

This is why, for a two-body system where there is a very large difference in the mass of the objects, the barycentre will lie within the more massive object. Therefore, it will appear that the lighter object orbits around the heavier one. An easy way to visualise this is the following:

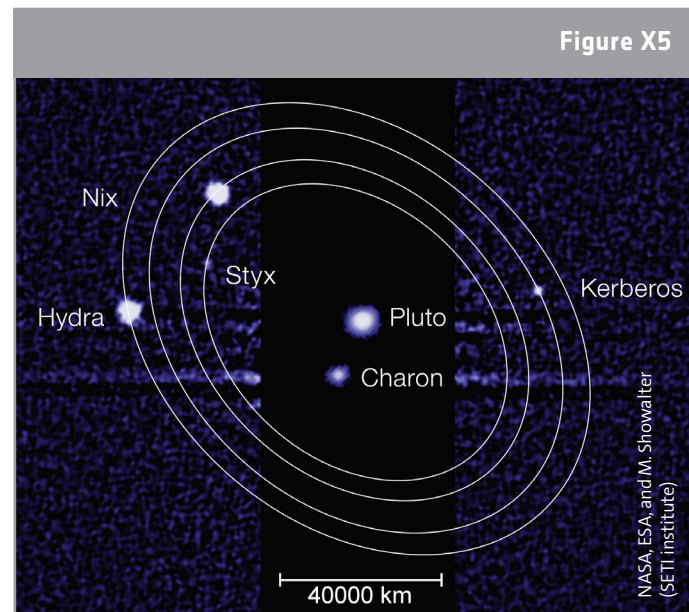
A **planet-moon** system is one where the barycentre lies within the heavier object (the planet).

A **double-planet** system is one where the barycentre lies outside the surfaces of both objects.

Barycentric principles apply to any orbiting system, such as binary and multiple star systems, as well as planets orbiting their host stars and satellites and spacecraft orbiting the Earth and other solar system bodies.

Is Pluto actually part of a 'double-dwarf planet' system?

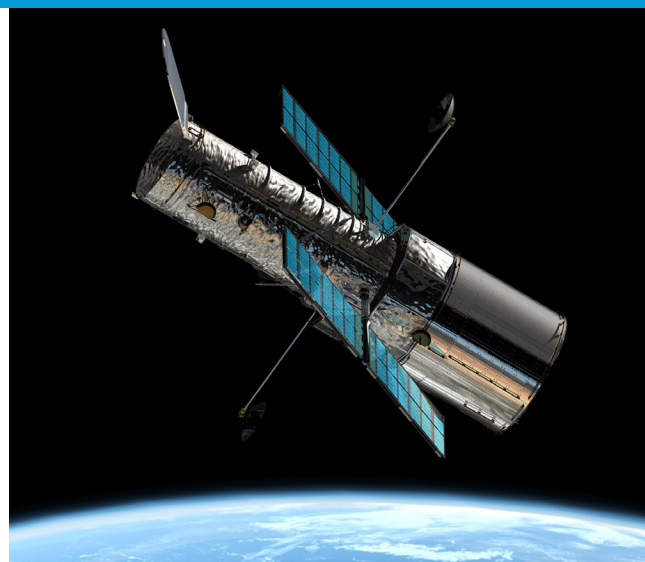
While Pluto may have been demoted to **dwarf planet*** status (in 2006), repeated observations of its moons suggest that the Pluto system may be more complex. Pluto is accompanied by five moons. The closest of these moons, Charon, is much closer in size and mass to Pluto than the other four moons. In fact, the whole system is in orbit around the barycentre between Pluto and Charon rather than the barycentre being located within the radius of Pluto as would be expected for a dwarf planet with five moons. Pluto and Charon are therefore sometimes referred to as a double-dwarf planet system accompanied by four smaller moons. Figure X5 shows a Hubble Space Telescope (HST) image of Pluto and Charon accompanied by their four small moons. The orbits of the four smaller moons are overlaid. From Figure X5 it is clear that the barycentre of the system lies between Pluto and Charon.



↑ Hubble Space Telescope (HST) image showing the four small moons orbiting the Pluto-Charon double-dwarf planet system. The orbital paths of the smaller moons are overlaid.

Did you know?

The Hubble Space Telescope (HST) is a joint ESA/NASA project. It was launched into an orbit 600 kilometres above the Earth in 1990, and is one of the largest and most successful space observatories ever. From its vantage point outside the Earth's constantly moving atmosphere, which distorts the light reaching the ground from space, HST has provided stunning high resolution images of thousands of space objects such as planets, binary star systems, galaxies, nebulae and star-forming regions. HST has dramatically improved our view of the Universe.

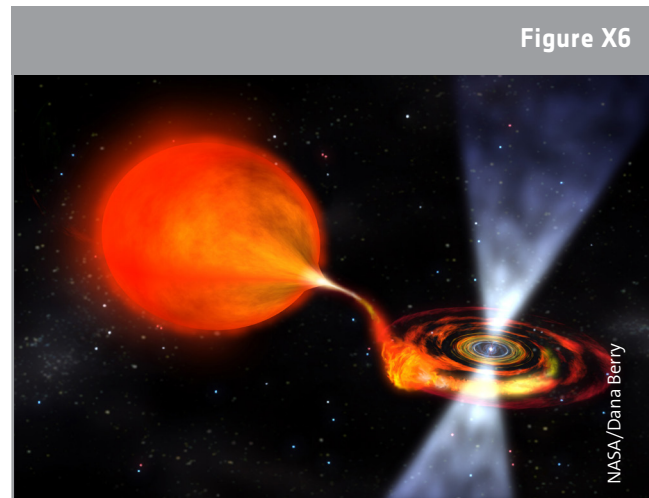


* **Dwarf planet:** a planetary-mass object that is neither a planet nor a natural satellite. A dwarf planet is massive enough for its shape to be roughly spherical, orbits the Sun directly but has not cleared the neighbourhood around its orbit. The term dwarf planet was adopted in 2006 by the International Astronomical Union. There are currently five objects in the Solar System classified as dwarf planets – Pluto, Ceres, Haumea, Makemake and Eris. Ceres is located within the Asteroid Belt whilst the other four dwarf planets lie beyond the orbit of Neptune. It is thought that many more dwarf planets may exist in the icy outer reaches of the Solar System.

What happens in binary star systems when two very massive objects orbit each other closely?

A binary star system consists of two stars that are close enough to each other so that gravitational interactions force them to orbit a common barycentre. Binary stars that are particularly close to each other will often experience a transfer of mass from one star to the other. Figure X6 shows an artist's impression of such a close binary system in which a rotating **neutron star*** called a **pulsar*** is drawing mass away from its companion star.

What would this transfer of mass do to the barycentre, and therefore the orbital characteristics of this binary system? As the pulsar draws more mass from the companion star, its mass will increase while the mass of the companion star will decrease. This will cause the barycentre to move closer towards the pulsar. Over time, the companion star will appear to orbit the pulsar.



↑ An artist's impression of a fast spinning star called a pulsar drawing mass from its companion star. The strong gravity from the dense pulsar (on the right) attracts material from the companion star (on the left).

* **Neutron star**: the stellar remnant of a large star that has exploded at the end of its life. Neutron stars are extremely small but have high mass and therefore a very high density.

Pulsar: a rotating neutron star with a strong magnetic field. Pulsars emit a beam of radiation which, if aligned with the Earth, can be seen as a periodic 'flash' at radio wavelengths.

Glossary

Astrometry: a branch of astronomy involving precise measurements of the positions and movements of celestial objects.

Barycentre: the centre of mass of a system.

Binary star: two stars in orbit about their common barycentre.

Centre of mass: the unique point in an object or system where the components of weight for each point have a resultant of zero. An object will balance if suspended on a point at this location.

Dwarf planet: a planetary-mass object that is neither a planet nor a natural satellite. A dwarf planet is massive enough for its shape to be roughly spherical, orbits the Sun directly but has not cleared the neighbourhood around its orbit. The term dwarf planet was adopted in 2006 by the International Astronomical Union. There are currently five objects in the Solar System classified as dwarf planets - Pluto, Ceres, Haumea, Makemake and Eris. Ceres is located within the Asteroid Belt whilst the other four dwarf planets lie beyond the orbit of Neptune. It is thought that many more dwarf planets may exist in the icy outer reaches of the Solar System.

Exoplanet/extrasolar planet: a planet that orbits a star other than the Sun.

Moment: a tendency to produce motion, especially a rotation about a point or axis.

Neutron star: the stellar remnant of a large star that has exploded at the end of its life. Neutron stars are extremely small but have high mass and therefore a very high density.

Pulsar: a rotating neutron star with a strong magnetic field. Pulsars emit a beam of radiation which, if aligned with the Earth, can be seen as a periodic 'flash' at radio wavelengths.

Radial velocity: the velocity of an object along the line-of-sight between two objects.

Links

Teach with space collection

ESA teach with space – marble-ous ellipses teacher's guide and student activities | Po2: esamultimedia.esa.int/docs/edu/Po2_Marble-ous_ellipses_teacher_guide.pdf

ESA teach with space – marble-ous ellipses video | VPo2: [www.esa.int/spaceinvideos/Videos/2014/07/Marble-ous_ellipses - classroom demonstration video VPo2](http://www.esa.int/spaceinvideos/Videos/2014/07/Marble-ous_ellipses_-_classroom_demonstration_video_VPo2)

ESA teach with space - cooking a comet video | VPo6: [www.esa.int/spaceinvideos/Videos/2014/10/Cooking a comet ingredients for life - classroom demonstration video VPo6](http://www.esa.int/spaceinvideos/Videos/2014/10/Cooking_a_comet_ingredients_for_life_-_classroom_demonstration_video_VPo6)

ESA teach with space – barycentric balls video | VPo7a: [www.esa.int/spaceinvideos/Videos/2015/04/Barycentric balls - classroom demonstration video VPo7a](http://www.esa.int/spaceinvideos/Videos/2015/04/Barycentric_balls_-_classroom_demonstration_video_VPo7a)

ESA teach with space – barycentric balls in space video | VPo7b: [www.esa.int/spaceinvideos/Videos/2015/04/Barycentric balls in space - classroom demonstration video VPo7b](http://www.esa.int/spaceinvideos/Videos/2015/04/Barycentric_balls_in_space_-_classroom_demonstration_video_VPo7b)

ESA related missions and science

ESA Gaia mission: www.esa.int/Our_Activities/Space_Science/Gaia

Little books of Gaia (in 7 European languages): www.esa.int/Education/Little_Books_of_Gaia

Gaia iPhone application: blogs.esa.int/gaia/2014/09/01/gaia-in-your-pocket-mapping-the-galaxy-with-the-new-gaia-app/

Science@ESA vodcast: Episode 6: Charting the Galaxy – from Hipparcos to Gaia: [www.esa.int/Education/Teachers_Corner/Science ESA Episode 6 Charting the Galaxy - from Hipparcos to Gaia](http://www.esa.int/Education/Teachers_Corner/Science_ESA_Episode_6_Charting_the_Galaxy_-_from_Hipparcos_to_Gaia)

ESA Hipparcos mission: www.esa.int/Our_Activities/Space_Science/Hipparcos_overview

Make your own Hipparcos star globe: www.esa.int/Our_Activities/Space_Science/Create_your_own_Hipparcos_star_globe2

ESA/NASA Hubble Space Telescope: sci.esa.int/hubble/

How to find an extrasolar planet: www.esa.int/Our_Activities/Space_Science/How_to_find_an_extrasolar_planet

NASA Lunar and Planetary Science database

Main page: nssdc.gsfc.nasa.gov/planetary/

Planetary factsheets index: nssdc.gsfc.nasa.gov/planetary/planetfact.html

Sun Factsheet: nssdc.gsfc.nasa.gov/planetary/factsheet/sunfact.html

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