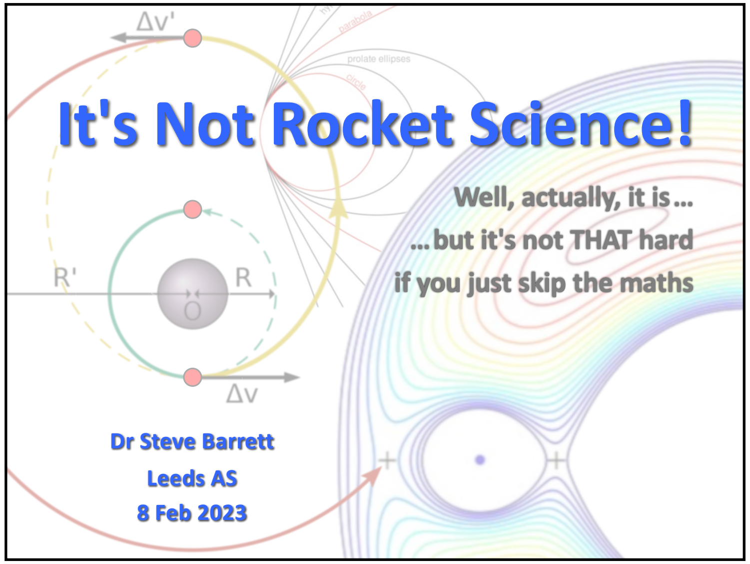

It's Not Rocket Science

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2

Contents

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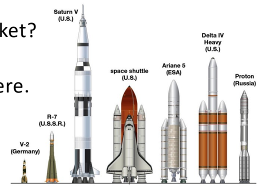
3

What Does a Rocket Do?

Q: What is the primary function of a rocket?

A: To lift objects up above the atmosphere.

Well, yes ... sort of.



The ISS and the HST are actually still **in** the atmosphere – it's just rather thin up there at an altitude of ~500 km.

To put an object into Earth orbit what is needed is horizontal speed.

(Getting as high as possible to reduce atmospheric drag is a good idea, but it is not strictly necessary.)

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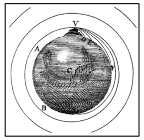
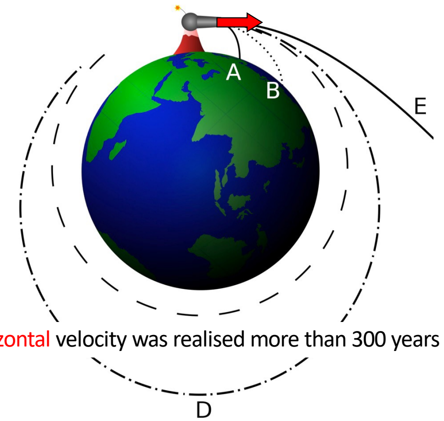
Newton's Cannonballs



Isaac Newton
Principia 1686



The need for horizontal velocity was realised more than 300 years ago

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Saturn V Launch

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Saturn V Launch

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Otherwise: What Goes Up ...

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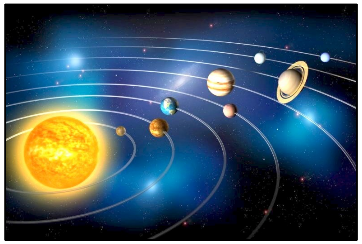
Orbits

Orbit : The path of an object affected by (only) gravity.

We are all used to the idea of planets in orbit around the Sun, or moons in orbit around their planets.



Kepler observed that the planets orbit in ellipses and Newton figured out why – his law of universal gravitation.

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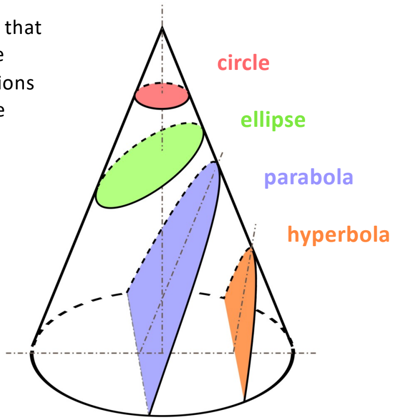
Conic Sections

Newton found that orbits have the shapes of sections through a cone



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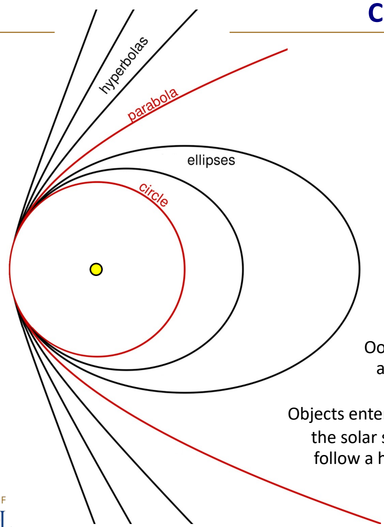
Conic Sections

These curves that describe orbits around the Sun are also the curves that define the shapes of mirrors that are suitable for focusing light.

This is because the maths is basically the same for both.



Planets follow closed elliptical orbits, but a comet falling into the solar system from way out in the Oort cloud follows a parabolic path.

Objects entering and leaving the solar system at speed follow a hyperbolic orbit.

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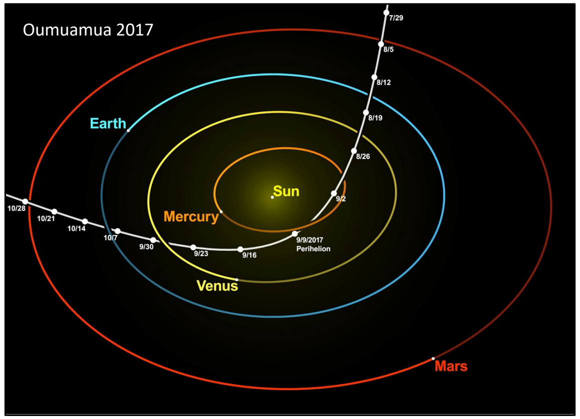
Hyperbolic Orbit



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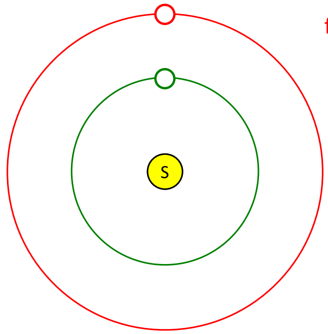
Orbit Size and Orbit Period

Green planet is closer to Sun

Gravitational pull from Sun is stronger

Planet moves faster to stay in orbit

Shorter period ('year')



Red planet is further from Sun

Gravitational pull from Sun is weaker

Planet moves more slowly to stay in orbit

Longer period ('year')

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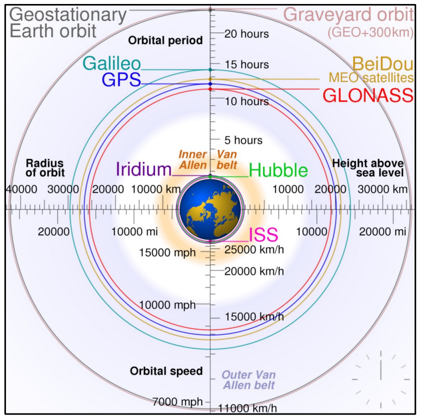
Earth Satellite Orbits



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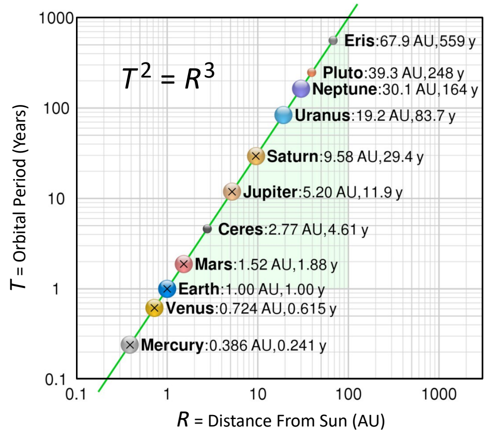
Planets Orbit the Sun



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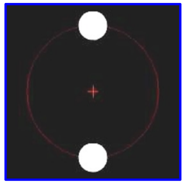
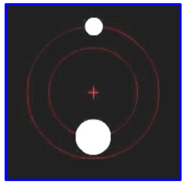
Circular Orbits

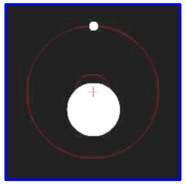
Two objects with equal mass orbit around the centre of mass (+)





If the objects have different masses, objects with larger mass move smaller distances

If the masses are very different, the centre of mass (+) may lie within the larger object



Even a small object (planet) can make a large object (star) wobble – this is how exoplanets can be detected

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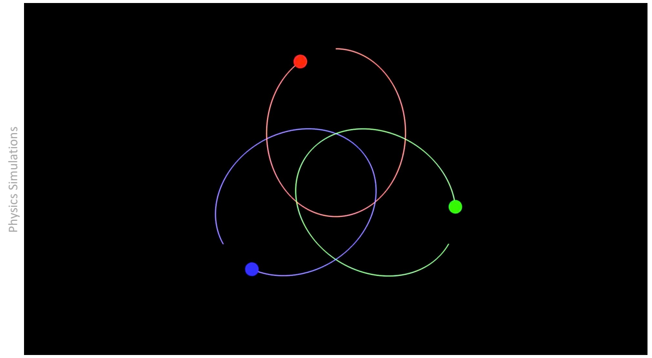
3-Body Problem

Describing the relative motion of two objects is a soluble problem



but for three or more objects there are very few analytic solutions

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Rocket Science

What does a rocket do?

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Circular – elliptical – parabolic – hyperbolic

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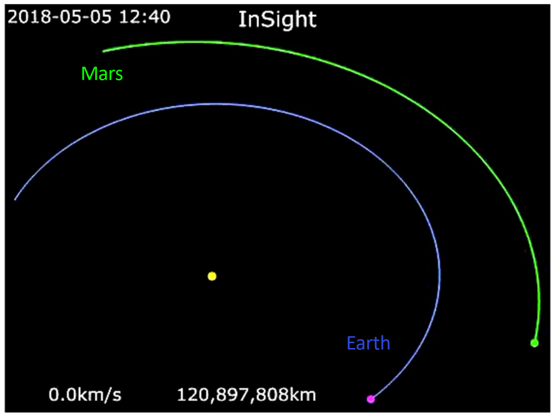
Earth to Mars



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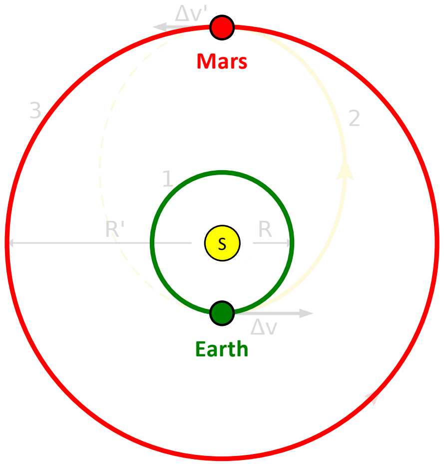
It's Not Rocket Science!

Hohmann Transfer



Not to scale

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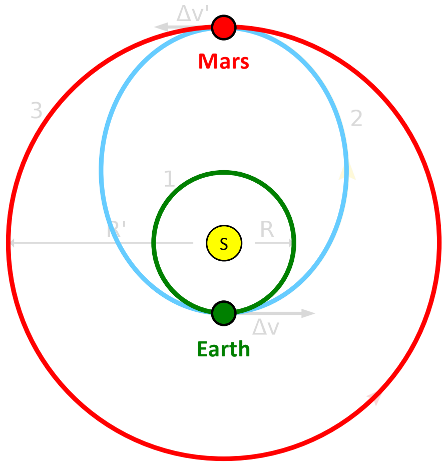
Hohmann Transfer



Not to scale

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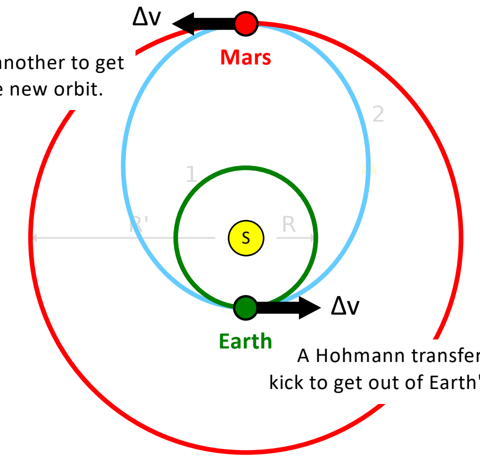
Hohmann Transfer



… and another to get into the new orbit.

A Hohmann transfer needs a kick to get out of Earth's orbit…

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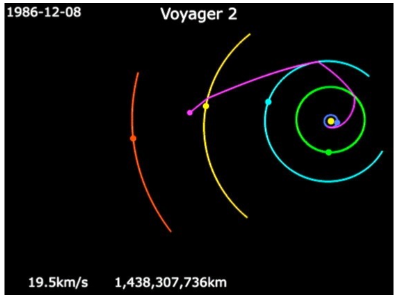
Gravity Assists

What about getting to other planets in the solar system?

In the 1960s it was realised that flying a spacecraft close to a planet can 'slingshot' it onwards at higher velocities.

Hence exploring the outer solar system can be carried out faster and cheaper.



In effect, the spacecraft robs the planet of some of its momentum.

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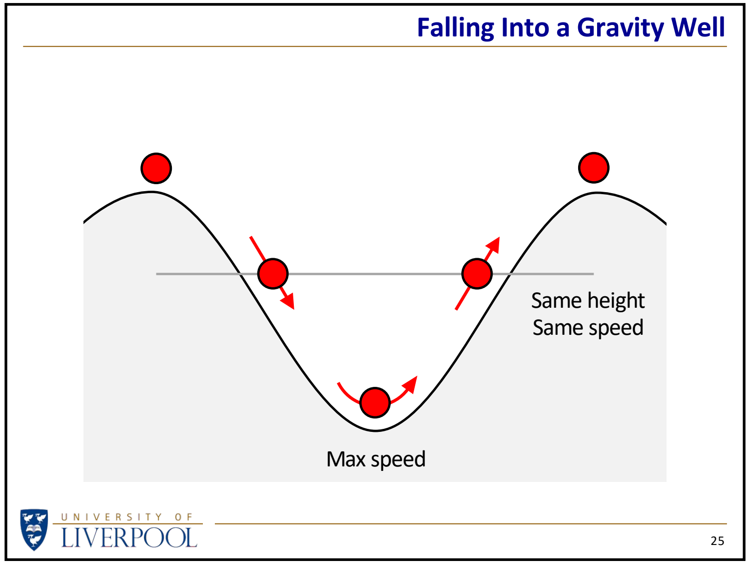
Falling Into a Gravity Well
Same height
Same speed
Max speed
UNIVERSITY OF LIVERPOOL
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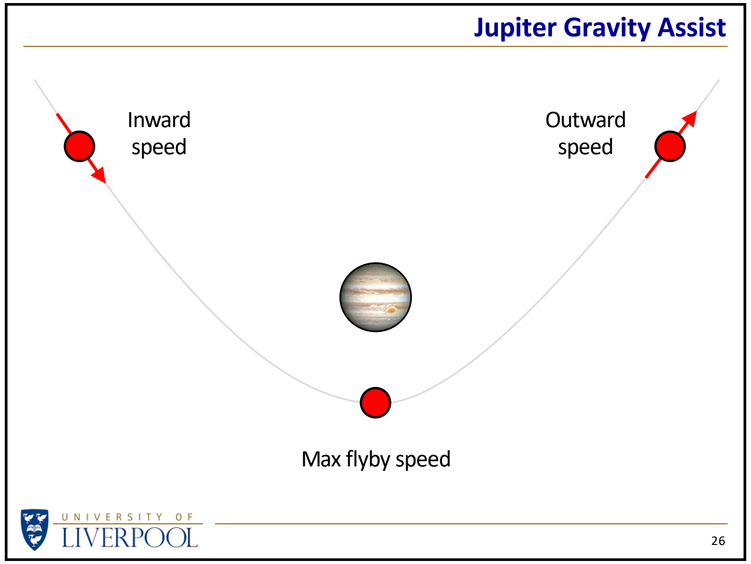
Jupiter Gravity Assist
Inward speed
Outward speed
Max flyby speed
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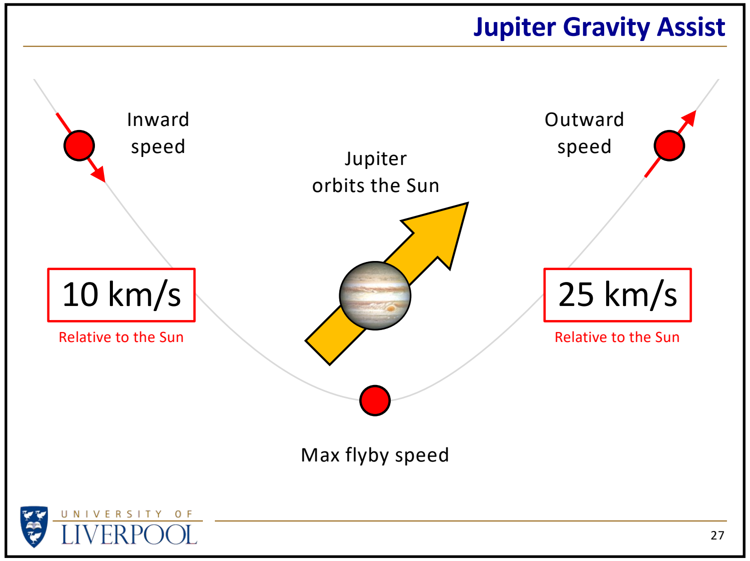
Jupiter Gravity Assist
Inward speed
Jupiter orbits the Sun
Outward speed
10 km/s
Relative to the Sun
25 km/s
Relative to the Sun
Max flyby speed
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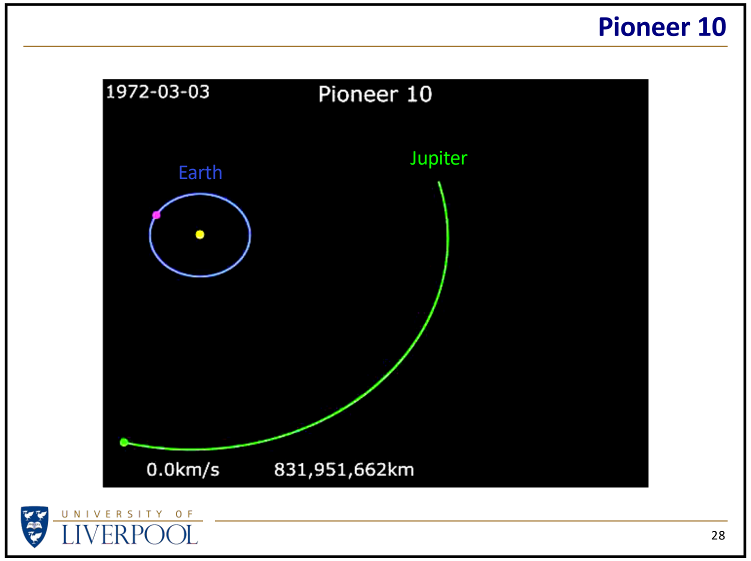
Pioneer 10
1972-03-03
Pioneer 10
Earth
Jupiter
0.0km/s
831,951,662km
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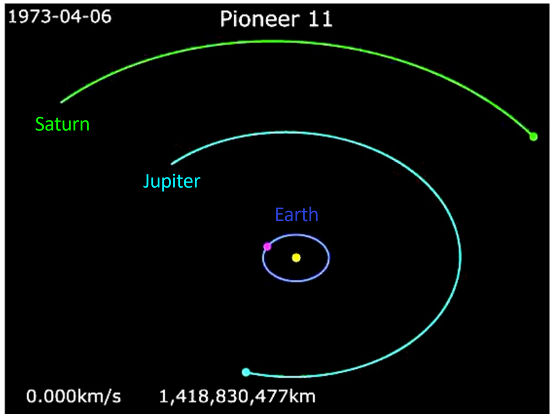
Pioneer 11



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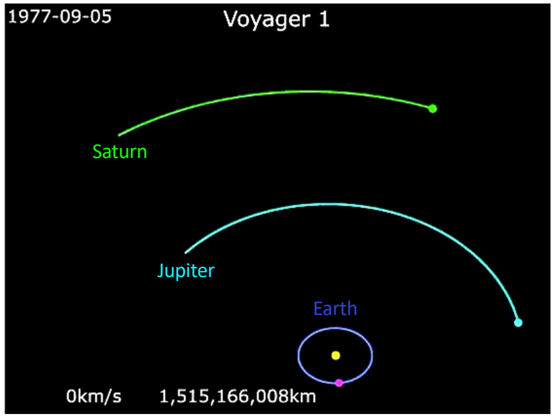
Voyager 1



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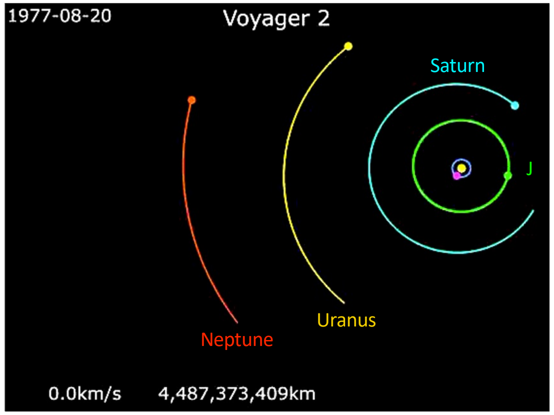
Voyager 2



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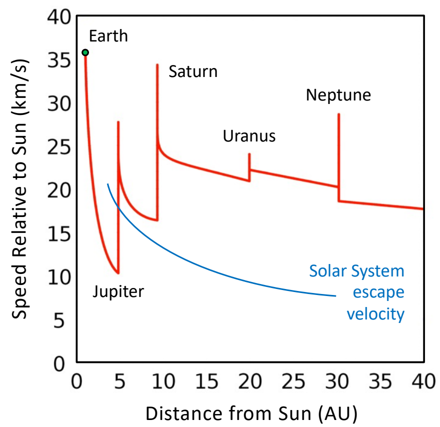
Voyager 2 Speed vs Distance



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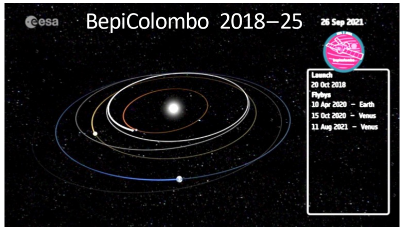
It's Not Rocket Science!

Gravity Assists

Using gravity assists to help cover the enormous distances between planets in the outer solar system seems like a very sensible idea.

What is not so obvious is that gravity assists are also used to visit the ***inner*** planets.

A planet flyby can be used to ***lose*** speed as a spacecraft 'falls' into the inner solar system.



A flyby can accelerate ***or*** decelerate, but in both cases fuel is saved.

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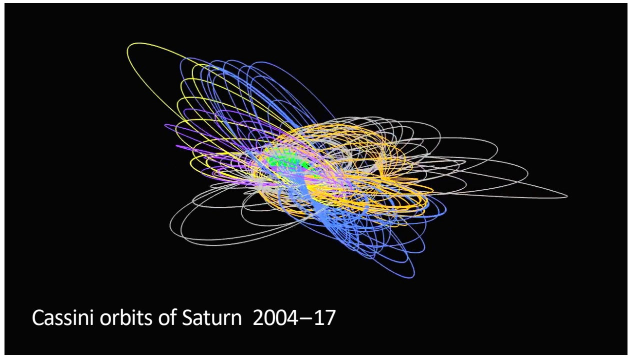
Changing Orbits Uses Fuel

Some spacecraft go into orbit around their target planet



Any orbital changes require fuel which reduces the mission lifetime

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Circular – elliptical – parabolic – hyperbolic

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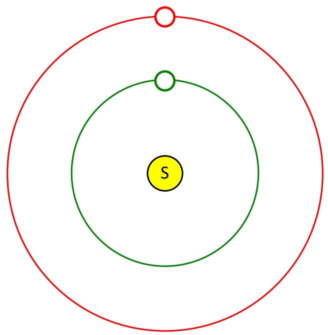
Orbit Size and Orbit Period

Green planet is closer to Sun

Gravitational pull from Sun is stronger

Planet moves faster to stay in orbit

Shorter period ('year')



Red planet is further from Sun

Gravitational pull from Sun is weaker

Planet moves more slowly to stay in orbit

Longer period ('year')

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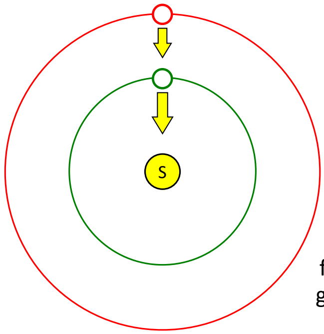
Orbit Size and Orbit Period

The arrows show the gravitational force of the Sun on each planet.

At a greater distance, the force is less.

Is that always the case?



We can't change the gravitational pull of the Sun…

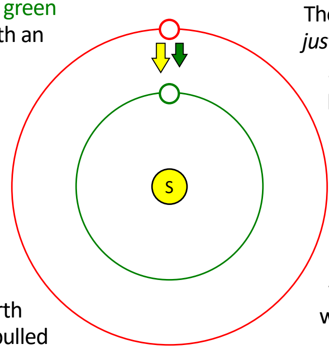
…but we can arrange it so that an object in the red orbit feels an additional gravitational force.

Lagrange Points

Let's assume that green is planet Earth with an orbital period of exactly 1 year.

The red orbit has a period of ***more*** than 1 year.

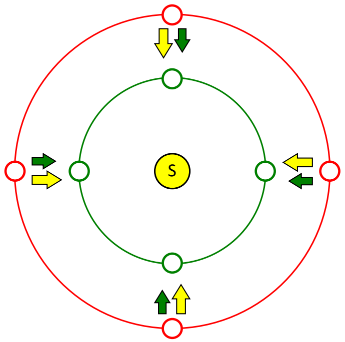
What if the red orbit is close enough to the Earth that an object is pulled by both the Sun ***AND*** the Earth?



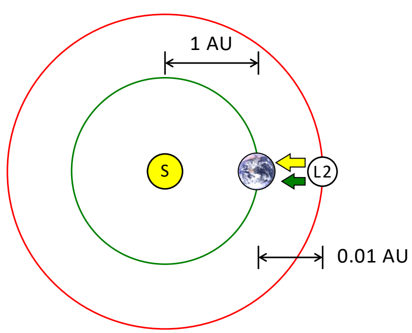
There is a red orbit at *just* the right distance such that the extra pull from the Earth makes the red object orbit faster with a period of 1 year.

That would mean that the red object would orbit the Sun 'with' the Earth.

Lagrange Point L2



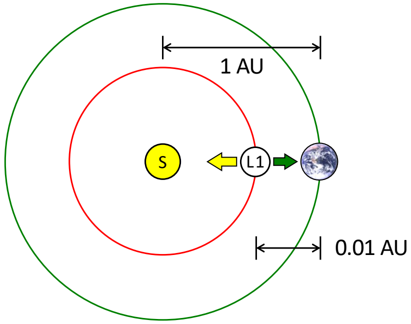
Lagrange Point L2



Not to scale

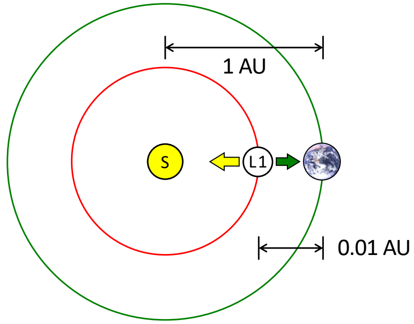
Lagrange Point L1

The idea is conceptually the same for L1 *inside* the Earth's orbit, but this time the Sun and the Earth pull in opposite directions.



Lagrange Point L1

L1 is a good location for spacecraft that observe the Sun, as the Earth never gets in the way.



Calculating Lagrange Points

Gravitational forces between two bodies fall off as the square of the distance between them, so we can use that to calculate the distance from Earth to L1 or L2:

$$\frac{M}{(R\pm r)^2} \pm \frac{m}{r^2} = \left(\left(\frac{M}{M+m}\right)R \pm r\right)\left(\frac{M+m}{R^3}\right)$$

M = mass of Sun R = distance Sun – Earth
m = mass of Earth r = distance Earth – L1/2

Just solve for r. Simples!

Calculating Lagrange Points

Gravitational forces between two bodies fall off as the square of the distance between them, so we can use that to calculate the distance from Earth to L1 or L2:

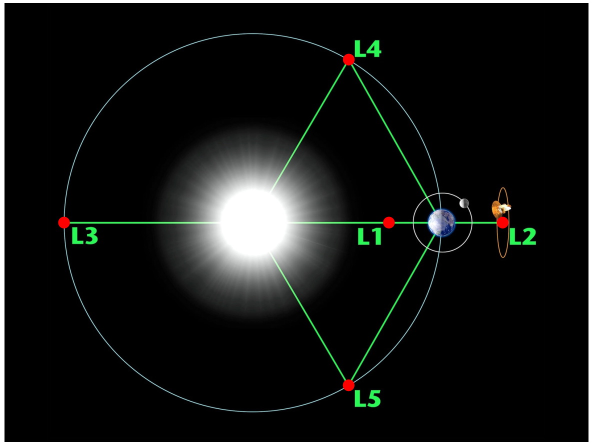
$$\frac{M}{(R\pm r)^2} \pm \frac{m}{r^2} = \left(\left(\frac{M}{M+m}\right)R \pm r\right)\left(\frac{M+m}{R^3}\right)$$

M = mass of Sun R = distance Sun – Earth
m = mass of Earth r = distance Earth – L1/2

Just solve for r. Simples!

... but it's not THAT hard if you just skip the maths

Lagrange Points 1–5



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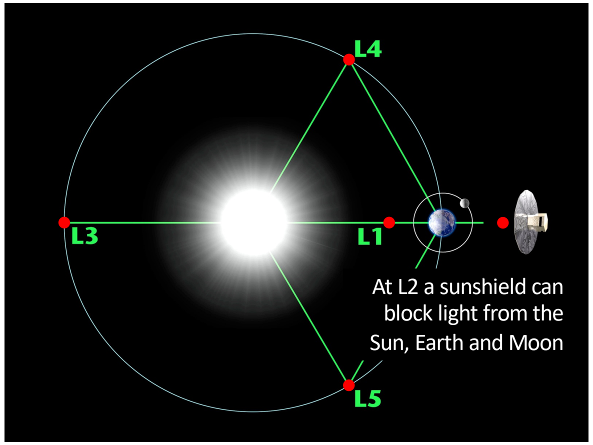
Why Park at L2?



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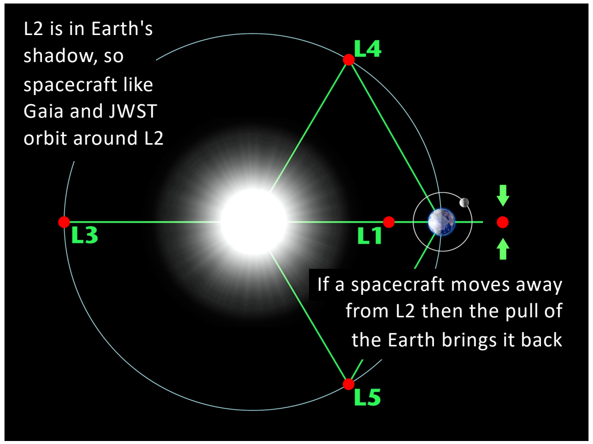
Why Park at L2?



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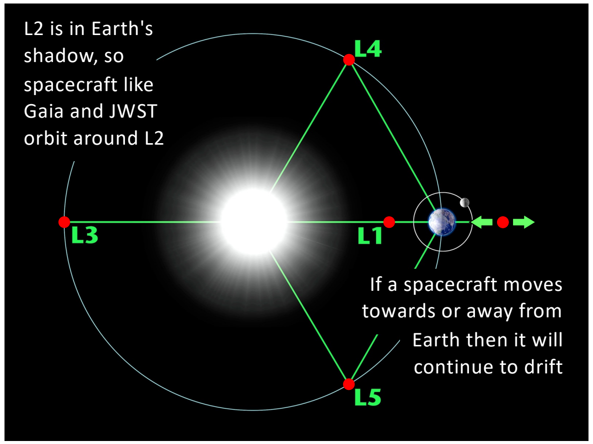
Why Park at L2?



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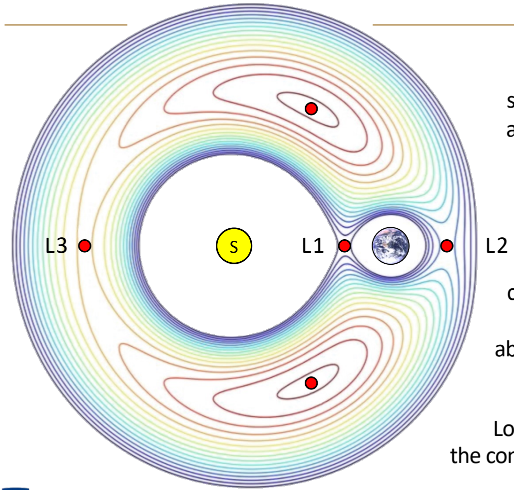
It's Not Rocket Science!

Parking at L2



The ability of a spacecraft to 'park' at a Lagrange point is sometimes visualised using this doughnut.

Imagine that the contours represent height and think about a ball wanting to roll 'downhill'.

Look more closely at the contours around L2 …

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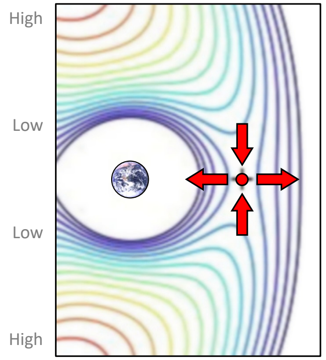
Parking at L2

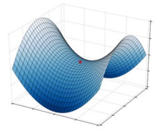


The arrows show the directions of 'downhill' in the vicinity of L2.

L2 is *not* on a 'hilltop'.

L2 is *not* in a 'well'.

L2 is at a saddle point.



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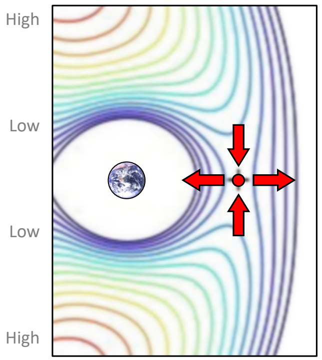
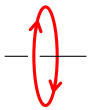
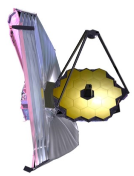
Parking at L2



Hence the JWST can park in a 'halo' orbit around L2, but it will slowly drift towards Earth …





… and so will need a station-keeping nudge every few months.

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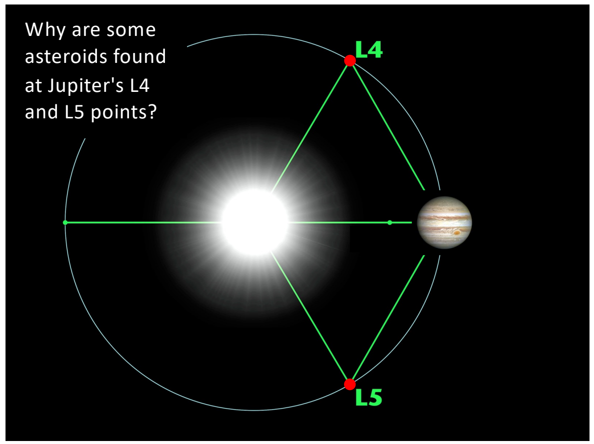
Objects at L4 and L5



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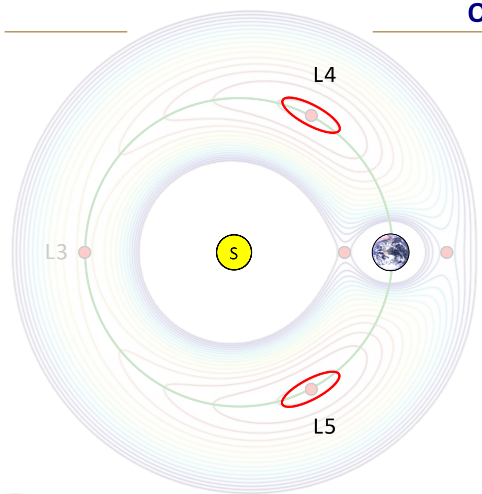
It's Not Rocket Science!

Objects at L4 and L5



Objects can orbit loosely around the L4 and L5 points.

There's not much there at the Earth L4 and L5 points.

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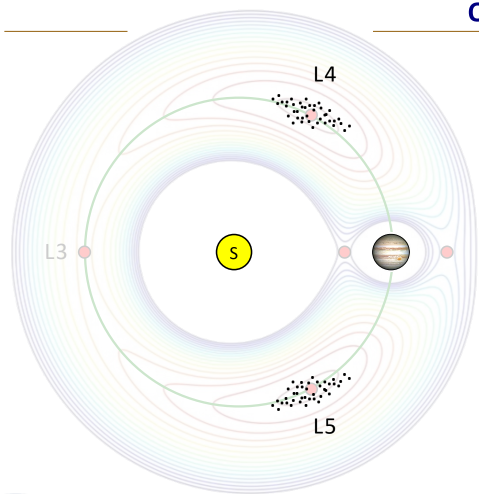
Objects at L4 and L5



Objects can orbit loosely around the L4 and L5 points.

There's not much there at the Earth L4 and L5 points.

Jupiter's stronger gravitational pull has collected some Trojan asteroids at its L4 and L5 points.

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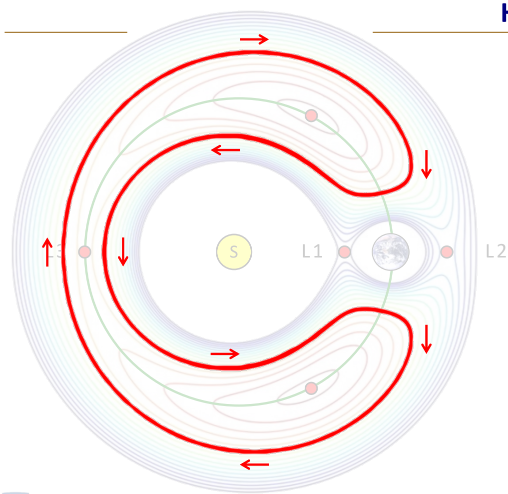
Horseshoe Orbits



Some orbits look really weird …

… but they still obey the rules:

When closer to the Sun the object goes faster than the Earth.

When further from the Sun the object goes slower than the Earth.

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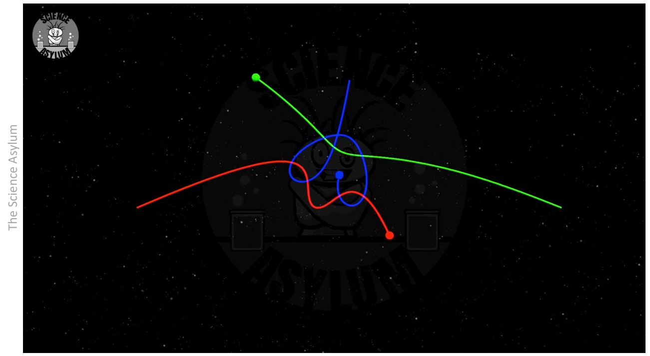
Open Orbits

Perhaps the weirdest of orbits are those that are ***not*** closed loops



Is it possible for the stars in a triple-star system to move this way?

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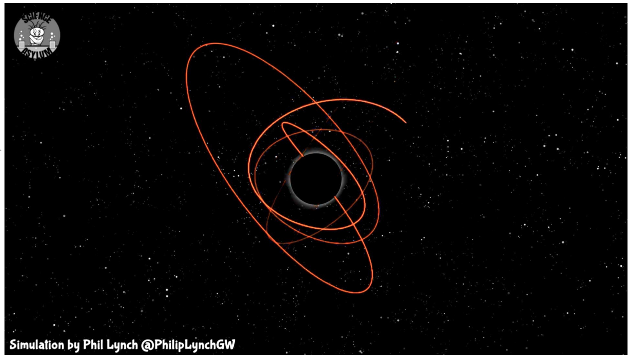
Open Orbits

...and don't get me started on orbits around black holes



Summary

Rocket Science
What does a rocket do?

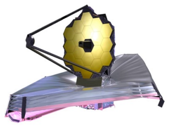
Orbits
Kepler, Newton and Buzz Aldrin
Circular – elliptical – parabolic – hyperbolic

Getting From A to B
Earth to Mars
Gravity assists to the rest of the solar system

Parking Places
What are Lagrange points all about?

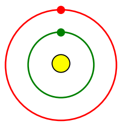
Summary

Why is "rocket science" considered to be so hard?



Yes, there are some objects in the solar system that move in ways that are not, at first sight, intuitive.

Yes, calculating how to put the JWST into orbit around L2 was not trivial (especially given the accuracy achieved).



But the underlying idea is straightforward enough: stronger gravitational pull leads to faster motion. (The Earth moves around the Sun faster than Mars)

That's really all there is to it. The rest is ***just*** maths.

After all ... it's not rocket science!