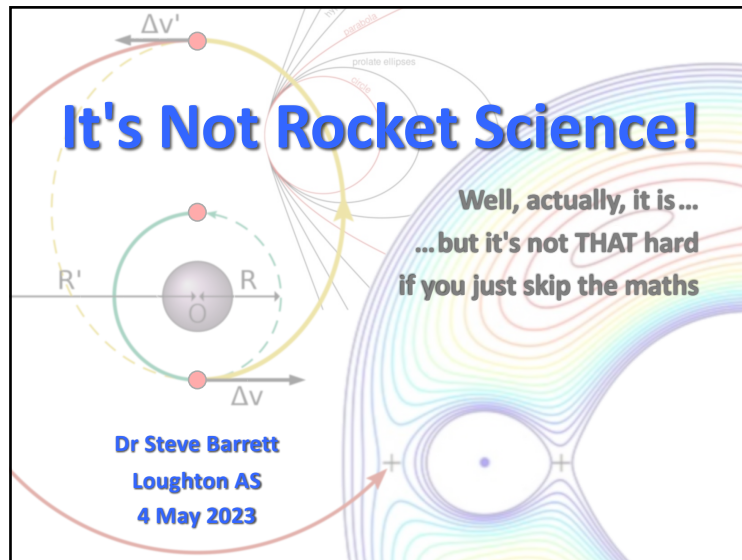


It's Not Rocket Science!



It's Not Rocket Science



UNIVERSITY OF
LIVERPOOL

2

Contents

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?

UNIVERSITY OF
LIVERPOOL

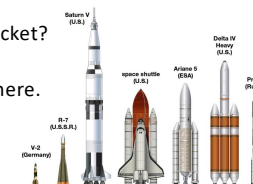
3

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.)

UNIVERSITY OF
LIVERPOOL

4

It's Not Rocket Science!

Newton's Cannonballs



Isaac Newton
Principia 1686

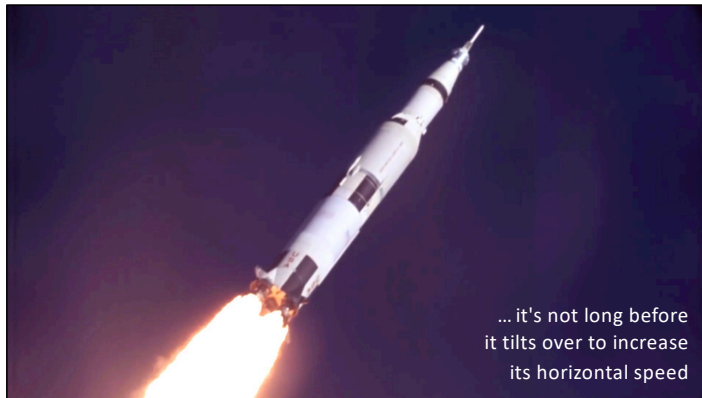
The need for **horizontal** velocity was realised more than 300 years ago

Saturn V Launch



Although initially
the rocket lifts
off vertically ...

Saturn V Launch



... it's not long before
it tilts over to increase
its horizontal speed

Otherwise: What Goes Up ...



Blue Origin
New Shepard
It goes vertically up ...
it comes vertically down
Altitude = 100 km
Flight time = 10 min

It's Not Rocket Science!

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

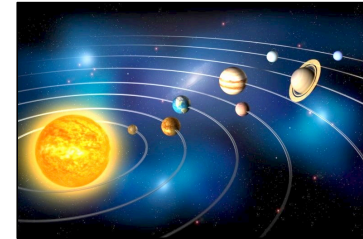
What are Lagrange points all about?

Orbits

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

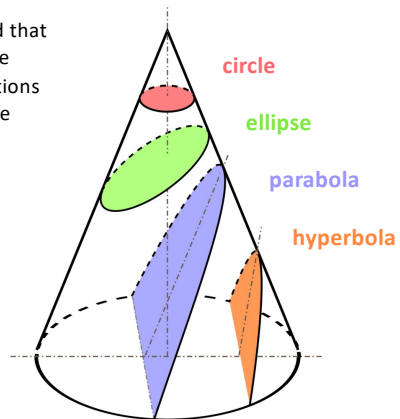
We are all used to the idea of planets in orbit around the Sun, or moons in orbit around their planets.

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



Conic Sections

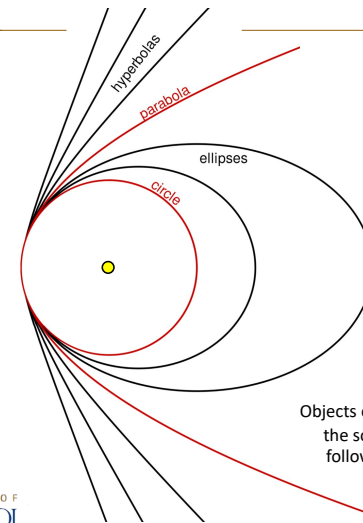
Newton found that orbits have the shapes of sections through a cone



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.

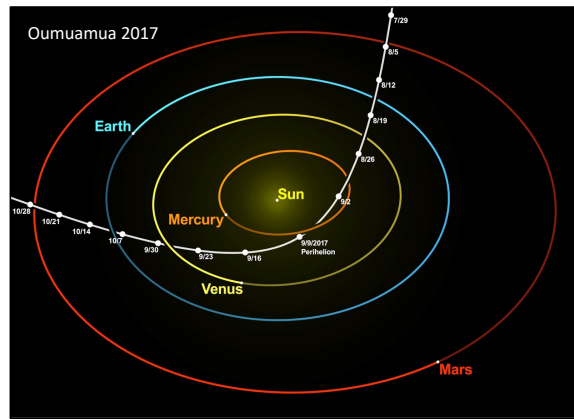


Planets follow closed elliptical orbits, but a comet falling into the solar system from way out in the Oort cloud follows a parabolic path.

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

It's Not Rocket Science!

Hyperbolic Orbit



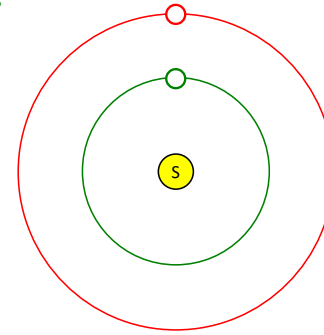
Orbit Size and Orbit Period

Green planet is
closer to Sun

Gravitational
pull from Sun
is stronger

Planet moves
faster to stay
in orbit

Shorter period
(‘year’)



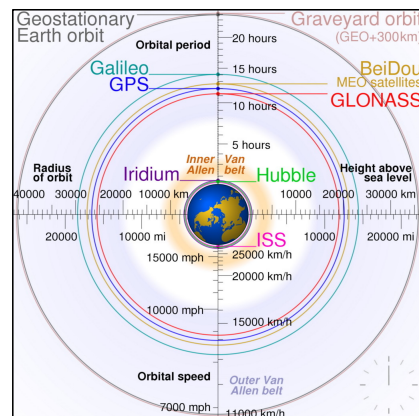
Red planet is
further from Sun

Gravitational
pull from Sun
is weaker

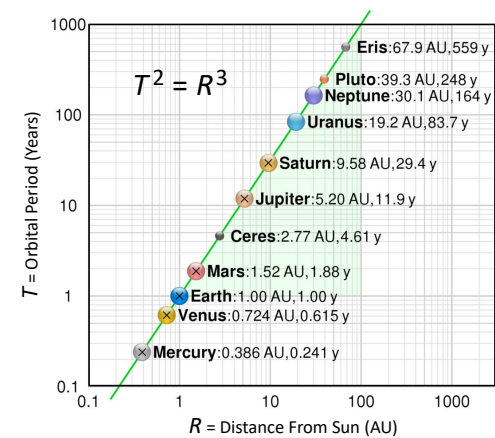
Planet moves
more slowly
to stay in orbit

Longer period
(‘year’)

Earth Satellite Orbits



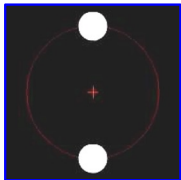
Planets Orbit the Sun




It's Not Rocket Science!

Circular Orbits

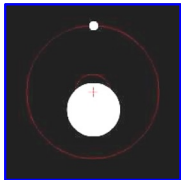
Two objects with equal mass orbit around the centre of mass (+)



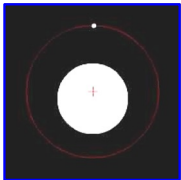
If the objects have different masses, objects with larger mass move smaller distances



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

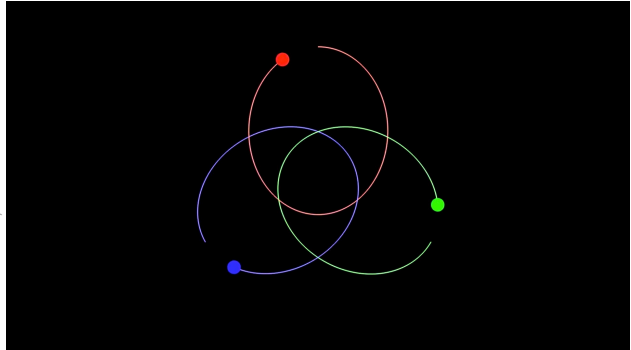


UNIVERSITY OF LIVERPOOL

17

3-Body Problem

Describing the relative motion of **two** objects is a soluble problem



Physics Simulations

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

UNIVERSITY OF LIVERPOOL

18

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

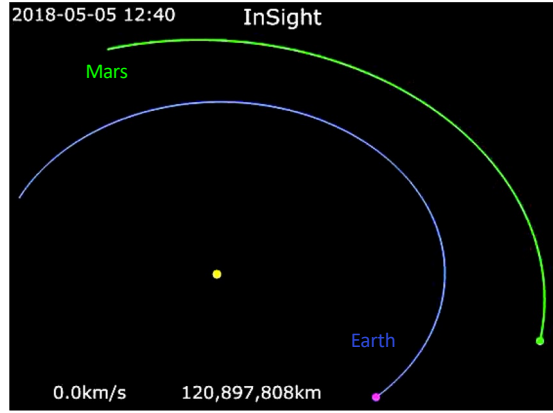
Parking Places
What are Lagrange points all about?

UNIVERSITY OF LIVERPOOL

19

Earth to Mars

2018-05-05 12:40 InSight

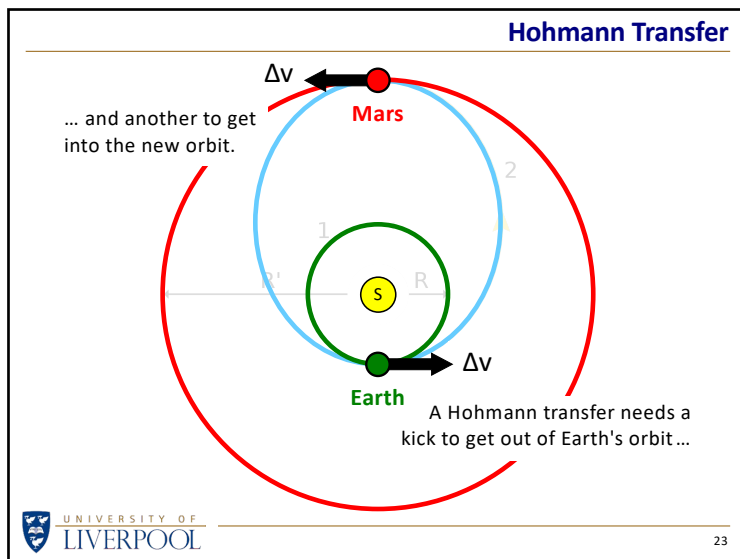
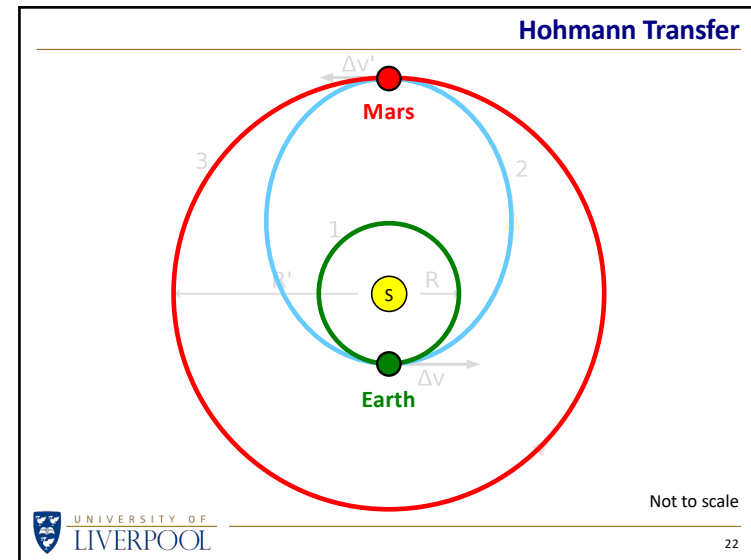
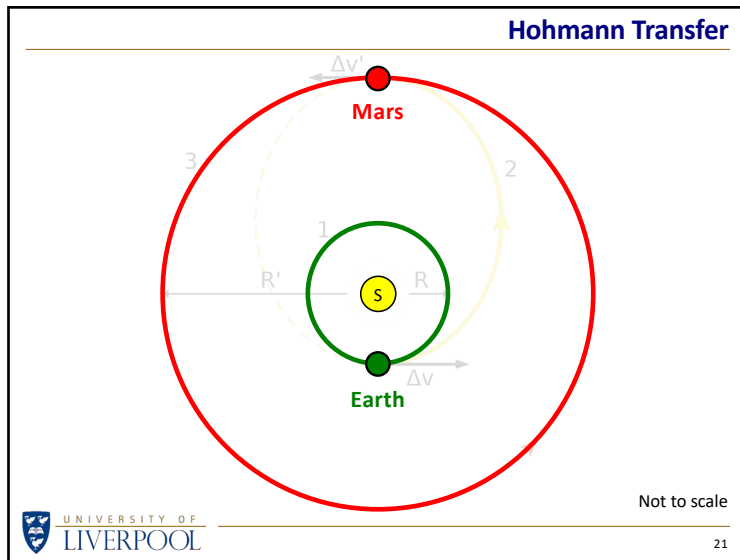


0.0km/s 120,897,808km

UNIVERSITY OF LIVERPOOL

20

It's Not Rocket Science!



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.

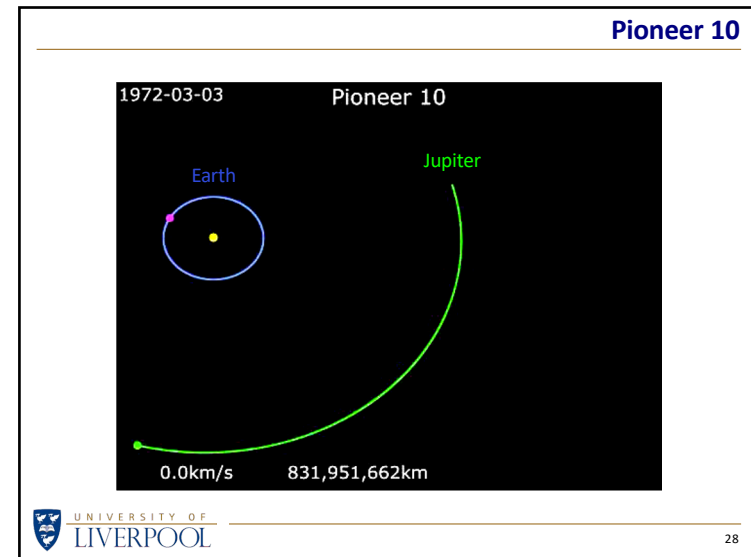
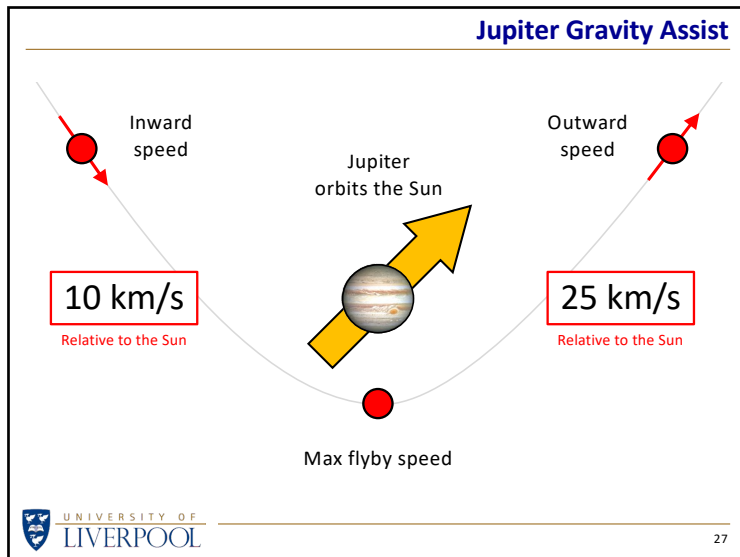
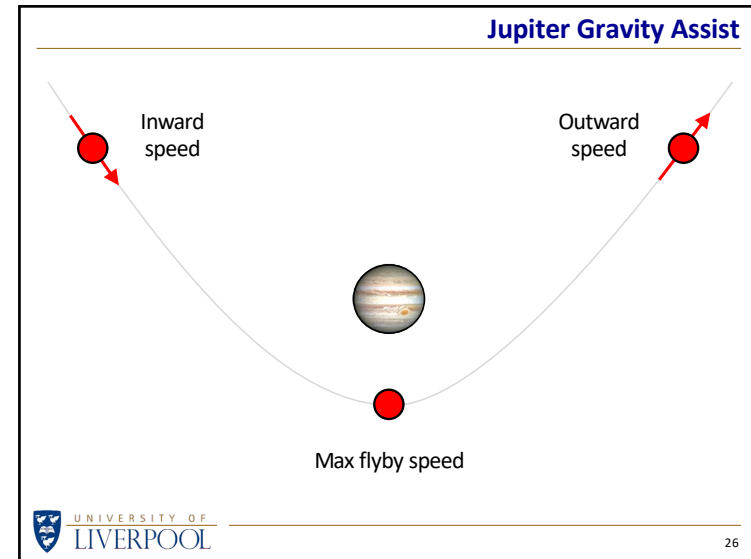
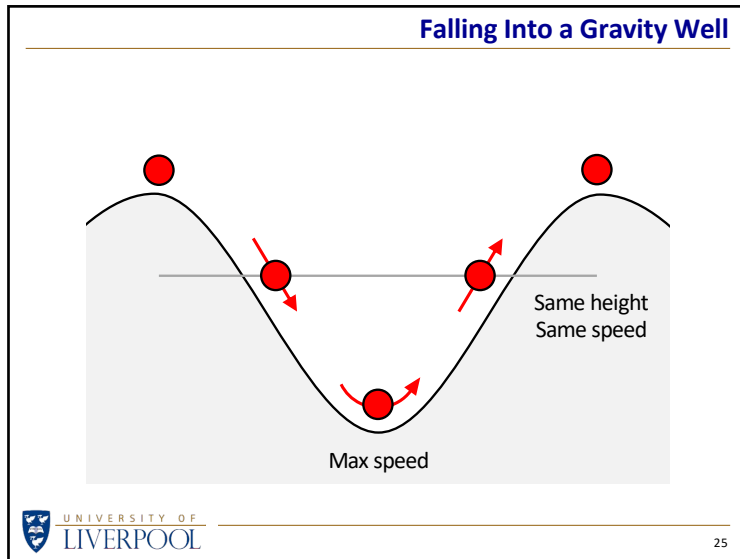
1986-12-08 Voyager 2

19.5km/s 1,438,307,736km

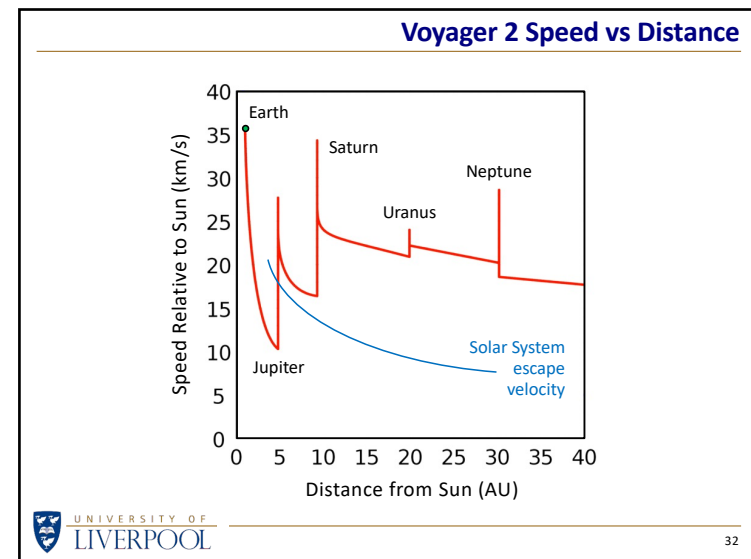
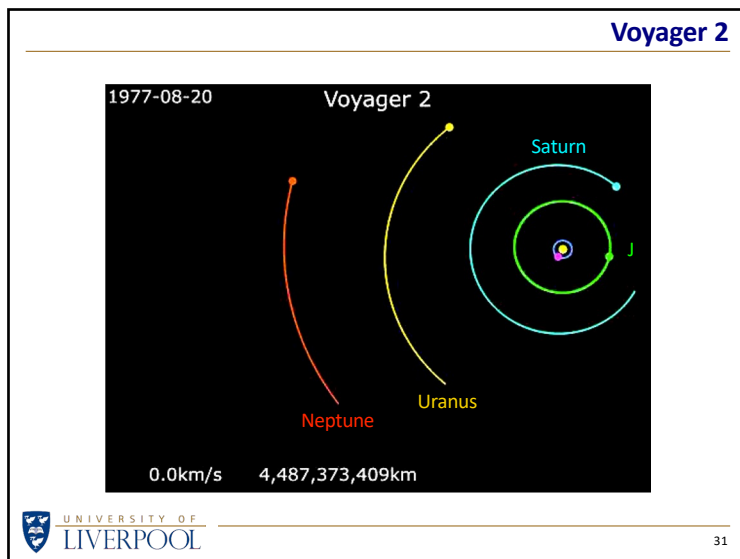
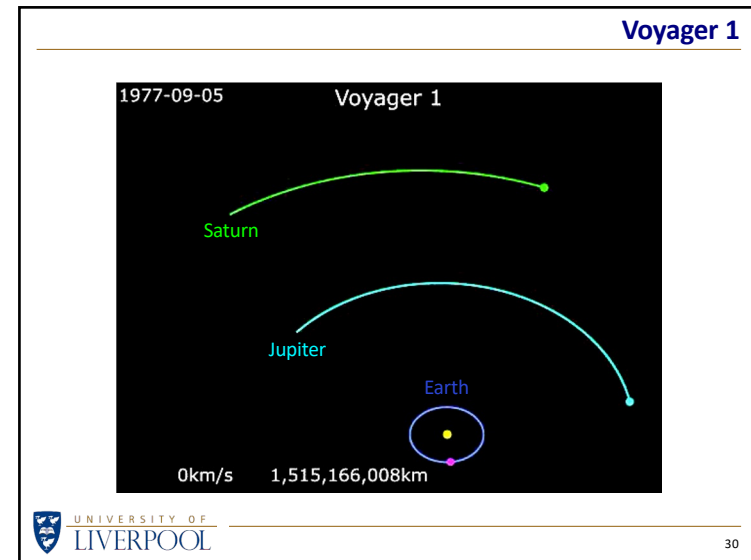
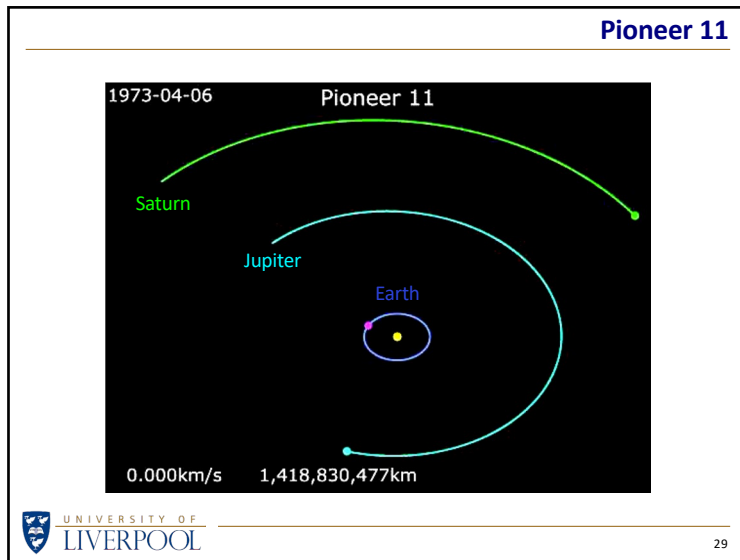
UNIVERSITY OF LIVERPOOL

24

It's Not Rocket Science!



It's Not Rocket Science!



It's Not Rocket Science!

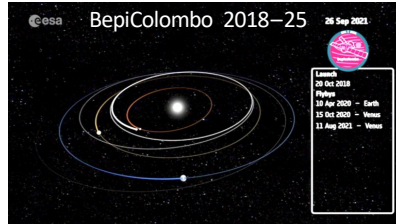
Gravity Assists

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.

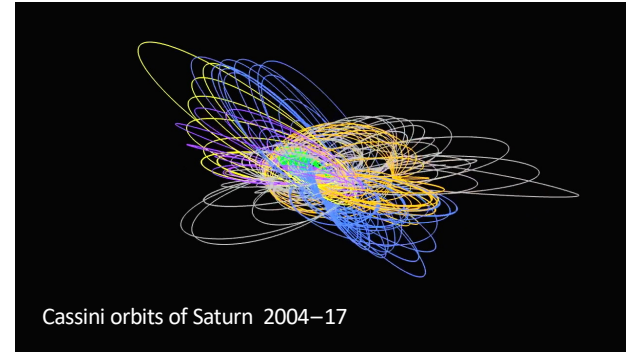
A planet flyby can be used to *lose* speed as a spacecraft 'falls' into the inner solar system.

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



Changing Orbits Uses Fuel

Some spacecraft go into orbit around their target planet



Any orbital changes require fuel which reduces the mission lifetime

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?

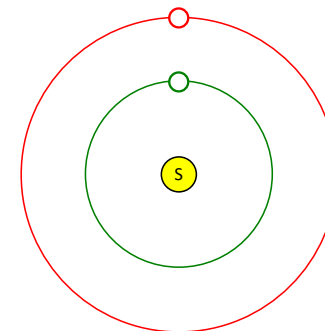
Orbit Size and Orbit Period

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’)

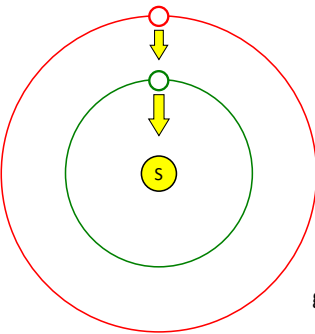
It's Not Rocket Science!

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.

UNIVERSITY OF LIVERPOOL

37

Lagrange Points

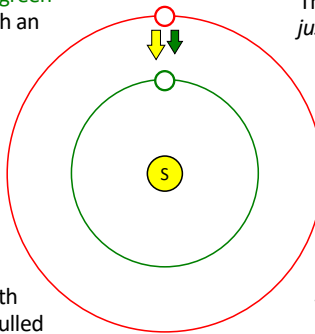
Let's assume that green is planet Earth with an orbital period of exactly 1 year.

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.

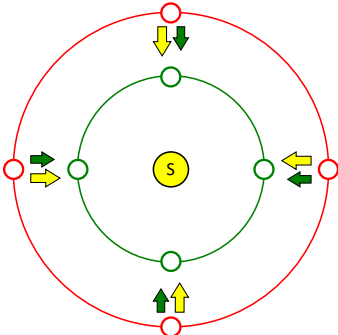
That would mean that the red object would orbit the Sun 'with' the Earth.



UNIVERSITY OF LIVERPOOL

38

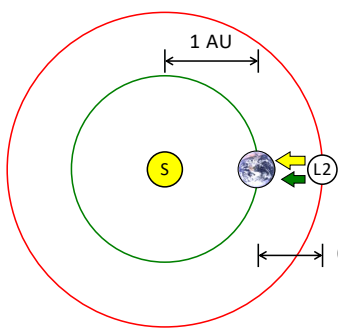
Lagrange Point L2



UNIVERSITY OF LIVERPOOL

39

Lagrange Point L2



1 AU

0.01 AU

Not to scale

UNIVERSITY OF LIVERPOOL

40

It's Not Rocket Science!

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.

41

Lagrange Point L1

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

42

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 . Simple!

43

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

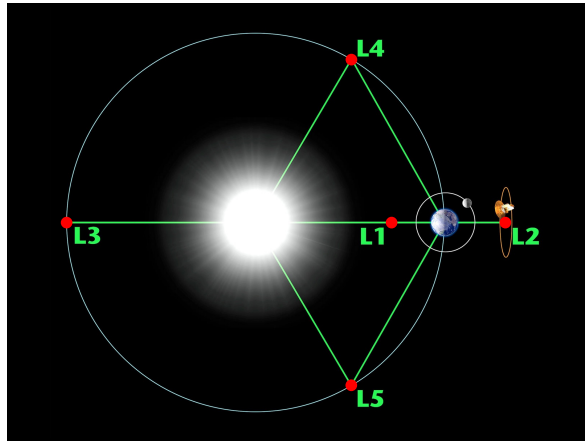
Just solve for r . Simple!

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

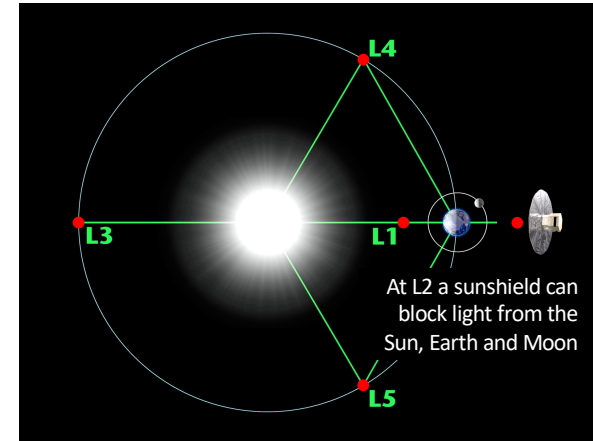
44

It's Not Rocket Science!

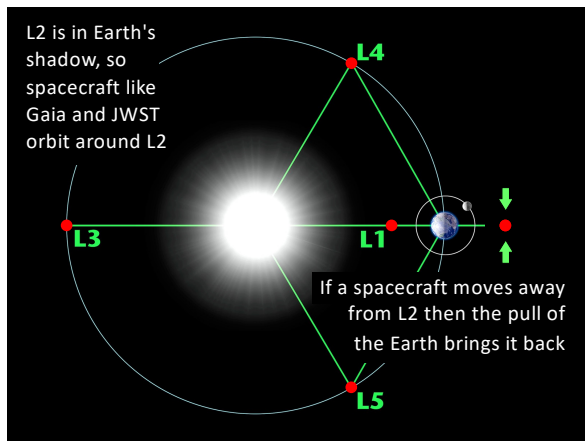
Lagrange Points 1–5



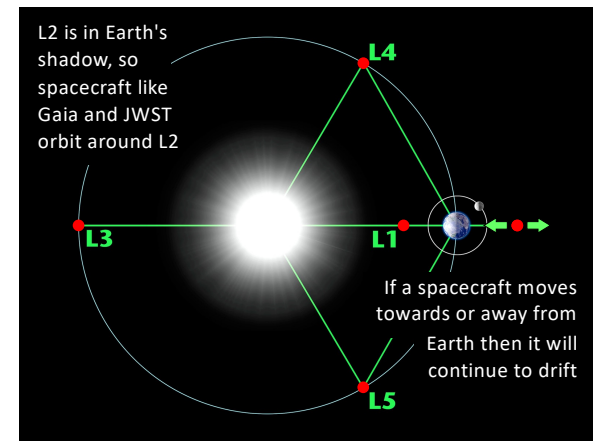
Why Park at L2?



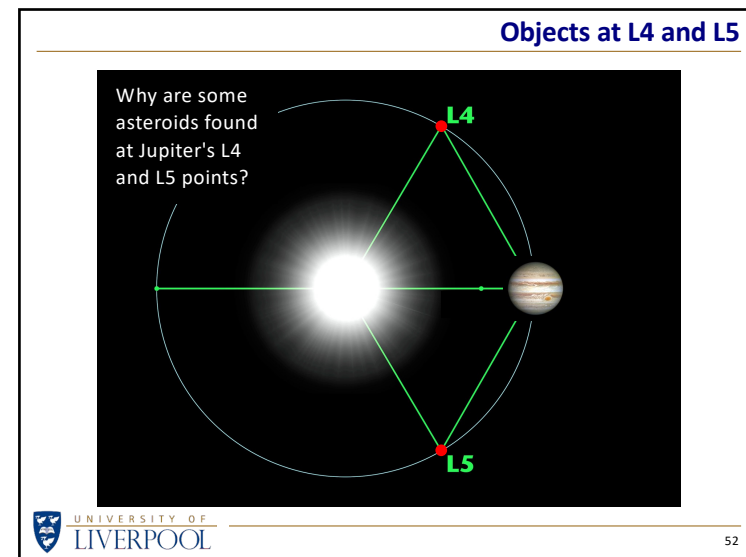
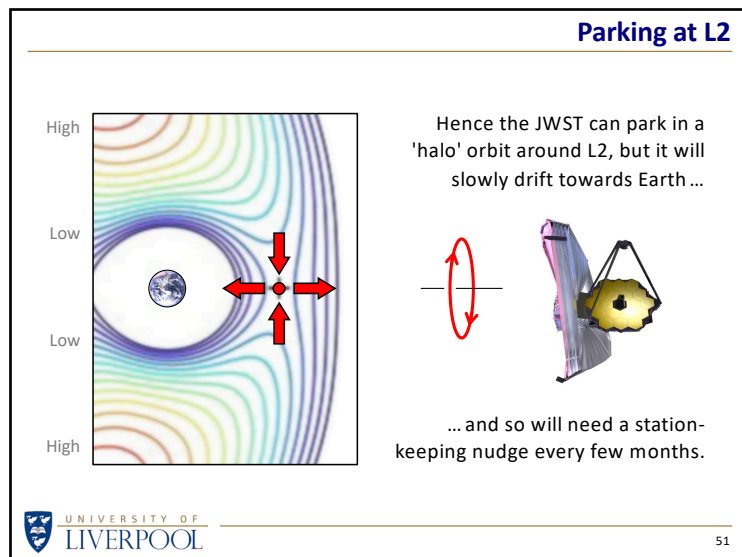
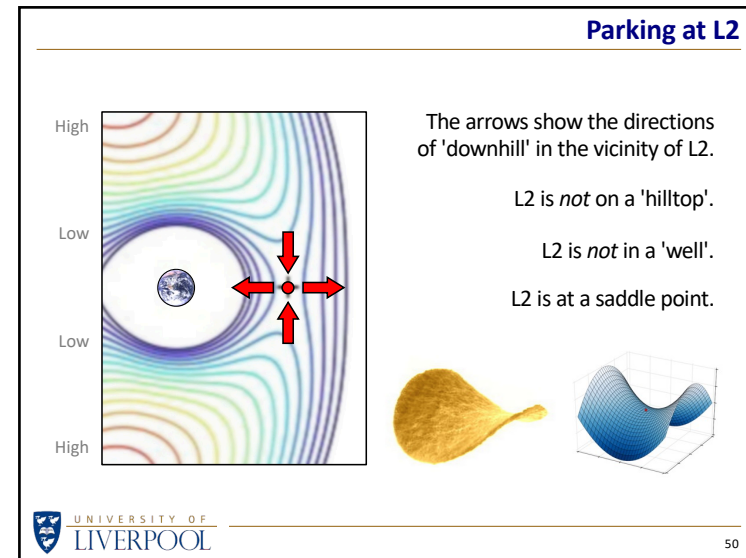
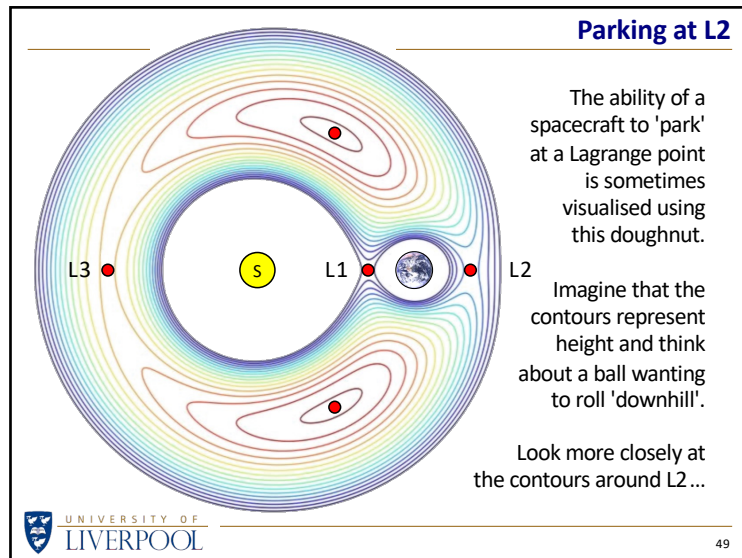
Why Park at L2?



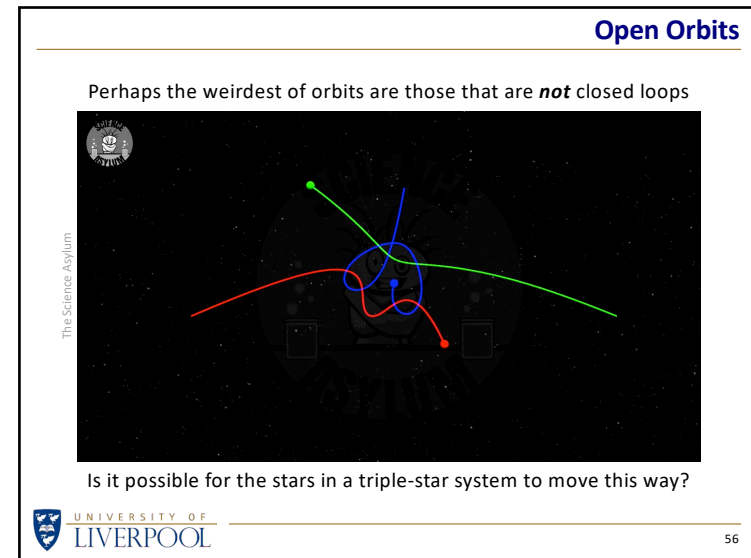
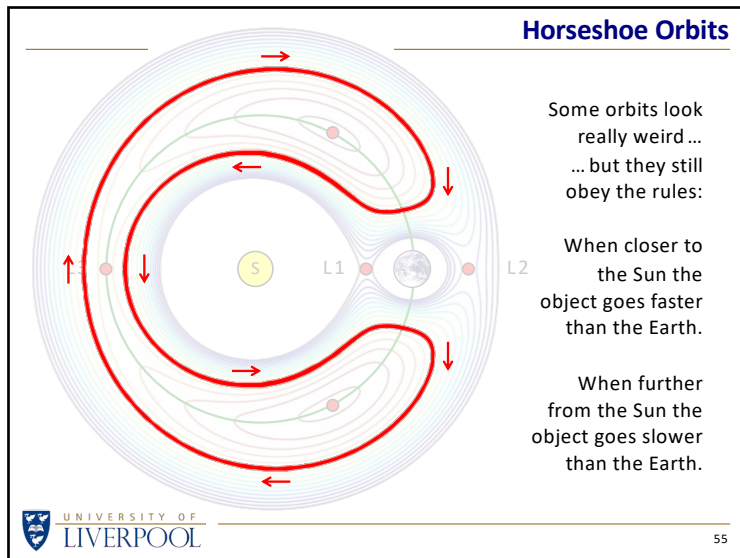
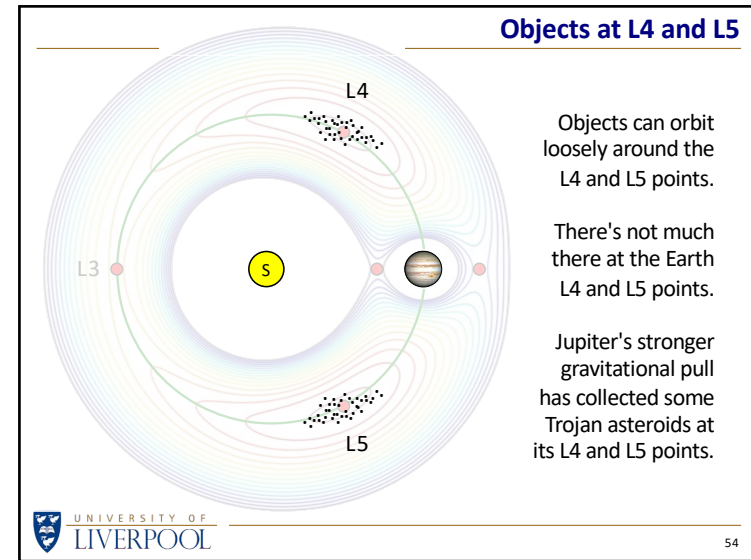
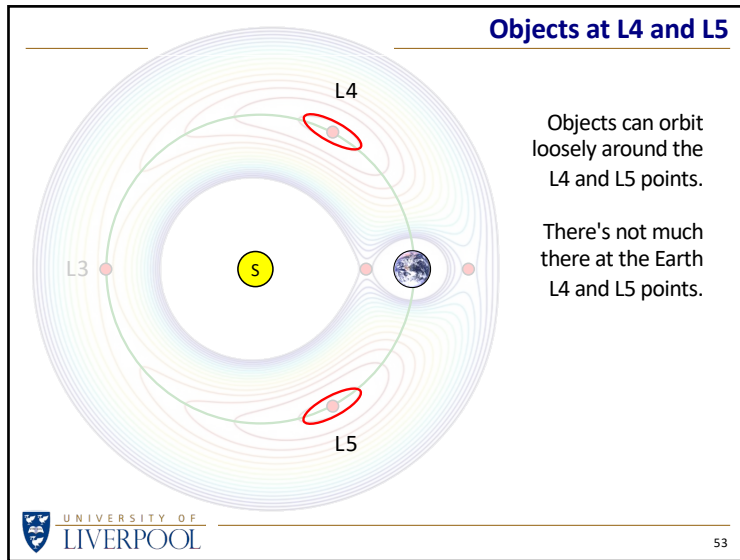
Why Park at L2?



It's Not Rocket Science!



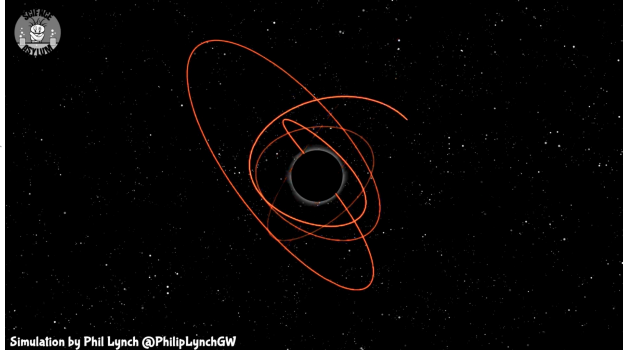
It's Not Rocket Science!



It's Not Rocket Science!

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

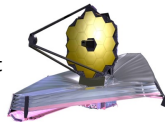
Parking Places

What are Lagrange points all about?

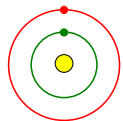
Summary

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!

