PHYSOC MONTHLY

DECEMBER 2021 EDITION

ROCKET SCIENCE

PHYSOC

@thephysicsociety

thephysicsociety.org

CONTENTS

DECEMBER 2021 EDITION

FOREWORD

Dear Reader,

Welcome back! You may have subscribed to PhySoc Monthly because of your love for physics. Maybe it's because of your general adoration for all that is factual and rational, or maybe you have a thirst for knowledge that just needs to be quenched.

In this newsletter issue, we are going to invite you to hop aboard our spacecraft, and join us on our journey from the earth to the moon! Sit back and relax as we embark on our exciting voyage, and we'll take you through the physics behind the different stages of a spacecraft's journey, and some of the most fundamental principles of rocket science. Yes, *rocket science.*

Warm Regards,
The Physics Society 2021-22

PHASE 1

Once a rocket has launched, the Earth's gravity is still pulling the rocket down. If you've seen pictures or videos of rockets a few seconds after they've launched, you must be familiar with the flames, hot gases, and smoke streaming out from the bottom. That's the exhaust, which comes from burning the rocket's propellants. This exhaust creates an upward force, called the **thrust**. While the rocket is travelling upwards within the earth, the thrust force needs to be greater than the force of gravity pulling down on the rocket.

Isaac Newton's third law of motion states that every action has an equal and opposite reaction. So the "action" force pushing the exhaust out of the rocket must be balanced by an equal force driving the rocket forward. Although the forces acting in the opposite directions are equal, their visible effects are quite different. This is due to Newton's second law - which states that:

*Force = Mass * Acceleration*

The key idea from this equation is that while the acceleration and mass are inversely proportional (which means that if one quantity increases, the other would decrease), the net force is directly proportional to both of these quantities.

Let's apply this principle to rockets. The action force rapidly accelerates the small mass of exhaust to hypersonic speeds (speeds that are more than 5 times the speed of sound) each second. The equal reaction force produces a far smaller acceleration in the opposite direction, because of the far greater mass of the rocket. See the relationship between mass and acceleration when the force remains constant? Well then folks, you've successfully understood one of the fundamental principles behind rocket travel mechanisms, so pat yourselves on the back for that!

But what happens next is different. The propellants, which by far, makes up the largest part of the rocket's mass, get used up as the engines constantly fire. Unsurprisingly, the mass of the rocket decreases quite significantly during its journey. In order for the left side of our equation to remain balanced with the right side (to keep the force constant, as we established before), the acceleration of the rocket has to increase as its mass decreases. So you can picture a rocket as starting off slowly, but travelling faster and faster as it climbs into higher levels in the earth's atmosphere. Newton's second law of motion can be restated in the following for a rocket: the greater the mass of a fuel burned, the greater the thrust of the rocket.

To enable a rocket to reach into low earth's orbit, it is necessary to achieve a certain speed. And that speed is the so-called **escape velocity**, which has a magnitude of 40,250 Km per hour, approximately 500 times the average speed of a car! Attaining space flight speeds requires the rocket engine to achieve the greatest action force possible in the shortest time. Only then can the rocket leave the earth and travel out into deep space.

Once the rocket, carrying our satellite, has made it to outer space escaping the Earth's atmosphere, how does it travel through space and make it to orbit? Now you may be a bit confused, thinking, "Alright, the rocket had air on Earth to push against and move upwards, but what would it do to zoom past in space considering there's no air?!" Don't you worry, we've got this sorted for you. Turns out, Newton's third law holds the answer to this mystery as well. As the rocket discharges burning fuel from one end, the force created by the engines will produce an equal thrust in the opposite direction, which will act on the rocket and move it forward! Basically, a rocket would move by pushing on the gas flaming from its engines. Easy, huh?

However, space engineers often find themselves in a paradox. A small amount of thrust produced by the burning fuel does indeed move the spacecraft forward, but if you want to reach your destination faster, more fuel would be crucial. This however means more weight and an added expense to the mission. This is why whenever we're shooting for faraway planets, some spacecraft use the gravity of a nearby planet to provide a 'speed boost', thereby helping reach said destination faster.

Now let's look at how this satellite would make its way into orbit around another celestial body (for ease of understanding let's take the Earth itself here). After a rocket has gotten a certain distance from Earth, it would release the satellite in it. As this satellite is released, it picks up some momentum (due to the rocket's motion) which pulls it in a certain direction. As this satellite moves away from Earth, the Earth's gravity pulls it in another direction. This balance between gravity and momentum is what would keep the satellite in orbit around Earth

Scientist Johannes Kepler developed a formula that determined the exact speed needed to orbit the Earth. This is given by:

$$V = \sqrt{(g_0 * R_e^2)/(R_e + h)}$$

h = Height of the orbit

R_e = Earth's radius

g_0 = Gravitational constant of earth = $9.81 m/s^2$

Looking at this equation, we see how an increase in height above the planet requires a lower orbital speed and vice versa for a decrease in height. This is because, when two objects are nearer to each other the force between them is stronger, just like a magnet. Due to this, there is a greater acceleration (Newton's second law) and therefore a greater change in velocity causing the object to move faster.

PHASE 2

Hello reader! In the second part of this article, we'll cover the journey of a spacecraft in orbit, which will include types of orbits, certain orbital manoeuvres and what has to happen for a spacecraft to meet a satellite. So let's get started!

To begin with, a spacecraft can enter different kinds of orbits.

- Satellites in **Geosynchronous orbit** have a time period of 24 hours- so one rotation around the Earth takes 24 hours, and that means that throughout its rotation the satellite remains above the same point on Earth. These satellites are ideal for certain types of communications and meteorology.

- **Geostationary orbits** are a type of geosynchronous orbit, but instead of the slight inclination, satellites in this orbit are parked directly over the equator.

- **Polar orbits** follow a path with an angle of 90° from the equator, passing over the poles - satellites used for mapping use a polar orbit, as they have access to every point on the planet's surface.

- **Lower Earth Orbits** are closer to the Earth's surface than the others we discussed, some can be as low as 160km, but they're generally below 1000km.

How are orbits changed?

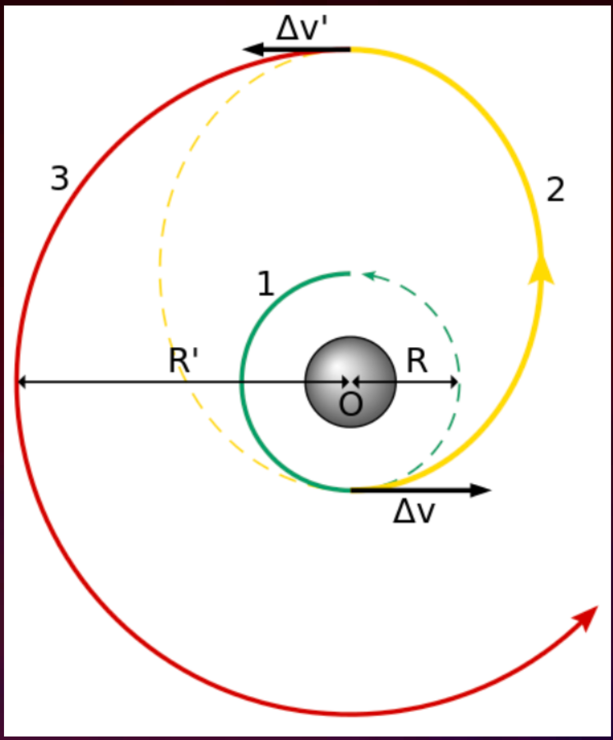
While travelling in a vacuum results in continuous motion, this only occurs in a perfect world. In reality, there is debris, some particles of gas and the gravity of other planets to contend with. At other times the motion of a spacecraft needs to be changed to meet with a satellite that needs to be restocked or to land on a planet. So how are orbits changed to facilitate this?

To change the altitude of an orbit, the speed of the satellite must be changed.

$$F_{net_r} = ma_r$$

$$G\frac{mM_E}{r^2} = \frac{mv^2}{r}$$

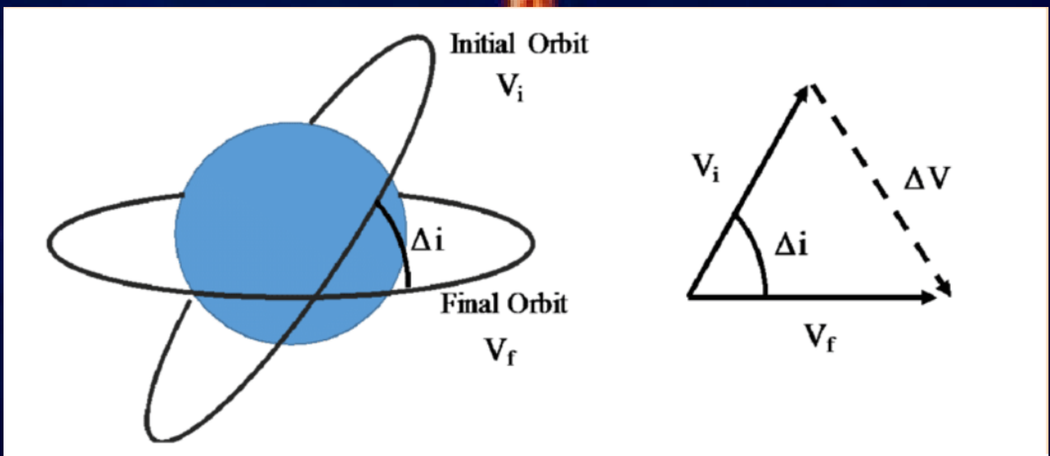
Since the mass is constant and gravity is almost constant we can assume that the force applied on the satellite is constant. As a result, to increase the radius the velocity must be increased. The thruster is, therefore, fired again parallel to the orbit at the apoapsis(highest point of the orbit) to re-circularize it, leaving it at a higher altitude.



(1)

Changing the inclination of an orbit

This is done to change the plane about which a satellite orbits. Here a thrust is applied perpendicular to the direction of motion, inducing a velocity vector perpendicular to the direction of movement. The initial horizontal velocity does not change. The sum of the 2 vectors leads to the final velocity and inclination. The vector diagram for this is shown below.



(2)

Space Rendezvous

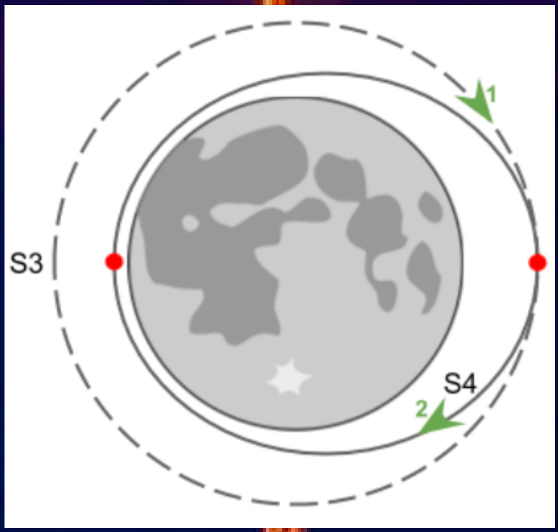
This is an orbital manoeuvre where two spacecrafts arrive in the same orbit, and come extremely close and stay at a constant distance from each other throughout the process - oftentimes the spacecrafts are a space station and a maintenance spacecraft. This process may precede docking to create a physical link between the bodies. This essentially happens every time a spacecraft brings new crew or supplies to a space station.

First, it's important to understand that a spacecraft can't just change its orbital velocity at the same altitude- each orbit corresponds to a specific orbital velocity- lower orbits have a higher orbital velocity. To catch the satellite, the chasing rocket can either enter a low and fast orbit or enter a higher slower orbit and let the satellite catch it. Once they are right above each other the resupply vehicle will change its altitude to that of the satellite. Now they will remain at an equal distance for the docking.

Now that we have learnt how orbits work and how to change them, it is time to fly further out and visit the moon. Read on to understand the landing mechanisms of a spacecraft. We'll see you there!

Landing on the Moon

As our spacecraft gets closer to the moon, it comes under the influence of the moon's gravitational field. Its trajectory is altered by the moon's gravitational pull, and the spacecraft eventually starts orbiting the moon. It then fires its thrusters so that with each orbit around the moon, the spacecraft gets a little bit closer to the moon's surface - you can imagine its trajectory in the shape of a spiral (jalebi) around the moon, where the spacecraft starts from the outermost curve and gets nearer and nearer to the moon's surface as it travels.



This process of getting closer to the moon usually takes a couple of days, and is necessary because landing onto the surface straight away would not only take too much fuel (due to the drastic change in trajectory) but would also cause the spacecraft to land too quickly, making it extremely difficult to control its landing speed.

Controlling and reducing landing speed on the surface also requires the action of thrusters, this time firing towards the surface to counteract the force of gravity of the moon - and thus starting with a low speed that is easier to control is imperative for the conservation of fuel and the safety of the spacecraft.

As the spacecraft travels on its spiral trajectory, it eventually reaches an optimum height from which descending directly to the surface is appropriate. However, it cannot just land anywhere, as some terrestrial features of the moon, such as craters, may affect the spacecraft's landing. Thus, to find the perfect landing spot, the spacecraft is fitted with special machines which include:

1. Lander Position Detection Camera (LPDC)
2. Lander Horizontal Velocity Camera (LHVC)
3. Lander Hazardous Detection and Avoidance Camera (LHDAC)
4. Laser Altimeter (LASA) *[Note: The altimeter is a device that measures the altitude of an object above a fixed level.]*

To find the right landing spot, the spacecraft has to first slow down and hover above the moon. It does this by using the LHVC, which as shown by its name, is an onboard camera that is used to estimate the horizontal velocity of the lander during the descent phase. It allows one to make an estimate of the speed required for the spacecraft to land safely and as mentioned earlier, it aids the thrusters with their job of reducing landing speed. While the spacecraft is hovering, the LASA maps the topography and shape of the surface of the planet and this together with the LHDAC (which uses sensors to detect and identify surface hazards in real-time) and LPDC, identifies the perfect spot for landing (this is known as the retargeting phase) and the coordinates of the landing spot are found.

Finally, the spacecraft is carefully manoeuvred by the central engine and touchdown sensors and safely landed on the planet's surface. "The eagle has landed".

Conclusion

Congratulations! We have successfully landed on the moon. The journey has had many defining stages, each with its own set of challenges, but all's well that ends well! So fuel your own rocket with your passion (and some of the knowledge you have gained by reading this article) and soar to the moon! As for returning back to earth, we hope that we have made you curious enough to figure that one out by yourself!

FURTHER READING

How does a rocket land back on Earth?: https://www.makeuseof.com/how-do-rockets-land-back-on-earth-the-amazing-tech-involved/#:~:text=Currently%2C%20SpaceX%20rockets%20use%204,using%20the%20launch%20tower%20arm.

BIBLIOGRAPHY

1. **Institute of Physics:** https://www.iop.org/explore-physics/moon/how-did-we-get-to-the-moon#gref
2. **How stuff works:** https://science.howstuffworks.com/lunar-landing.htm
3. **Science Direct:** https://www.sciencedirect.com/topics/earth-and-planetary-sciences/laser-altimeter
4. **The European Space Agency:** https://www.esa.int/Enabling_Support/Space_Transportation/Types_of_orbits
5. **GeoSciences:** https://geo.libretexts.org/Courses/University_of_California_Davis/GEL_056%3A_Introduction_to_Geophysics/Geophysics_is_everywhere_in_geology.../03%3A_Planetary_Geophysics/3.01%3A_Orbital_Mechanics
6. **NASA:** https://www.nasa.gov/offices/nesc/articles/space-rendezvous