SCIENCE
FOR PEOPLE

SOLAR SYSTEM EXPLORATION AND INDIA'S CONTRIBUTION

A Beginner's Guide

Dr. Tirtha Pratim Das

Solar System Exploration and India's Contribution: A Beginner's Guide

Dr. Tirtha Pratim Das

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Foreword

If you are already an expert in the domain of solar and planetary sciences, this book is not for you. This book is, rather, meant for the non-experts who are not yet in a position to grasp the concepts and scientific results reported in peer reviewed scientific journals. Presently, there is no dearth of scientific articles being published in journals on different facets of the solar system. However, there remains a gap between the students, non-expert common space enthusiasts, and the reputed scholars who are serious researchers on this subject. "Solar System Exploration and India's Contribution: A Beginner's Guide" is a humble attempt to bridge that gap.

This book, therefore, serves as an accessible introduction to the solar system and its exploration. This is not a complete account of the solar system. There are other wonderful books on this subject for that purpose. This book delves into the major topics like formation of our solar system, classification of the solar system bodies, attributes of planetary systems, to name a few, in a systematic way, so as to paint the canvas of the solar system and the state-of-the-art of its exploration, rather than getting into intricate details.

The book also delves into the various tools and techniques that have improved our understanding of the solar system. We also learn how technology has transformed our perspective, allowing us to peer into the atmospheres of distant planets, analyze their surface compositions, and even listen for the whispers of their magnetic fields.

As we delve deeper, the book clarifies the scientific criteria that define a planet, distinguishing them from other celestial bodies like asteroids and comets. We explore the fascinating world of asteroids, remnants of the solar system's formation, and comets, icy messengers from the outer solar system that leave behind breath-taking celestial displays. The book also sheds light on the interplanetary dust, a ubiquitous component that fills the vast emptiness of space.

Understanding the attributes of a planetary body is crucial for unravelling its story. The book explores the significance of factors like orbit, mass, size, temperature, rotation, shape, and the presence of a magnetic field. We delve into the composition of planetary surfaces, their internal structures, and the atmospheres that shroud some of these celestial bodies.

Furthermore, the book emphasizes the profound influence of the Sun on Earth, highlighting the intricate interplay between solar radiation, heat, and the constant flow of particles that shape our planet's environment. We explore the concepts of weather, space weather, and planetary space weather, understanding how these phenomena interact and affect various celestial bodies.

Equipped with this foundational knowledge, the book delves into the fascinating realm of space exploration, outlining the different techniques employed to study the solar system. We discover why space-based observations are often preferred and how space science missions are meticulously planned and executed. The book details various space-based techniques used to study planetary bodies, providing a glimpse into the tools that help to study the solar system.

Having set the stage, the book dedicates sections to briefly outline India's contributions to solar system exploration, through several space science missions. The book has discussed the lunar exploration program, highlighting the Chandrayaan missions that have yielded valuable scientific insights. The book also covers India's Mars exploration endeavours, specifically the Mars Orbiter Mission (MOM), and the scientific discoveries it has made. The Aditya-L1 mission, India's first dedicated solar observatory, is also discussed, showcasing the country's growing ambitions in solar research.

Understanding the vast amount of data collected through planetary exploration missions is crucial. The book introduces the Indian Space Science Data Centre (ISSDC) and the International Planetary Data Alliance (IPDA), highlighting the importance of data sharing and collaboration in unraveling the mysteries of our solar system.

As you delve into this book, prepare to embark on a captivating journey of systematic understanding of the subject. I have taken extreme care to keep the number of pages limited, so as to ensure that the reader finds this work as a friendly capsule of knowledge to comprehend. Also, this book does not include any confidential information. All the information presented in this book are available in the public domain. This book, in its present form, is available free of cost, and not meant for any commercial use.

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Formation of the Solar System

Around 4.5 billion years ago, our solar system began its journey from a dense, swirling cloud of interstellar gas and dust. The trigger for this celestial dance might have been a nearby supernova[1], its explosive shockwave setting off the collapse of this primordial cloud. As gravity took hold, the cloud condensed and flattened into a spinning disk known as a solar nebula. Eventually, material gathered at the center, forming what would become our sun, while the surrounding debris coalesced into protoplanetary disks, laying the groundwork for the formation of planets, moons, asteroids, and comets. This grand spectacle of creation, shaped by the laws of physics and the whims of chance, set the stage for the remarkable journey of exploration that humanity embarked upon.

Why do we study the Solar System

Exploring the solar system is a matter of beyond satisfying curiosity; it's about understanding our origins, our place in the universe, and our potential future. By studying other planets, moons, asteroids, and comets (we will discuss more about these subsequently), we gain insights into Earth's past, present, and

[1] **Supernova:** A supernova explosion represents the cataclysmic explosion of a massive star, marking the dramatic conclusion of its stellar lifecycle. These behemoths, exceeding eight times the solar mass, face a critical juncture when their internal nuclear fuel dwindles. Unable to withstand its own immense gravity, the core undergoes a rapid collapse, triggering a violent outward shockwave. This colossal detonation, briefly outshining entire galaxies, propels the star's outer layers into the interstellar medium. In its wake, the supernova event not only sculpts the surrounding environment with heavy elements forged in the explosion, but also leaves behind a super-dense remnant – either a neutron star or a black hole.

potential future. We learn about the conditions necessary for life and the mechanisms that drive planetary evolution.

This quest extends our gaze beyond our solar system, prompting us to explore exo-solar systems (the solar systems other than our very own one), where we search for habitable worlds and signs of life. The motivations for exploring the solar system and beyond are intertwined, driven by our innate curiosity, our desire for knowledge, and our quest to uncover the wholesome picture, of which we are a part.

The Sun

Central to our solar system lies the Sun, a luminous sphere of hot plasma[2] that provides light, heat, and energy to the planets orbiting around it. With a diameter of about 1.4 million kilometers, the Sun dwarfs all other objects in the solar system and accounts for most of its total mass. Through the process of nuclear fusion, the Sun converts hydrogen into helium, releasing immense amounts of energy in the form of light and heat. This energy drives the complex dynamics of our solar system, influencing planetary orbits, weather patterns, and the conditions necessary for life to thrive on Earth. Studying the Sun allows us

[2] Plasma is the fourth state of matter, distinct from solid, liquid, and gas, characterized by ionized particles—atoms that have lost or gained electrons, resulting in a mixture of positively charged ions and free electrons. Plasma is highly conductive and responsive to electromagnetic forces. In the context of the Sun, plasma is the dominant form of matter. The extreme temperatures and pressures in the Sun's core cause hydrogen atoms to undergo nuclear fusion, converting them into helium and releasing vast amounts of energy. This process generates the high temperatures and densities necessary for the creation of plasma.

to better understand the fundamental processes that govern the solar system, and our place within it.

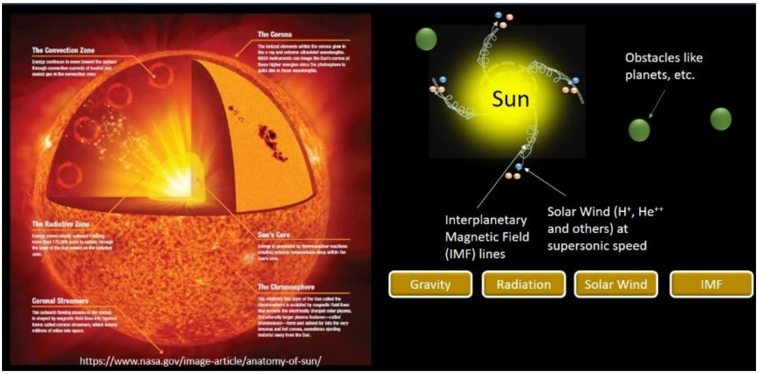

Figure 1: (Left) Anatomy of the Sun picture courtesy NASA ; (Right) Schematic of the emissions of particles, radiationand field from the Sun.

The core of the Sun can be looked upon as a huge nuclear fusion reactor, where Scientists estimate that the Sun converts roughly 9.43×10^{36} hydrogen atoms into helium every second. In the process of fusing hydrogen into helium[3], a small amount of mass

[3] The primary fusion reaction that takes place in the Sun's is a series of steps that convert hydrogen (protons) into helium, releasing a tremendous amount of energy in the process. Here's a breakdown of the reaction:

Step 1 (P-P Chain):

Two protons (hydrogen nuclei) undergo a weak nuclear force interaction, briefly forming a deuterium nucleus (one proton and one neutron) along with a positron (anti-electron) and an electron neutrino.

Equation: $p^+ + p^+ \rightarrow {}^2H^1 + e^+ + \nu\_e$

Step 2:

The positron (e^+) quickly collides with an electron (e^-), leading to their annihilation and releasing energy in the form of gamma rays.

Equation: $e^+ + e^- \rightarrow \gamma + \gamma$

The deuterium nucleus (${}^2H^1$) then fuses with another proton (p^+) to form a helium-3 nucleus (${}^3He^2$) and releases another gamma ray.

Equation: ${}^2H^1 + p^+ \rightarrow {}^3He^2 + \gamma$

is converted into a tremendous amount of energy, according to Einstein's famous equation $E=mc^2$. This conversion of mass to energy results in the Sun releasing tremendous amount of energy. I leave it to you to compute how much of energy is released by the Sun in every second, as an exercise. This incredible rate of fusion is what powers the Sun's immense energy output.

Radially outwards from the core of the Sun, we encounter the Radiative Zone of the Sun, where energy embarks on a leisurely journey, taking more than 1.7 lacs years to traverse this vast expanse of the Sun. Continuing its ascent, energy enters the Convection Zone, where it rides on the currents of heated and cooled gas. As we approach the surface of the Sun, we encounter the Chromosphere, and finally, we reach the region of the solar atmosphere called the Corona. Overall, the Sun is an example of a huge sphere of plasma, the fourth state of matter. Plasma, as you know, is a hot, charged gas, where there is an overall charge-neutrality, where atoms have been stripped of some of their electrons. This makes the Sun's material highly conductive and influenced by magnetic fields.

Step 3:
Two helium-3 nuclei ($^3He^2$) fuse to form a helium-4 nucleus ($^4He^2$), also known as a regular alpha particle, along with two protons (p^+).
Equation: $^3He^2 + {}^3He^2 \rightarrow {}^4He^2 + 2p^+$

Overall Reaction:
By combining these steps, the overall reaction for the proton-proton chain becomes:
$4p^+ \rightarrow {}^4He^2 + 2e^+ + 2\nu\_e + 6\gamma$
This reaction signifies that four protons are fused into one helium-4 nucleus, releasing two positrons, two electron neutrinos, and six gamma rays in the process. The released energy, in the form of gamma rays, travels outward through the Sun's interior, eventually heating the layers above and powering the Sun's light and heat.

As a result of the nuclear reaction in the Sun's core, Sun emits not only radiation, but also emits charged particles that are rich in H^+ (Hydrogen ion, i.e. proton) and He^{++} (doubly ionized Helium), along with some heavier element ions. These positively charged ions are balanced by electrons, and the overall charge balance is maintained. These positive and negative charges blow out of the Sun and spread in the heliosphere. We call these particles collectively, 'Solar Wind'. As you know, a moving charged particle has a magnetic field associated with it, the same happens with the solar wind particles. The solar magnetic field, which is also called the 'Interplanetary Magnetic Field' (IMF) emanate from the Sun and spread out in the solar system. Because of the spin rotation of the Sun the magnetic field lines look like spirals if you see the Sun from the top side; this geometry of the IMF is also called the Parker Spiral. It is along the Parker Spiral lines of the IMF, the solar wind particles travel in helical trajectories.

While the solar radiation, solar wind, and the IMF all spread out to the deep space, there are, in between, obstacles like planets, natural satellites, and other solar system bodies. As a result, the radiation, solar wind and IMF interact with those obstacles, and the nature of their interaction largely depends on the attributes or properties of those obstacles. In this discussion, I shall present a brief overview on what are the possible ways of interaction between the solar radiation, solar wind and the IMF with the planetary bodies. The region of space containing the IMF and Solar Wind is called the 'Heliosphere'; beyond which the solar influences merge with the interstellar medium.

To summarise, if we list the influences of the Sun on us, there will be (i) gravity, (ii) radiation, (iii) solar wind, and (iv) the IMF.

Members of the Solar System

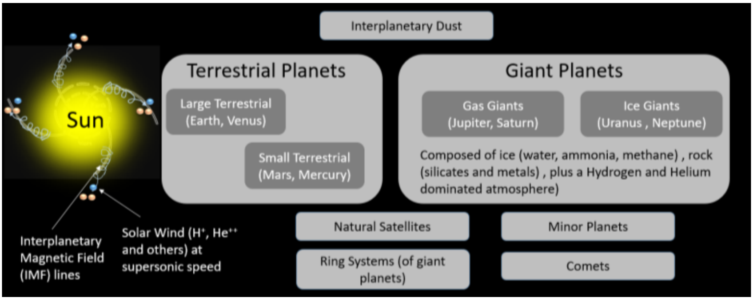

Figure 2: Grouping of the members of the solar system

The solar system has most (more than 99.8%) of its mass concentrated at the Sun, and only a fraction of the mass of the entire solar system accounts for the other members. A way to look at the solar system is that, the Solar system primarily comprises the Sun and some debris. The next biggest object to the Sun is the planet Jupiter, and then comes the planet Saturn. Rest are insignificant in terms of their contribution to the overall mass of the solar system. However, if you consider the total angular momentum of the solar system, about 98% of the total angular momentum is contributed by the planets.

In the inventory of the solar system, we have four giant planets and four terrestrial planets. The giant planets are also classified into Gas giants (Jupiter and Saturn) and Ice giants (Uranus and Neptune). The terrestrial planets are Mercury, Venus, Earth and Mars, counting radially outwards from the Sun. They all differ in their composition and several other attributes, which make their studies interesting. Apart from the planets, the solar system consists of natural satellites, minor planets, comets, ring systems of the giant planets, and last but not the least, the interplanetary dust. We shall discuss about some of these members shortly.

Visualisation of the Solar System

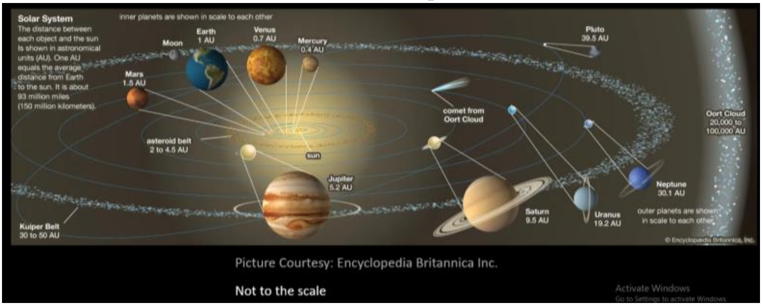

Figure 3: Visualization of the solar system. Picture courtesy: Encyclopedia Britannica Inc.

Solar system is best visualized once you observe from outside. This picture presents an artistic view of the solar system. The giant planets are shown zoomed, depicting their ring systems. This picture also features a comet, as a wanderer in the solar system. You can also visualize the Kuiper belt and the Oort cloud. The Kuiper belt is a vast, icy ring beyond Neptune filled with leftover debris from our solar system's formation. Far beyond the Kuiper Belt, the Oort Cloud is a giant sphere of icy bodies that may be the source of long-period comets. The energy received by any planetary body from the Sun depends on its distance from the Sun and its own size; in this context, the Goldilocks zone is the region around a star, in this case, the Sun, where it's just right for liquid water, and potentially life, to exist on a planet. Forms of life exist on the Earth, as Earth is located in the Goldilocks zone of our solar system, and also the other parameters like atmospheric pressure, composition, etc. support the formation and sustenance of life.

Spacecrafts the crossed the Solar System

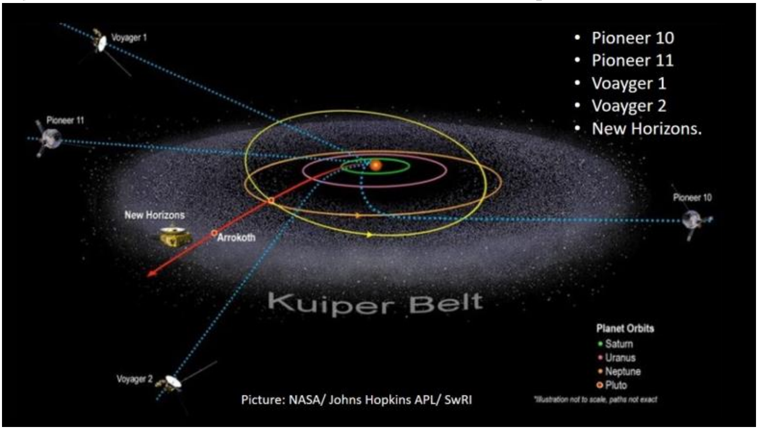

Figure 4: Spacecrafts that crossed the solar system. Picture courtesy: NASA

Since the beginning of the space-era, mankind has sent several missions to space to study the solar system. Missions have been sent to several planets and their natural satellites, as well as to the asteroids. In addition to these, 5 spacecrafts are headed out of the solar system, into what we call the interstellar space. These are the Pioneers 10 and 11, Voaygers 1 and 2, and New Horizons. The picture shows the trajectories of those spacecrafts. Among these, the New Horizons mission was launched in 2006, it completed flybys of Pluto in 2015 and heading out of the solar system, after having several discoveries of dust impacts, an extended Kuiper Belt or even a second one, in its credit.

How Technology Changed our Understanding

As mentioned, there are several objects in the solar system which are beyond the planet Neptune. They are called Trans-Neptunian objects (TNOs). The TNOs have been discovered through a combination of traditional optical telescopes, advanced digital imaging techniques, and dedicated surveys. Several dedicated surveys have been conducted specifically to search for TNOs and other objects in the outer solar system. These surveys use specialized telescopes and observing strategies optimized for detecting faint and distant objects. Examples of such surveys include the Deep Ecliptic Survey (DES), the Palomar Distant Solar System Survey (PDSSS), and the Outer Solar System Origins Survey (OSSOS).

TNOs are significant because they provide insights into the early formation and evolution of the solar system. They represent remnants of the primordial material from which the planets formed and can help astronomers understand the dynamics of the outer solar system.

The discovery and studies of the TNOs were not limited to science, but also forced the astronomers to rethink the very definition of planets. The astronomers came across several examples of dwarf planets[4] where two celestial bodies (the dwarf planet and its natural satellite) of comparable size were seen

[4] One of the most significant discoveries in the Kuiper Belt was Eris, a TNO that is slightly smaller than Pluto but more massive. Eris's discovery in 2005 raised questions about the status of Pluto and its classification as a planet.

sharing their orbit around the Sun, just like Pluto does, along with Charon.

Pluto was discovered in 1930 by American astronomer Clyde Tombaugh. At the time of its discovery, Pluto was considered the ninth planet in the solar system. However, it was soon realized that Pluto was significantly smaller than the other planets and had an unusual orbit that was inclined and highly elliptical.

The discovery of Eris and other TNOs prompted the IAU to reconsider the definition of what constitutes a planet. In August 2006, the IAU introduced a formal definition of a planet.

What all are needed to qualify as a 'Planet'

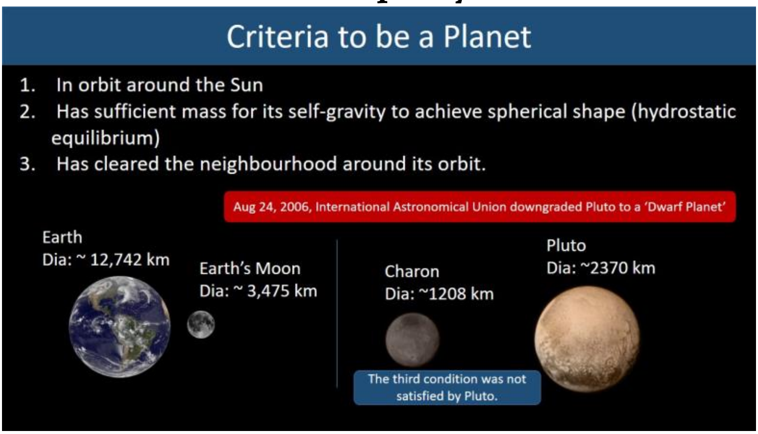

Figure 5: IAU's criteria for a planet. The Pluto-Charon and Earth-Moon systems are shown side by side for comparison.

During the year 2006 annual meeting of the International Astronomical Union (IAU)[5], a major decision was made. The planet is defined to be a celestial body that would satisfy a set of three criteria. They are: (1) The celestial body should be in orbit around the Sun, (2) it should have sufficient mass for its self-gravity to achieve spherical shape (we call this condition 'hydrostatic equilibrium'), and last, but not the least, (3) it should have cleared the neighbourhood around its orbit. The meaning of the third criteria is that the celestial body should not have any other planetary body in its orbit around the Sun, which is of the size comparable with itself.

It was because of the non-compliance to the third criteria that the celestial body Pluto, which was, so far, referred to as the ninth planet in the Solar system, got demoted to the category of the 'Dwarf planet'. Pluto shared its orbit with Charon, whose size is almost half the diameter of Pluto; thus, according to the set of criteria, although the first two are satisfied, the third condition was not met. For the sake of perspective, here I have shown the Earth-Moon system; the Moon's diameter is approximately one-third of that of the Earth.

[5] The International Astronomical Union (IAU) is an assembly of the astronomers from different parts of the world, promoting astronomy through research, education, and even naming celestial bodies like planets and stars. IAU was founded in 1919; it helps astronomers collaborate across borders.

How to classify the Solar System Bodies

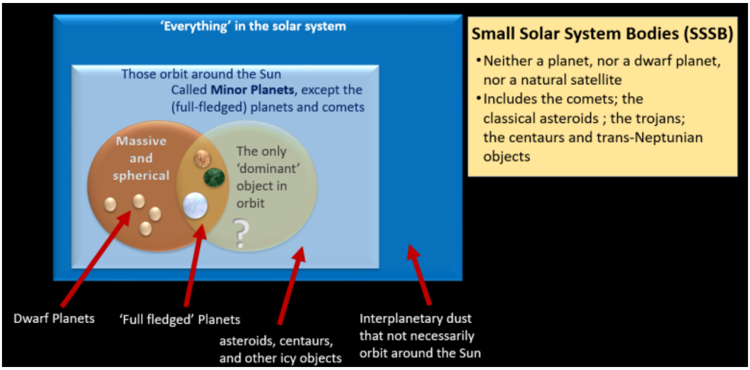

Figure 6: Classification of the solar system bodies

The IAU has done a classification of the solar system bodies. I have attempted to represent the classification with the help of Venn diagram, although I found the matter not very straightforward. Yet, this picture offers a reasonably good way to visualize the classification of the solar system objects.

The deep blue outer rectangle represents 'everything' in the solar system, i.e. the Universal set, while the light blue inner rectangle represents the solar system objects those orbit around the Sun. Clearly, the area outside the light blue rectangle represents the objects that are not orbiting around the Sun. Examples may include interplanetary dust, which not necessarily orbit the Sun.

Now, coming back to the light blue rectangle, there are two circular, overlapping sets drawn. The light orange coloured set represents the solar system bodies that have enough matter to attain a spherical shape because of self-gravity. The light green coloured set represents the solar system bodies that have established their ‘dominance’ in their respective orbits, i.e. ‘have cleared their neighbourhood’. The intersection of these two sets, i.e. the light orange and light green coloured sets, represent the full-fledged planets that satisfy all the three criteria to be called as a planet.

However, the subset represented by the light orange set, minus its intersection with the light green set, is the regime of the Dwarf planets like Pluto.

Now, having said this, what about the subset that is defined by the light green set, minus its intersection with the light orange set? I have put a question mark there; because it is physically difficult to think of any solar system body that is massive and bulky enough to be dominant in its own orbit around the Sun, and yet not attaining a spherical shape. Perhaps that is a null set, I am throwing this question open to you.

The light blue rectangle, minus the two circular sets, represent the minor planets.

Comets are not represented here. IAU has come up with a definition of the Small Solar System Bodies (SSSB), which says that SSSBs are neither planets, nor dwarf planets, nor a natural satellites, but include the comets; the classical asteroids; the trojans[6]; the centaurs[7] and trans-Neptunian objects.

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[6] Trojans are asteroids that share the orbit of a larger planet, but they don't collide with it. These asteroids occupy spaces near specific points, called Lagrangian points, ahead of or behind the planet, where they are held in place by a delicate balance of gravitational forces.

[7] Centaurs are icy bodies, like a mix of asteroids and comets, found between Jupiter and Neptune.

In our discussion, we will often use a term, 'planetary body'. By that term, we will refer to all the members of the solar system, except the interplanetary dust.

What are 'Asteroids'?

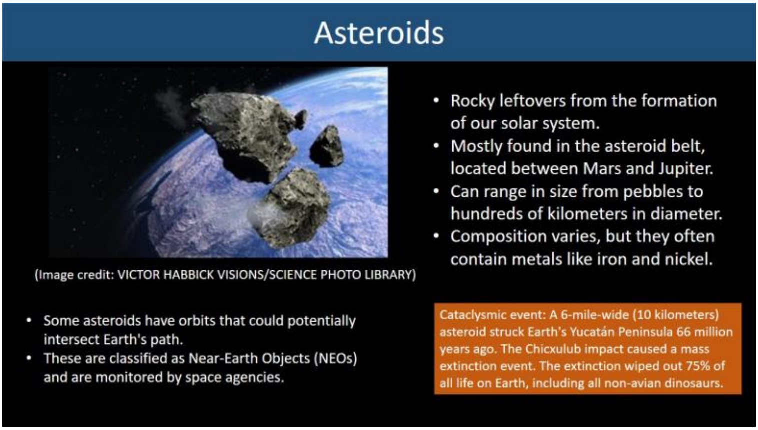

Figure 7: Major information about asteroids

Asteroids are the rocky leftovers from the formation of our solar system. Asteroids are mostly found in the asteroid belt, located between Mars and Jupiter. They can range in size from pebbles to hundreds of kilometers in diameter. Their composition varies, but they often contain metals like iron and nickel.

Some of the asteroids have orbits that could potentially intersect Earth's path. These are classified as Near-Earth Objects (NEOs) and are monitored by space agencies. You are aware of the cataclysmic event, where a 6-mile-wide (10 kilometers) asteroid struck Earth's Yucatán Peninsula about 66 million years ago, causing a mass extinction event. The extinction wiped out 75% of all life on Earth, including all non-avian dinosaurs. Non-avian dinosaurs are the one who could not fly.

What are 'Comets'?

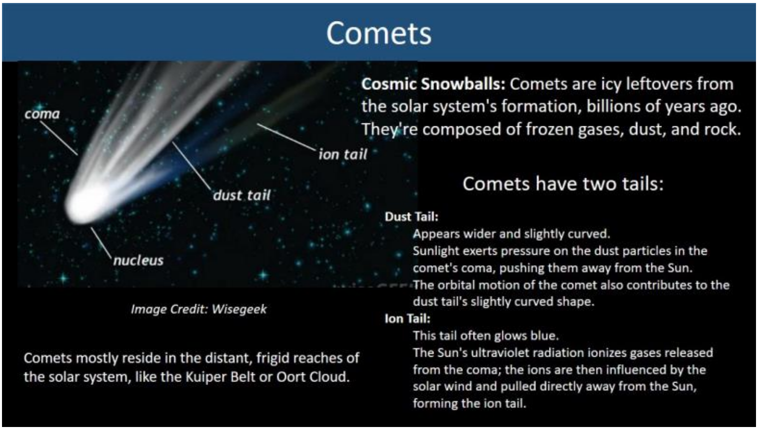

Figure 8: : Major information about comets

Speaking about the comets, they are icy leftovers from the solar system's formation, billions of years ago. They're composed of frozen gases, dust, and rock. Comets mostly reside in the distant, frigid reaches of the solar system, like the Kuiper Belt or Oort Cloud.

A comet's core is the rocky, icy "dirty snowball" called the nucleus. When it nears the Sun, the nucleus heats up, releasing gas and dust that form a hazy envelope around it, known as the coma.

Comets are seen to have two tails, a dust tail and an ion tail. The dust tail appears wider and slightly curved. Sunlight exerts pressure on the dust particles in the comet's coma, pushing them away from the Sun. The orbital motion of the comet also contributes to the dust tail's slightly curved shape.

The ion tail of the comets often glows blue. The Sun's ultraviolet radiation ionizes gases released from the coma; the ions are then influenced by the solar wind and pulled directly away from the Sun, forming the ion tail.

What are 'Meteoroids', 'Meteors' and 'Meteorites' ?

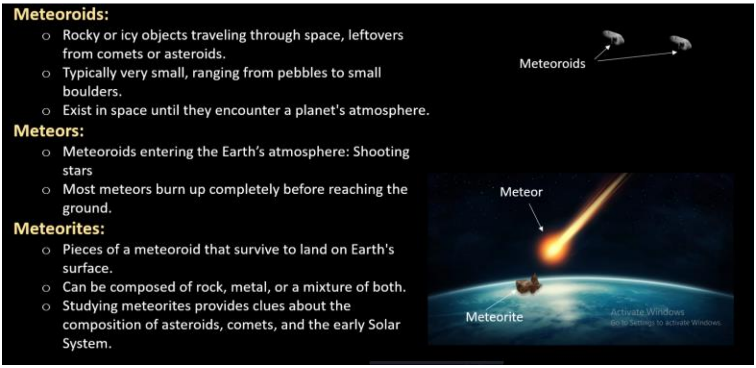

Figure 9: Basic differences between meteoroids, meteors and meteorites

Although the terms Meteoroids, Meteors and Meteorites sound similar, they are not the same. If you have seen 'shooting starts' falling from the sky, they are the Meteors.

By now, you have appreciated that there are several near-Earth-Objects (NEO) that are in the vicinity of the Earth. Meteoroids fall under that category. They are rocky or icy objects traveling through space, mostly the leftovers from comets or asteroids. They are typically very small, ranging from pebbles to small boulders. They exist in space until they encounter a planet's atmosphere.

Meteoroids entering the Earth's atmosphere are called Meteors, commonly known as Shooting stars. Most meteors burn up completely in the Earth's atmosphere because of friction with the air, before reaching the ground. As they burn up, they appear like stars falling down from the sky.

However, some of the pieces of a meteor may survive to land on Earth's surface. They are given the name of Meteorites. Meteorites can be composed of rock, metal, or a mixture of both. Studying meteorites provides clues about the composition of asteroids, comets, and the early Solar System.

The Interplanetary Dust

Our solar system isn't just a collection of planets and moons; it also includes tiny travelers, known as interplanetary dust particles (IDPs). These hitchhikers in the solar system, ranging from a fraction of a micrometer to a meter in size, hold valuable clues to the formation and evolution of our solar system.

There are two primary sources of IDPs: asteroids and comets. Asteroids shed dust through collisions and impacts. Comets, on the other hand, are icy bodies that release dust and gas as they venture closer to the Sun, their ices sublimating (transitioning directly from solid to gas) in the warmth.

IDPs are a diverse bunch, with compositions that vary depending on their origin. Asteroidal dust is primarily composed of minerals like silicates and iron, while cometary dust can contain a rich mix of organic compounds, ices, and minerals. Studying these particles allows scientists to piece together the history of the materials that formed our solar system and potentially even shed light on the origins of life.

These tiny particles aren't just passive observers; they play an active role in our solar system. When Earth plows through streams of dust left behind by comets, the dust particles burn up in our atmosphere, creating the dazzling displays known as meteor showers.

Yet another effect of the IPD is the delivery of volatiles[8]. Cometary dust is thought to have played a crucial role in delivering water and other volatile elements to the early Earth, potentially contributing to the conditions necessary for life's emergence.

Over time, dust particles can collide and clump together, potentially forming the building blocks of larger celestial bodies like asteroids and planets.

Scientists are eager to unravel the secrets locked within these cosmic dust motes. Missions like NASA's Stardust spacecraft have captured interstellar dust particles directly, while ground-based observatories and analysis of meteorites (large IDPs that survive passage through the atmosphere) provide valuable data.

By studying the composition and origin of interplanetary dust, we gain a deeper understanding of the formation and evolution of our solar system, the potential for life elsewhere in the universe,

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[8] Volatiles are chemical elements or compounds with relatively low boiling points, easily transitioning from a solid or liquid state to a gas. In the context of our solar system, these volatile elements, like water and methane, are crucial for understanding planetary formation and the potential for life.

and the ongoing dynamic processes that shape our celestial neighborhood.

Attributes of a Planetary Body

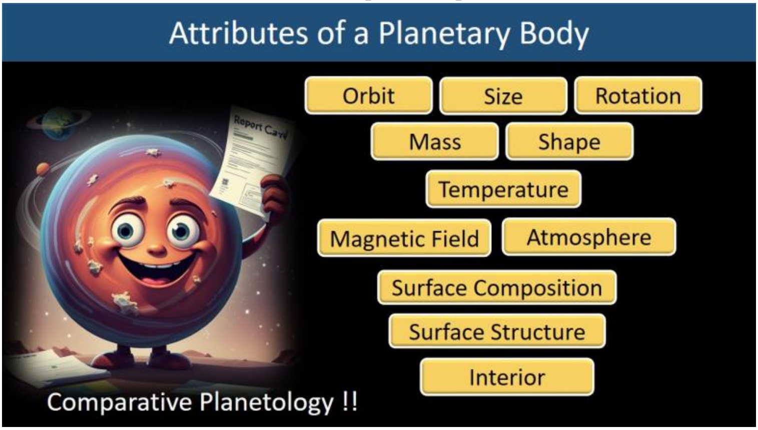

Figure 10: The basic attributes of facets of a planetary body. These attributes bring out the diversities among the planetary bodies, which is the subject matter of comparative planetology.

There are several attributes of properties of a planetary body, like orbit, size, rotation, mass, shape, temperature, presence of a magnetic field, atmosphere, composition of the material that make the surface of the planet, structure of the surface, interior of the body, to name a few.

These attributes are used to characterize a planetary body. That, in turn, helps to draw a comparison between the planetary bodies. Comparing the planetary bodies in terms of their attributes is a subject matter of 'Comparative Planetology'. In-depth study of comparative planetology helps to understand the different ways each planetary body has evolved with time. Although all the members of the solar system started their journey *almost* at the same time, say, approximately 4.5 Billion years ago, they have evolved in different ways; much like although the life on Earth started from unicellular organism, different paths of evolution have presented the diversity of different species.

The attributes of a planetary body, serve, yet another purpose. As the planetary bodies, in general, differ in one or more attributes from one another, they offer opportunities to select the appropriate planetary body for studying a particular type of interaction of the solar influences with the planetary body. We will cite an example on this shortly, but let us, for the time being, have a brief round of discussion about the importance of these attributes of the planetary bodies.

Orbit

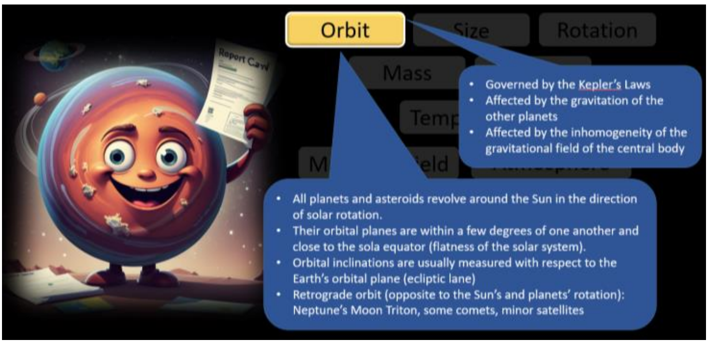

Figure 11: Major points to remember about the orbit of planetary bodies

The first and foremost attribute of a planetary body that comes to our mind is its orbit. Primarily the orbits are governed by the Kepler's laws, although there are effects from the gravity of the other planets, especially the massive ones, as well as the inhomogeneity of the gravitational field of the central body. An orbits pf the planetary bodies are almost on the same plane, with reference to the Earth's orbital plane, which is known as the ecliptic plane. A few of the planetary bodies have retrograde orbits.

Mass

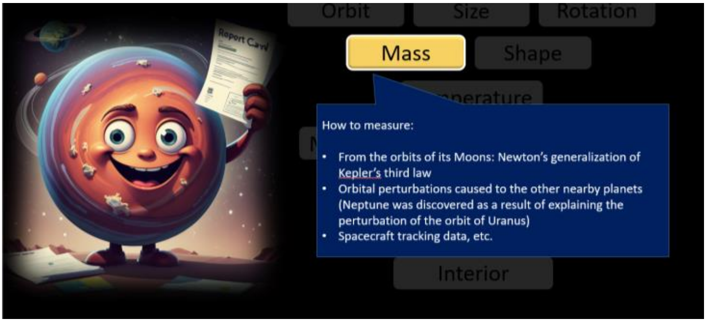

Figure 12: Major points to remember about the mass of the planetary bodies

The mass of a planetary body is a measure of the quantity of material that has gone into the making of it. More the mass, more its gravity, and more the heat retaining capacity. The mass of a planetary body may be estimated by studying its perturbative effects on the other nearby planetary bodies, or the orbits if its moons (if any), and also from the spacecraft tracking data.

Size

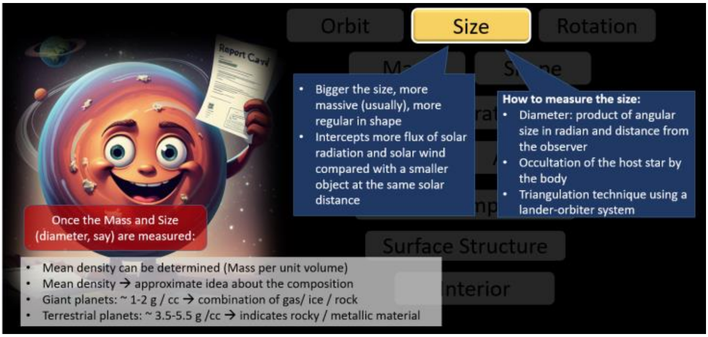

Figure 13: Major points to remember about the size of the planetary bodies

The size of a planetary body determines how much of solar radiation and solar wind will be intercepted by it. Bigger the size, it is more spherical, due to the hydrostatic equilibrium. The size of the planetary body can be determined by direct imaging, and also with other techniques.

Once the mass and size of a planetary body are determined, one can estimate its mean density, which, in turn, can provide an approximate idea about its bulk composition.

Temperature

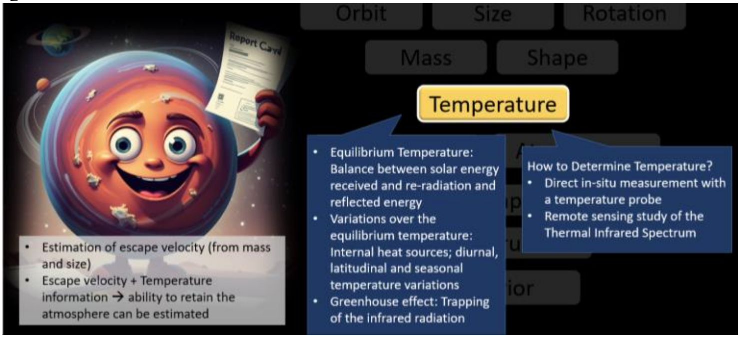

Figure 14: Major points to remember about the temperature of the planetary bodies

The temperature of a planetary body is dictated by several factors, like the balance between the solar energy received and the energy re-radiated and reflected back by the planetary body; if there is any internal heat source in the planetary body; whether there is greenhouse effect due to its atmosphere, to name a few.

Temperature of a planetary body can be measured by remote sensing techniques by studying the thermal infrared spectrum, and also by direct measurement at a specific location.

Once the temperature of a planetary body is known, one can calculate the probability of the escape of atmosphere from the planetary body.

Rotation

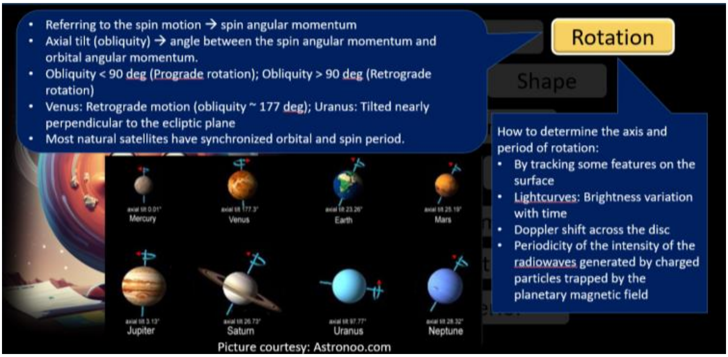

Figure 15: Major points to remember about the rotation of the planetary bodies

Here, I am referring to the spin rotation of the planetary body. The spin angular momentum of the planets is an important component of the total angular momentum of the solar system. Planets display diversities in terms of their spin rates, and also the inclination of their spin axes with respect to the ecliptic plane.

Spin of a planetary body can be determined by tracking some of its surface features, studying the brightness variation over time, Doppler shift across the disc, and several other techniques.

Shape

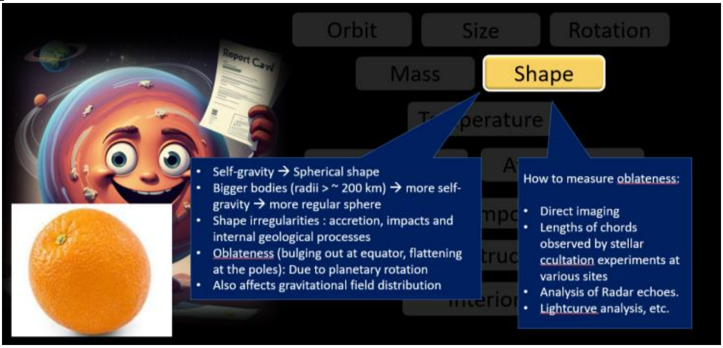

Figure 16: Major points to remember about the shape of the planetary bodies

The planetary bodies with reasonably good quantity of material in them, are spherical in shape due to their self-gravity. There are shape irregularities as well; mostly due to the processes like accretion, impacts and internal geological processes. There is also an oblateness observed due to the planetary rotation, which manifests as bulging out at the equatorial region and flattening at the poles, like an orange. The oblateness of a planetary body is also responsible for causing slight deviation of its gravitational field from perfect spherical symmetry.

The oblateness is measured by several techniques that include direct imaging, occultation experiments, radar echoes, to name a few.

Magnetic Field

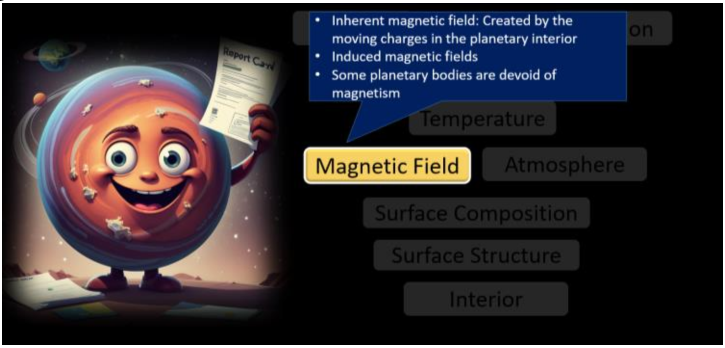

Figure 17: Major points to remember about the magnetic field of the planetary bodies

Some of the planetary bodies have magnetic fields. Among them, some have inherent magnetic fields due to the motion of the charges in their interior (like Earth), some do not have so, but have an induced magnetic field due to the partial ionization of their atmosphere (like Mars). Some of the planetary bodies do not have either. The magnetic field of a planetary body, and its type determine the nature of the interaction of the solar wind with the planetary body.

Surface Composition

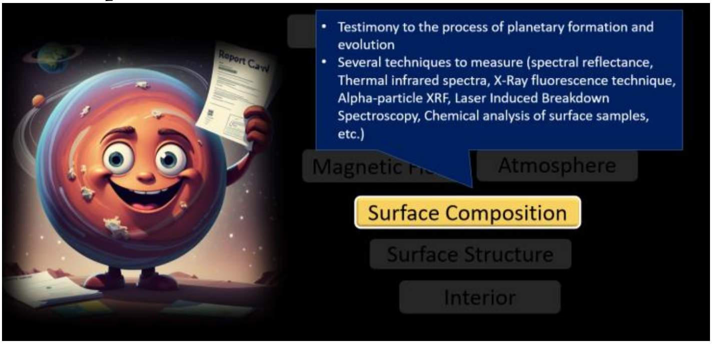

Figure 18: Major points to remember about the surface composition of the planetary bodies

Surface composition of a planetary body is yet another important attribute. When we speak about the composition of the materials of a planetary surface, we mean the mineral composition, as well as the elemental composition. In several cases, different elements remain bound to the lunar minerals. Study of the surface composition of a planetary body helps us to infer about the process of it formation and evolution. One can measure the surface composition with several techniques like thermal infrared spectrometry, X-Ray Fluorescence, to name a few.

Surface Structure

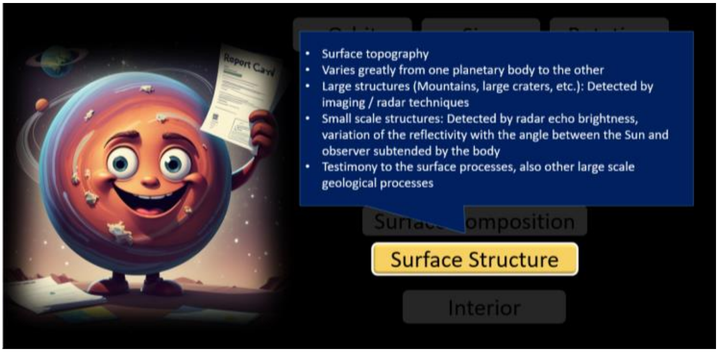

Figure 19: Major points to remember about the surface structure of the planetary bodies

When refer to 'surface structure', we mean the topography of the surface, i.e. the mountains, craters, flat regions, presence of boulders, etc.. There could be both large and small scale structures of interest. Study of different structures help us to infer about the geological processes during the formation and evolution of the planetary body, as well as the impact processes. The surface structures are usually studied with imaging and radar techniques.

Atmosphere

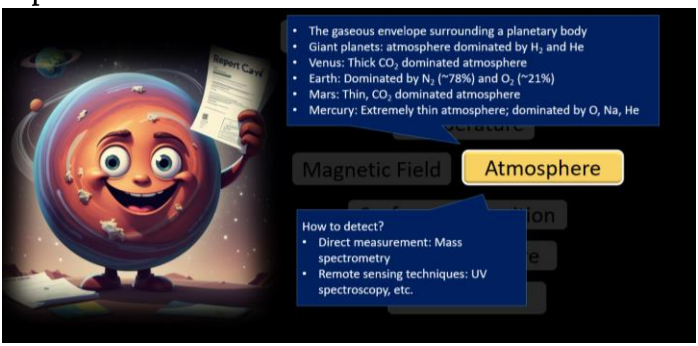

Figure 20: Major points to remember about the atmosphere of the planetary bodies

Yet another very important attribute of a planetary body is its atmosphere. Not necessarily all the planetary bodies have atmosphere. Even the planetary bodies that do have atmosphere, the atmospheric composition and density may not be necessarily the same. The gravity and temperature of a planetary body play important roles to determine whether it can hold atmosphere around it. Planetary atmospheres are measured with direct techniques like mass spectrometry, as well as with remote sensing techniques like UV signatures coming from different elements. Also the technique of absorption spectroscopy is used in some cases to determine the atmospheric constituents of a planetary body.

Interior

Figure 21: Major points to remember about the interior of the planetary bodies

The interior or internal structure of a planetary body is also an important attribute, as it embeds into it enormous clues about its formation and subsequent geological processes. Unlike the surface and the atmosphere, the interior of a planetary body is not observable directly. Indirect ways of guessing the internal structure of a planetary body includes techniques like studying its gravitational field, rotation rate, seismic signatures, magnetic field (if any, due to the internal dynamo processes).

Thus, we have a fairly good understanding about the significance of the set of attributes of a planetary body, and the techniques that are widely used to determine them.

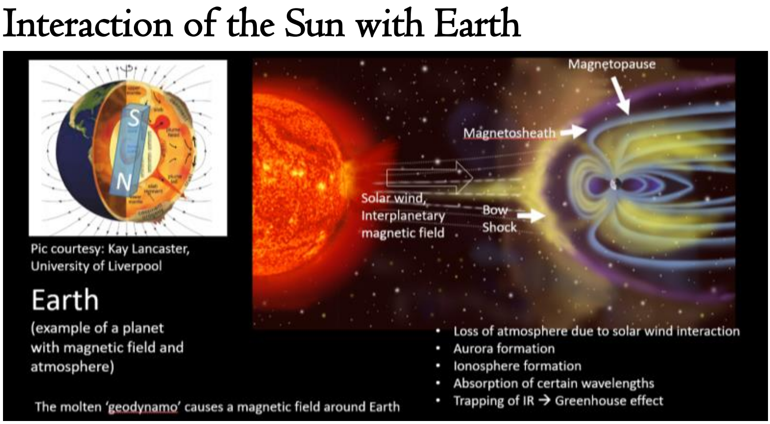

Figure 22: The Sun-Earth connection. Picture courtesy: University of Liverpool (for the schematic of the Earth's interior) and ESA (for the Sun-Earth connection schematic)

I mentioned that some of these attributes of a planetary body determine how do the 'influences from the Sun' interact with it. Let us consider, as an example, the Sun-Earth interaction. Earth has an atmosphere, and also, a global magnetic field, which is also called the geomagnetic field, that is often approximated by a hypothetical bar magnet in its interior.

Let us first speak about the atmosphere. The atmosphere of the Earth is responsible for many things; in includes the absorption of certain wavelengths from the Sun in the higher energy side which would have been extremely harmful for life; greenhouse effect, where the long wavelength is trapped in the near-Earth atmosphere increasing the average surface temperature of the Earth, to name a few.

The solar radiation also causes loss of a fraction of the Earth's atmosphere, as well as the formation of the ionosphere. While each of these processes have their own complexities, the interaction between the interplanetary magnetic field and the solar wind ions with the geomagnetic field seems to be more complex.

The charged particles, i.e. the solar wind ions emitted by the Sun at speeds much greater than the speed of sound (we call them supersonic speeds), get slowed down and get deflected by the Earth's magnetic field. This phenomenon forms what is known as a bow-shock in the upfront direction. There is a power-play between the interplanetary magnetic field and the geomagnetic field, and thus, the magnetic field lines of the Earth get tapered out in the direction opposite to the Sun, forming a tail-like structure, which is referred to as the geomagnetic tail, or geotail.

Often, the magnetic field from the Sun, i.e. the interplanetary magnetic field recombines with the geomagnetic field if their directions are opposite. They repel if their directions are same. The direction of the vertical component of the Sun's magnetic field may flip, while that of the geomagnetic field does not, at least, in a shorter time scale (not considering the flipping of the Earth's magnetic field which happens in geological time scales of Millions or a few tens of thousands of years). Thus, at any given time, the direction of the vertical component of the Sun's magnetic field determines the nature of its interaction with the Earth's magnetic field.

Between the edges of the geomagnetic field, which is referred to as the Magnetopause, and the bow shock, there is a region called the Magnetosheath. This is a zone where the highly energetic charged particles are present, while the geomagnetic field strength is relatively weak. The geomagnetic field has cusps at the polar regions, through which some of the high energy charged particles can precipitate. The interaction of those charged particles with the constituents of the atmosphere can cause emission of light of different colours, which look spectacular during night. That's how the aurorae are formed.

Figure 23: A picture of aurora borealis. Picture courtesy: National Geographic

This is a picture of the aurora borealis, where the green colour is caused by the relaxation of the excited Oxygen molecules at altitudes of 100 to 300 km. The blue and purple colours, on the other hand, are produced by the excitation and subsequent relaxation of the nitrogen molecules at relatively lower altitudes.

Thus, the phenomenon of aurora may be looked upon as a result of the presence of both atmosphere and a dipole magnetic field in a planetary body.

Weather, Space Weather and Planetary Space Weather

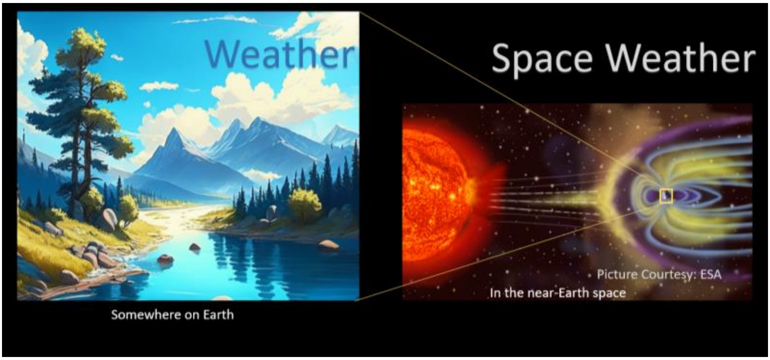

Figure 24: The notions of 'weather' and the 'space weather.

The term '**weather**' refers to the state of the environment close to the Earth's surface, within then protection of the atmosphere and the geomagnetic field.

On the contrary, the moment we step out of the safety zone offered by the Earth's atmosphere and the geomagnetic field, we expose ourselves to the harsh conditions of the space, which is often referred to as the '**Space Weather**'. Often, in planetary science, we use the term '**Planetary Space Weather**'. This term indicates that the nature of the interactions of the solar wind, radiation and the magnetic field from the Sun are not identical for all the planetary bodies. It depends on the set of attributes of the planetary body. Thus, planetary space weather is closely connected with comparative planetology. Since, so far, we have cited the example of Sun-Earth interaction, the diversity of the types of interactions will be better appreciated if we cite yet another example; this time, the Sun-Moon interaction.

Sun-Moon Interaction: Case-study of a planetary space weather

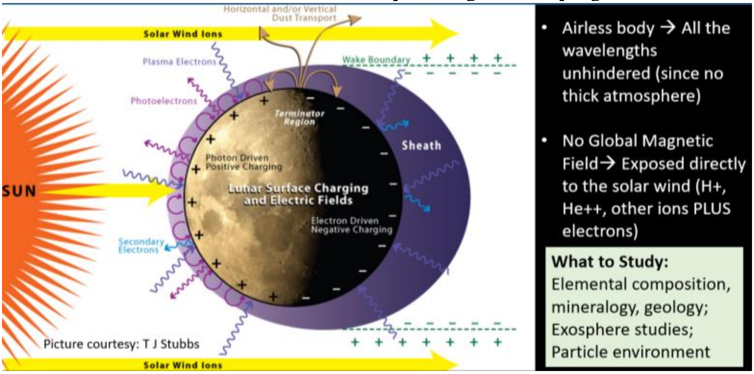

Figure 25: The Sun-Moon connection: Picture courtesy T J Stubbs.

Contrary to the Earth, Moon does not have a significant atmosphere (we often call it the lunar exosphere). It does not have an inherent magnetic field, either. As a result of being practically atmosphere-less, all the wavelengths of the solar radiation reach the lunar surface unobstructed. This causes photoelectric effect on the sun-lit side of the Moon, raising the electrical potential of the day-side surface.

As there is no global magnetic field in Moon, the surface of the Moon is directly exposed to the solar wind ions and electrons. Here, we are not discussing about small patches of magnetic fields on the Moon's surface, called the minimagnetospheres. In general, in a bigger scale, the Moon can be treated as a non-magnetic body. The lines of the interplanetary magnetic field, therefore, do not find any hindrance for its passage.

The deposition of the solar wind ions on the Moon's surface is also responsible for elevating its day-side surface potential. Thus, there is a significant electrical potential difference existing at the

Moon's day-night transition regions, or the terminators. The lunar dust particles also get electrically charged and levitated; in fact, the charged dust of the Moon can be used as a tracer to study the electrical potential of the Moon's surface, and its spatial, as well as temporal variation.

So, by now, you can appreciate, who different is the nature of the Sun-Moon interaction from the Sun-Earth interaction, and how important are the set of parameters or attributes that define the characteristics of a planetary body.

Planetary Space Weather, in general

	With Atmosphere	**Without Atmosphere**
With Dipole Magnetic Field	• Magnetic reconnection • Formation of magnetopause and bow-shock • Aurora • Ionosphere • Atmospheric loss • Photochemistry Earth	• Direct solar wind interaction along cusp lines, causing surface effects • Formation of magnetopause and bow-shock Mercury
Without Dipole Magnetic Field	• Direct solar wind assault • Erosion of the atmosphere • Ionosphere • Induced magnetosphere • Photochemistry Mars	• Unimpeded solar wind impact • Extreme diurnal variation of temperature • No aurora event Earth's Moon

Figure 26: A matrix to easily remember the fundamentals of planetary space weather

After having discussed two specific cases, i.e the Sun-Earth and the Sun-Moon interaction, let us generalize the discussion. This table is an approximate summary of the Sun-Planet interaction, in general. In this context, the term 'Planet' is not limited to only the planets by definition, but to all solar system bodies where these attributes are of relevance.

The table is self-explanatory, and its detailed explanation is a subject matter of great depth. Of these four broad cases, I have already discussed two.

Life in the Solar System

While Earth remains the only confirmed cradle of life in our solar system, the search for extra-terrestrial life continues with unwavering curiosity. Scientists are actively exploring various celestial bodies, looking for signs of past or present life, and some places offer intriguing possibilities.

Our planet's unique conditions likely played a crucial role in the emergence of life. Earth's early atmosphere, devoid of the free oxygen we have today, contained a mix of chemicals like methane, ammonia, water vapor, and hydrogen – the potential building blocks of life. Energy sources like sunlight, lightning, and volcanic activity might have triggered the formation of organic molecules, setting the stage for life's genesis.

There are challenges for life to born and sustain at the other planets, although today's science does not rule out the possibilities of such discoveries. Most planets within our solar system present harsh environments, with scorching heat, freezing temperatures, or crushing pressure, making it difficult for life as we know it to exist on the surface. Venus, once thought to be Earth's twin, succumbed to a runaway greenhouse effect, rendering its surface uninhabitable. Yet, the extremophiles on Earth have displayed evidences of survival in extreme environmental conditions.

Thus, scientists are always hopeful to discover extraterrestrial life. Mars, with its thin atmosphere and freezing temperatures, might harbor life underground near potential water sources. The icy moons of Jupiter (Europa) and Saturn (Enceladus) possess subsurface oceans, thus offering potential environments for life even under extreme cold conditions.

Currently the two fundamental questions that drive the domain of Astrobiology are: (i) how did life originate on Earth, and (ii) are there forms of extra-terrestrial life?

The question of how life arose on Earth has captivated scientists for centuries. While the definitive answer remains elusive, several compelling theories continue to shape our understanding. One prominent theory revolves around the concept of a primordial soup.

In 1952, a milestone experiment by Stanley Miller, a graduate student at the University of Chicago, and Harold Urey, a Nobel laureate in chemistry, shed light on the potential beginnings of life on Earth. They built a setup to recreate the conditions believed to have existed in Earth's early atmosphere – a mix of simple gases like ammonia, methane, water vapour, and hydrogen. By perturbing this simulated atmosphere with electrical sparks (mimicking lightning), they were able to produce amino acids, the building blocks of proteins, in the resulting liquid. This experiment provided crucial evidence that the early Earth environment could have facilitated the formation of the fundamental molecules necessary for life to arise.

While the exact gases in Earth's early atmosphere might have differed from the ones used in Miller and Urey's experiment, their work opened a new door in science: prebiotic chemistry. This field explores how chemical reactions without living things could have laid the groundwork for life's emergence.

Another interesting theory suggests that the building blocks of life might have hitched a ride from space. Scientists believe meteorites and comets, traveling through the early solar system, could have delivered these essential ingredients to Earth. Research by scientists shows that complex organic molecules could readily form in the early solar system, potentially forming the seeds of life, that might have rained down on our planet.

Furthermore, studies indicate that amino acids, the building blocks of proteins, could survive the fiery crash of comets, potentially seeding Earth with the necessary components. Evidence for this comes from finding extraterrestrial organic material in ancient Earth rocks, possibly delivered by micrometeorites, and the recent discovery of over 20 different types of amino acids in samples returned from asteroid Ryugu by Japan's Hayabusa2 mission.

The search for how life arose on Earth is a continuous journey, with each discovery adding a new piece to the puzzle. While the definitive answer remains elusive, scientists are exploring various possibilities, including the primordial soup theory, the early Earth's chemistry, and the potential role of extraterrestrial arrivals, all in an effort to unravel this profound mystery.

Intelligence in the Solar System

While the search for forms of extra-terrestrial life is an important quest for the humankind, yet another matter of curiosity is whether there is any intelligent living being elsewhere in the solar system, and even beyond. Scientists call this Extra-Terrestrial Intelligence (ETI).

The concept of ETI, or non-human intelligence, refers to hypothetical life forms on other planets that possess advanced cognitive abilities and technological capabilities similar to our own. While no definitive proof of such life has been found, the search for ETI continues to be a compelling scientific endeavor driven by our inherent curiosity and the vastness of the cosmos.

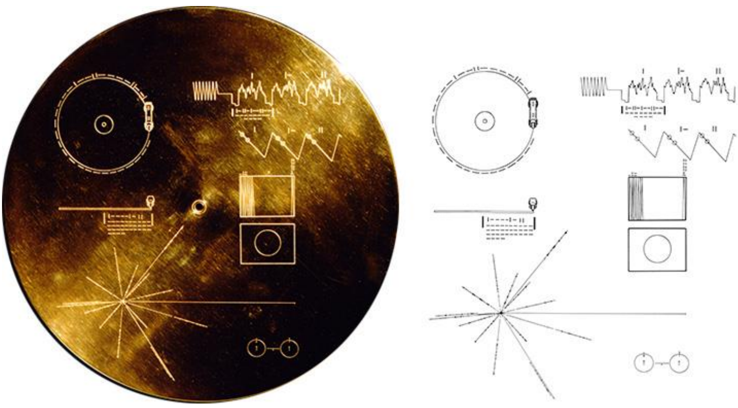

Figure 27: The Golden Record cover shown with its extraterrestrial instructions. Credit: NASA/JPL (Taken from https://voyager.jpl.nasa.gov/golden-record/golden-record-cover/)

One of the most intriguing attempts to communicate with potential ETI came with the Voyager missions. Launched in 1977, both Voyager 1 and 2 spacecraft carried a golden record, a phonograph record containing sounds and images that depict life and culture on Earth. This record includes greetings in multiple languages, natural sounds like whale songs and thunder, and musical selections from various cultures. While the spacecraft are unlikely to encounter any intelligent life for millennia, the golden record serves as a symbolic message in a bottle, a hopeful attempt to connect with any advanced civilization that might intercept it in the vast expanse of space.

Another significant effort in the search for ETI is the Search for Extraterrestrial Intelligence (SETI) project. Founded in 1960, SETI encompasses a diverse range of scientific endeavors aimed at detecting potential signs of intelligent life from other worlds. This primarily involves searching for electromagnetic signals, particularly radio waves that might carry deliberate messages from extraterrestrial civilizations. The rationale behind this approach lies in the belief that radio waves are a relatively universal and persistent form of communication that can travel vast interstellar distances.

Several large-scale SETI projects are currently underway, utilizing powerful radio telescopes and sophisticated computer algorithms to analyze vast amounts of data from targeted regions of the cosmos. While no definitive evidence of deliberate extraterrestrial transmissions has been found to date, the ongoing efforts of SETI researchers continue to push the boundaries of our technological capabilities and potentially pave the way for future breakthroughs.

Beyond the search for deliberate signals, scientists also consider other potential signs of ETI. These include Artificial structures around distant stars, such as Dyson spheres (hypothetical megastructures built to harness a star's energy), Technosignatures that are indicators of technological activity, such as the presence of unusual atmospheric compositions (like what happens on Earth today sue to human-induced effects) or the detection of industrial waste products around distant stars, and Megalithic structures, where large, artificially constructed monuments on other planets or moons could be a sign of past or present intelligent life.

While the search for ETI remains a challenging endeavor, the vastness of the universe and the ever-increasing advancements in scientific technology offer a glimmer of hope. As we continue to explore the cosmos and refine our methods of detection, the possibility of encountering intelligent life beyond Earth becomes increasingly plausible.

The potential implications of such a discovery are profound. It would fundamentally alter our understanding of the universe's potential for life, challenge our current conceptions of intelligence, and potentially lead to the establishment of interstellar communication and collaboration. The ongoing search for ETI represents a significant leap in humanity's quest for self-discovery.

Techniques to study the solar system

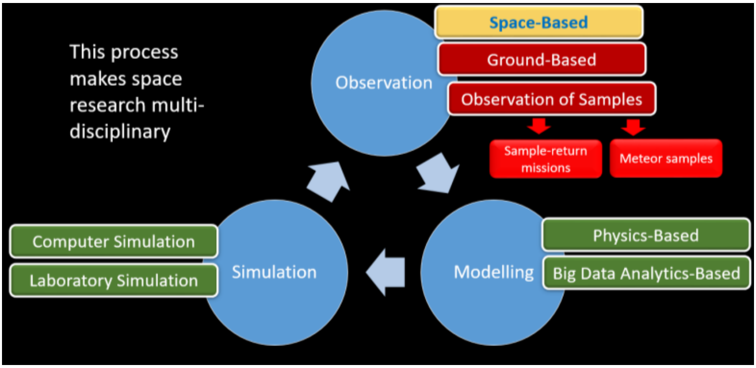

Figure 28: Basic techniques of studying the solar system. This schematic shows the different facets of observation, modelling, and simulation, and also their inter-dependencies.

With this introduction, you have appreciated that there are lots of characteristic features or attributes, as well as processes that need to be studied towards the understanding of the solar system.

The three major techniques to study the solar system are (i) Observation, (ii) Modelling, and (iii) Simulation. These three form a cycle; hence, it is not a relevant question to ask which one of these three comes first. The observations can be ground-based, with the help of telescopes or observatories; space-based, with the help of orbiters, landers, rovers and other robotic exploration platforms; and there is yet another type of observation, which is the observation of the samples from the planetary bodies. The samples from the planetary bodies may be accessed through sample-return missions, or in the form of meteorites.

Coming to the technique of modelling, there are fundamentally two branches. One is physics-based theoretical modelling, where you attempt explaining the observations by using the physical principles. You arrive at equations with a set of parameters that explain your observations. Contrary to this technique, there is a technique that does not care about the physics of the process, but emphasizes on identification of certain patterns in the observation data. This technique is called Big Data Analytics (BDA) based modelling, where you generate Artificial Intelligence / Machine Learning / Deep Learning models to replicate some physical processes, using the observational data.

Very closely associated with modelling, is the technique called simulation. Often people take modelling and simulation as a combined technique. That, any ways, depends on the perspective. In the realm of simulation, there are two broad classes. The first one is the computer simulation, wherein you feed the theoretical model and run the codes to generate outputs. In computer simulation, often you may simulate the variation of certain parameters by adding random numbers about the mean values of each parameter and see the dispersion of the overall result. This technique is, in general, called the Monte Carlo simulation.

Yet another branch of simulation is laboratory simulation, where, you artificially create an environment which you wish to study, in a controlled chamber. You may not be able to simulate all the parameters or conditions in the laboratory, but depending on the physical process you wish to study, the most important parameters may be identified, and the same can be simulated.

The insight gained by the process of modelling and simulation are often used to refine the process of observation. The process of observation, in turn, helps to refine the parameters for conducting modelling and simulation. In technical terms, we call this process 'constraining of the model parameters using observation'.

Thus, observation, modelling and simulation collectively constitute a process of understanding the solar system.

Coming back to observation, the space-based observation has certain major advantages, which we will discuss next.

Why space-based observations are preferred

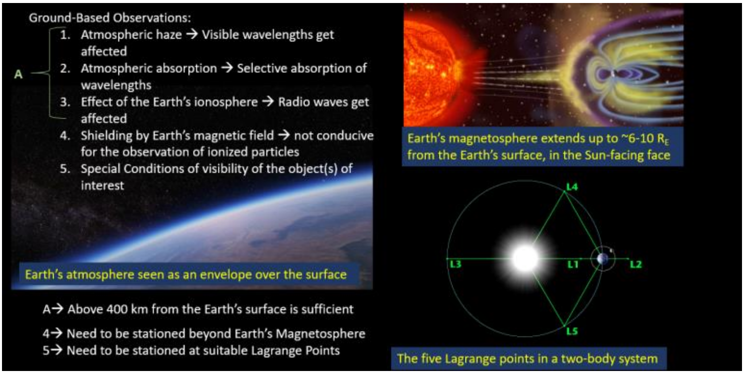

Figure 29: A quick note to remember about the advantages of space-based observations.

Ground based observations with telescopes are prone to get distorted by the presence of atmosphere due to the atmospheric haze, and absorption of certain wavelengths by the atmosphere. Also, the ionosphere affects the propagation of the radio-waves. So, if you want to make any observation of any planetary body avoiding all these effects, you, i.e. your observation platform needs to be placed at an altitude of around 400 km. Thus, you need to opt for space-based observation.

There may be certain cases, where avoiding merely the atmosphere and ionosphere does not satisfy the need of your observation; you may need to go beyond the Earth's magnetic field. These requirements emerge when you are interested to study the solar wind which are otherwise deflected by the geomagnetic field, or, the study of the structure of the magnetosphere itself. You need to choose your orbit accordingly. It is even a specialized case of space-based observation.

There may be still specialized requirements, like continuous, unobstructed view of the Sun. In that case you have to choose the First Sun-Earth Lagrange point as the vantage point of your observation, where the gravity of the Sun nullifies the gravity of the Earth. There are other four Lagrange points for a given two-body system, like the Sun-Earth system, which offer distinct advantages.

Thus, the space-based observations offer you certain advantages which are absent in the case of ground based observations. Now, the question is that: planning for a systematic space-based observation to answer a set of scientific questions call for a space mission; how to configure a space science mission?

We shall present briefly the fundamental steps of defining any space science mission, which is applicable to the solar system exploration as well.

How are the space science missions defined

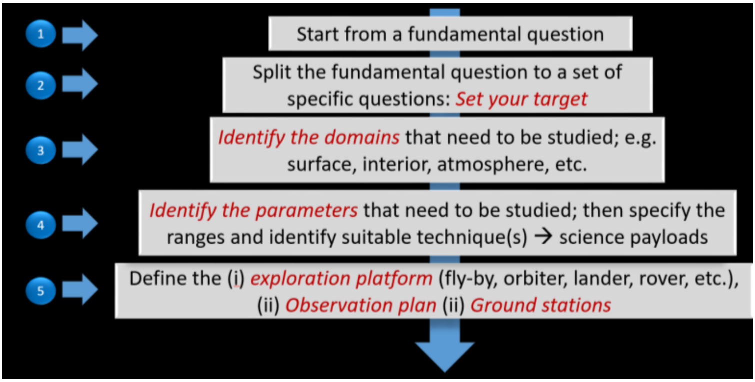

Figure 30: Logical steps for configuring a space science mission

In **step 1**, it starts from a fundamental question. A fundamental question often sounds more philosophical than scientific. It may sound like 'How did it all begin and how did they evolve, and where are they headed to…'

The fundamental questions are always abstract, and it needs to be broken down to a set of specific questions, which may be semi-fundamental, or a bit more objective. That is **step 2**. During this step, where one has derived a set of scientific questions by disintegrating the unique fundamental questions, the target planetary body is chosen. Based on the scientific problem one needs to address, an appropriate planetary body is selected as the target.

After having selected the target planetary body for observation, in **step 3**, the question that is asked is 'What all attributes of the target planetary body need to be studied?' This step may be termed as the ‘domain identification step’, where one decides whether to study the surface, interior, of the atmosphere of the planetary body, or a combination of a few such attributes.

After having identified the domains for study the next step, i.e. **step 4**, is the selection of parameters for observation. The parameters could be like surface roughness, surface reflectivity at a given wavelength, etc.. In this step, while arriving at the list of parameters for observation, the ranges of the values of the parameters are also decided. Also decided is the desirable accuracy levels in the determination of the values of these parameters. These lead to the identification of techniques for observation, like altimetry, infrared spectrometry, etc.. The techniques chosen, in turn, lead to the identification of the scientific instruments, which are also called scientific ‘payloads’ for observations. In these examples, the payloads could be a laser altimeter, an infrared spectrometer, etc.. While defining the payloads for the missions, their specifications are also defined. As for example, for an infrared spectrometer, a few important specifications may be the wavelength range, wavelength resolution, sensitivity of the detector, noise level, to name a few.

After having arrived at the set of payloads with the desired specifications, in **step 5**, it is the time for selecting the suitable platform for observation. Depending on the observation technique, the suitable observation platform may be an orbiter, a lander, or a rover, or a hopper, etc.. The planning doesn’t end here. After selecting the correct observation platform, one needs to have an observation plan, readiness of the ground stations for supporting the science mission, to name a few. An important activity concerning the ground station is to ensure that the data that would come from space-borne payloads are processed properly, without errors, and are archived for the analysis by the scientists. That is called the data pipeline.

Even after placing the science mission to space, the scientists meticulously conduct observations by operating the science payloads, and download the data through the antenna.

Space-based Techniques for studying the planetary bodies

At these juncture, it will not be out of context to tell briefly about the techniques of space-based observation. The techniques of space-based observation can be classified into two broad classes. One is called Remote Sensing observation, and the other one is called In-situ observation. In remote sensing observation, the subject of observation is not in contact with the scientific payload. The observation happens remotely. On the other hand, in the in-situ observation techniques, the subject under observation is in direct contact with the scientific payload. Each of these classes have their own advantages. While the remote sensing observations offer the opportunity to study a planetary body globally, the in-situ techniques facilitate direct observation of a specific place of a planetary body. The spatial coverage of a remote sensing observation is more, which is not the case for the in-situ observations. On the other hand, the in-situ observations offer very sensitive observations, which are not often possible with remote sensing technique. Another problem with remote sensing techniques is that in certain cases one has to account for the medium that intervenes between the scientific payload and the subject under observation. Until proper corrections are made on the first level of the observation data to compensate for the effects of the intervening medium, the results may be erroneous.

Remote sending techniques may also be classified into two sub-classes. One is passive remote sensing, and the other is active remote sensing. In passive remote sensing, information is derived by the scientific payload by analyzing the wave or particle emitted or reflected by the subject under observation. In active remote sensing, there is a source of electromagnetic wave or something similar, which is used to shine the subject under observation, and the reflected signal is studied. Radar is an example of active remote sensing.

India's Contributions to Solar System Exploration

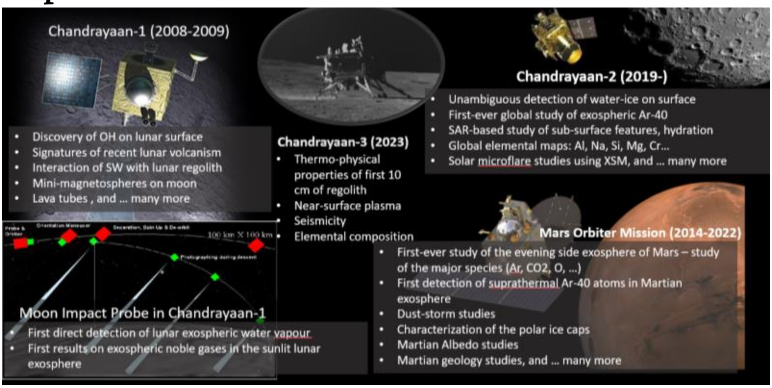

Figure 31: A quick summary of the major science results from India's planetary exploration missions. The list is not complete, though.

At this juncture, I must draw your attention to the contributions made by the Indian planetary exploration missions. India's space program has witnessed remarkable strides in recent years, fuelled by a steadfast commitment to scientific exploration. This dedication extends beyond Earth's orbit, venturing into the realm of planetary science with a focused exploration of the Moon and Mars. This section delves into the motivations behind India's selection of these celestial bodies as its initial targets and explores the outline of its lunar and Martian missions, highlighting their scientific contributions.

The Moon, Earth's closest celestial neighbour, has long captivated humanity's imagination. Its proximity offers a readily accessible platform for honing the technologies and techniques crucial for future interplanetary endeavours. Recognizing this, India's Chandrayaan program has embarked on a series of missions aimed at unravelling the Moon's secrets. So far, three missions have been sent by India to the Moon. The Chandrayaan-1 mission was launched in 2008, Chandrayaan-2 in 2029, while the Chandrayaan-3 was launched in 2023. From mapping its surface mineralogy to detecting the presence of water ice, these missions have significantly enhanced our understanding of our lunar companion.

Mars, the Red Planet, has also captured the scientific community's fascination due to its potential for harbouring past or even present life. India's Mars Orbiter Mission (Mangalyaan), launched in 2013, marked a historic achievement, making India the first Asian nation and the fourth space agency to successfully orbit Mars. This mission not only demonstrated India's technological prowess but also provided valuable data on Martian atmospheric composition, surface features, and potential habitability.

The selection of the Moon and Mars as initial targets reflects a strategic approach. The Moon serves as a stepping stone, allowing India to test and refine crucial technologies like soft landing and rover operations before venturing further into the solar system. Mars, with its potential for harboring life, presents a compelling scientific objective that aligns with India's long-term goal of expanding our knowledge of the universe and the possibility of life beyond Earth.

As a part of the exploration of the Solar system, India has also sent a dedicated mission called Aditya-L1 to study different facets of the Sun, in year 2023, which reached the desired orbit on Jan 6, 2024. The Aditya-L1 spacecraft is strategically located at the first Lagrange point between the Sun and the Earth. It is the point where the gravitational forces of the Earth and the Sun cancel each other. The point is located 1.5 million kilometres away from the Earth, towards the Sun, on the hypothetical line that joins the centres of the Earth and the Sun, given that the Sun-Earth distance is about 150 million kilometres. A spacecraft injected to an orbit around that point gets an advantage of continuous (un-obstructed) view of the Sun, as well as the opportunity to study the charged particles from the Sun staying away from the magnetosphere of the Earth, which would have diverted away the solar charged particles.

This section delves deeper into the specific missions undertaken by India in its Lunar, Martian and Solar exploration endeavours, detailing their scientific objectives, technological advancements, and the significant contributions they have made to our understanding of these celestial bodies. By examining these missions, we gain a comprehensive perspective on India's dedication to pushing the boundaries of space exploration and its unwavering commitment to unravelling the mysteries of the Solar system.

India's Lunar Exploration Programme

Driven by inherent scientific curiosity, India embarked on its lunar exploration journey through the Chandrayaan series of missions, aimed at understanding the Moon's composition, evolution, and potential for harboring resources.

The scientific motivations behind studying the Moon are multifaceted. It serves as a natural laboratory, offering insights into the early history of our solar system and the processes that shaped planets like Earth. Studying the Moon's geological composition allows us to understand the formation and evolution of similar planetary bodies. Additionally, the Moon's surface may hold clues about the presence of water ice, a vital resource for future space exploration endeavors.

India's Chandrayaan series, so far, completed three distinct missions, each contributing significantly to our understanding of the Moon:

- **Chandrayaan-1 (2008):** This pioneering mission launched India's lunar exploration journey. It carried a suite of sophisticated instruments that mapped the Moon's surface mineralogy, detected the presence of water molecules, and provided valuable data on its exosphere.

- **Chandrayaan-2 (2019):** This ambitious mission aimed for a soft landing near the lunar south pole, a region with potential water ice deposits. While the lander Vikram faced challenges during descent, the orbiter continues to gather valuable data on lunar surface composition and atmospheric characteristics.
- **Chandrayaan-3 (2023):** This mission successfully landed near the lunar south pole, demonstrating India's capability for soft landing and rover operations on the Moon. It aims to further investigate the lunar surface composition and potential resources in this region.

Each of these missions will be outlined in the following sections, highlighting their scientific objectives, and the significant contributions they have made to our understanding of the Earth's Moon.

Chandrayaan-1

India's Chandrayaan-1 mission, a landmark endeavor in the nation's spacefaring journey, launched in 2008 with the goal of addressing a few scientific questions about the Moon's origin and evolution through high-resolution remote sensing studies. The sophisticated suite of instruments onboard the spacecraft, from India as well as abroad, played a crucial role in achieving this objective.

Three imaging spectrometers and a low-energy X-ray spectrometer worked in tandem, employing hyper-spectral imaging across ultraviolet, visible, and near-infrared wavelengths to map the Moon's surface mineralogy and chemical composition with exceptional detail. A terrain mapping camera provided high-resolution 3D images of the lunar landscape, further enhanced by a laser ranging instrument for precise altitude measurements.

Chandrayaan-I also boasted three unique instruments deployed for the first time in planetary exploration: a high-energy X-γ ray spectrometer, a sub-keV atom reflecting analyzer, and a miniature imaging radar. These instruments delved into the mysteries of the lunar surface, investigating the movement of volatile substances, the presence of a potential mini-magnetosphere, and the possibility of water ice in the perpetually shadowed polar regions. Additionally, a radiation dose monitor measured the intensity of energetic particles encountered during the lunar journey and in orbit.

Beyond the main spacecraft, an impact probe, which was named as the Moon Impact Probe (MIP), carrying an imaging system, a radar altimeter, and a mass spectrometer called CHACE (Chandra's Altitudinal Composition Explorer) was released to crash-land at a predetermined lunar site.

The Chandrayaan-I spacecraft itself was a remarkable feat of engineering, meticulously adapted from the proven Indian remote sensing satellite platform with modifications specifically tailored for the harsh lunar environment. Launched by a modified version of the indigenous Polar Satellite Launch Vehicle (PSLV-XL), it successfully entered a 100-kilometer circular polar orbit around the Moon, with a planned mission life of two years.

While the mission faced technical challenges eventually leading to the loss of communication with the spacecraft, Chandrayaan-I left an undeniable mark on the Indian space program. It not only gathered valuable scientific data about the Moon but also played a pivotal role in establishing India's deep space network and space science data centre, paving the way for future ambitious space exploration endeavours.

Major Science Contributions from Chandrayaan-1

Detection of Water Molecules

Prior to Chandrayaan-1, the Moon was widely believed to be a bone-dry celestial body. This notion was challenged in 2008 when the mission's Moon Mineralogy Mapper (M3) instrument, provided by NASA, detected the presence of Hydroxyl molecules on the lunar surface at higher latitudes, and by India's CHACE instrument onboard the MIP which directly sensed the water molecules in vapour phase in the sunlit lunar exosphere. This epoch-changing discovery reignited global interest in lunar exploration and opened up new avenues for investigating the possibility of lunar water resources.

Study of Lunar Exospheric Noble Gases in Day-side

The CHACE instrument in the MIP in Chandrayaan-1 studied, for the first time, the latitudinal and altitudinal distribution of the major lunar exospheric noble gases (^{40}Ar, ^{20}Ne and ^{4}He). In addition to these noble gases, the distribution of another non-condensable gas in the lunar exosphere, H_2, is also addressed. These studies have provided significant inputs towards the understanding of the composition and dynamics of the sunlit lunar exosphere.

The studies have brought out the spatial heterogeneity and indications of inter-hemispherical asymmetry of radiogenic activity in the lunar interior through the measurement of the

^{40}Ar:^{36}Ar ratio. Also, the upper limit of the He density under extreme conditions of the major controlling factors: i.e. when the lunar exosphere is sunlit, the Moon is on the verge of coming out of the Earth's magnetotail, and the solar wind proton flux level is low.

Evidence of Recent Volcanic Activity

Another long-held assumption was that the Moon had been geologically inactive for billions of years. However, Chandrayaan-1's data revealed evidence of young volcanic activity on the lunar surface, likely occurring within the past few hundred million years. This finding significantly altered our understanding of the Moon's geological evolution and suggests that internal processes may be more active than previously thought.

Lunar Surface Interaction with Solar Wind

Before Chandrayaan-1, it was believed that the Moon completely absorbed the solar wind particles bombarding its surface. However, the mission's Sub-keV Atom Reflecting Analyzer (SARA) revealed a surprising twist. It detected that approximately 20% of the impinging solar wind protons are actually reflected back into space as energetic neutral hydrogen atoms. This discovery challenged existing models of solar wind-moon interactions and opened up new avenues for studying the lunar surface's magnetic properties.

Unveiling the Lunar Wake Region

The lunar wake region, the area behind the Moon shielded from the direct solar wind, was previously thought to be devoid of any solar influence. However, Chandrayaan-1's observations using the SARA instrument revealed the presence of ion populations within this region. This finding indicates a more complex and dynamic interaction between the Moon and the solar wind than previously understood.

Potential for Future Human Habitation

The harsh lunar environment, with its intense radiation and extreme temperature variations, was thought to pose insurmountable challenges for human settlement. However, Chandrayaan-1's data, particularly from its Terrain Mapping Camera (TMC), identified potential sites for future human habitation. These include buried lava tubes, which could provide natural shelters and protection from the harsh lunar surface conditions. This discovery offers a glimmer of hope for the potential of establishing a permanent human presence on the Moon in the future.

Chandrayaan-2

As a logical step, the Chandrayaan-2 mission was configured with an orbiter, a lander, and a rover. The rover was supposed to be carried within the lander. Thus, the lander-rover system was called the lander module. Due to technical reasons, the lander module was unable to soft-land on the Lunar surface.

Results on Lunar Hydration

While the Chandrayaan-2 mission faced a setback with its lander module, the orbiting instruments have made significant contributions to our understanding of the Moon. One of the most important results was about lunar hydration. The Imaging Infrared Spectrometer (IIRS) definitively confirmed the presence of water on the Moon by detecting unambiguous signatures of both OH and H_2O molecules. Furthermore, the Dual Frequency Synthetic Aperture Radar (DFSAR) identified and provided detailed studies of water-ice regions concentrated in the polar areas. Interestingly, IIRS observations also suggest potential hydration in lunar volcanic areas, hinting at a more complex and widespread distribution of water than previously imagined.

Results on Lunar Surface Characteristics

Chandrayaan-2 has also shed new light on the lunar surface characteristics. The Orbiter High Resolution Camera (OHRC) captured high-resolution images, revealing a landscape dotted with small craters (less than 5 meters in diameter) and boulders reaching heights of 1-2 meters. Notably, OHRC identified over 100 boulders within Permanently Shadowed Regions (PSRs), suggesting a similar distribution compared to non-PSR areas as confirmed by the Chandrayaan Surface Feature Detection Camera (CSFD). Additionally, OHRC played a crucial role in identifying and dating volcanic domes approximately 64 million years old, providing compelling evidence of recent lunar volcanic activity. The Terrain Mapping Camera-2 (TMC-2) further contributed to our understanding of lunar tectonics by revealing polygonal crater rims and quantifying lunar crustal shortening, offering insights into the Moon's geological history and neotectonic processes. Moreover, the DFSAR employed a full-polarimetric technique to measure the dielectric constant of the lunar surface, providing valuable data for further analysis.

Results on Surface Elemental Composition

Beyond the surface, Chandrayaan-2's instruments delved into the elemental composition of the Moon. The CLASS instrument made history by generating the first comprehensive map of sodium distribution across the lunar surface. Additionally, it produced global maps of key elements like Magnesium, Silicon, and Aluminum, while also successfully detecting trace constituents such as Chromium and Manganese.

Results on Neutral and Ion Exosphere

The mission also explored the lunar neutral and ion exosphere. CHACE-2 produced the first global map of exospheric ^{40}Ar, and data on neutral Neon and CO_2 is expected to provide further insights in the near future. DFRS contributed by studying the electron density profile within the lunar exosphere, offering valuable information about its composition and structure.

Solar and Magnetospheric Observations

Solar and magnetospheric observations were another highlight of the mission. CLASS detected an enhanced flux of suprathermal electrons in the Earth's geomagnetic tail, while the XSM instrument achieved a remarkable feat: for the first time, it provided absolute abundance measurements of key elements like Magnesium, Aluminum, and Silicon within the quiet solar corona. Furthermore, XSM identified and characterized around 100 "sub-A class" microflares in the quiet corona, offering new perspectives on the mechanisms responsible for coronal heating.

Thus, the scientific data collected by the scientific instruments onboard Chandrayaan-2 orbiter have significantly enhanced our understanding of the Moon's composition, geological history, and the presence of water ice. These findings pave the way for future lunar exploration and offer a wealth of information to guide further research endeavors, solidifying Chandrayaan-2's place as a landmark mission in lunar science.

Chandrayaan-3

Launched in 2023 with LVM3 M4 launch vehicle, the Chandrayaan-3 mission marked a resounding success for India's spacefaring ambitions. This meticulously planned endeavor aimed to develop and showcase critical technologies essential for future interplanetary missions, with a specific focus on achieving a soft landing on the Moon and deploying a robotic rover for exploration. Chandrayaan-3 has achieved soft-landing on the lunar surface on August 23, 2024, at 69.373450 degree South, 32.319845 degree East lunar coordinates. The landing site of Chandrayaan-3 has been named as *Statio Shiv Shakti*.

Figure 32: The picture of the Vikram lander standing on the lunar surface, as clicked by the rover. Picture courtesy: ISRO

The mission comprised three key components. The **Lander Module,** designed to execute a soft landing at a predetermined lunar site, was equipped with scientific instruments, as the platform for deploying the rover and conducting in-situ experiments on the lunar surface. The **Rover** embarked on a pre-defined path after deployment from the Lander, carrying out elemental analysis of the lunar surface throughout its mobility period. The **Propulsion Module** played a vital role in carrying the Lander from its launch to its final lunar orbit, a ~ 100-kilometer circular polar orbit. After separation from the Lander, the propulsion module also conducted a scientific experiment on obtaining spectro-polarimetric signatures of the Earth from the lunar orbit as an additional mission objective.

The primary goals of the Chandrayaan-3 mission were:

1. **Demonstrating a Safe and Soft Landing on the Lunar Surface:** This objective required the Lander to navigate the complexities of lunar descent and achieve a controlled touchdown on the designated site.

2. **Deploying and Operating a Rover on the Moon:** The successful deployment and operation of the rover marked a significant advancement in India's robotic exploration capabilities.

3. **Conducting In-Situ Scientific Experiments:** Both the Lander and the rover carried scientific payloads designed to analyze the lunar surface composition and gather valuable data for furthering our understanding of the Moon.

Chandrayaan-3 stands as a testament to India's growing prowess in space exploration. By successfully demonstrating critical technologies for soft landing and rover operations on the Moon, this mission has paved the way for even more ambitious lunar endeavors in the future, solidifying India's position as a leading player in the global space exploration arena.

Both the lander and the rover housed scientific instruments dedicated to analyzing the Moon's composition, thermal properties, plasma environment, and seismic activity.

Following were the scientific instruments mounted on the Chandrayaan-3 lander.

- **Radio Anatomy of Moon Bound Hypersensitive ionosphere and Atmosphere (RAMBHA):** This instrument, including the RAMBHA-Langmuir Probe, aimed to measure the near-surface plasma (ions and electrons) density and its variations over time, providing insights into the lunar ionosphere and exosphere.

- **Chandra's Surface Thermo Physical Experiment (ChaSTE):** This instrument focused on measuring the thermal properties of the lunar surface, particularly in the vicinity of the south pole, where temperatures can plunge to incredibly low levels. Understanding these thermal properties is crucial for future lunar exploration endeavors.

- **Instrument for Lunar Seismic Activity (ILSA):** This instrument served as a sensitive seismometer, meticulously recording lunar ground vibrations, including seismic activity, around the landing site.

- **Laser Retroreflector Array (LRA):** This passive instrument, from NASA, consists of an array of corner cube reflectors designed to reflect laser pulses sent from the LRO orbiter. By precisely measuring the time it takes for these pulses to travel to the Moon and back, scientists can gain valuable insights into the Moon's orbit and its subtle variations.

Rover Payloads:

- **Alpha Particle X-ray Spectrometer (APXS):** This instrument carried by the rover was designed to analyze the elemental composition of the lunar surface by measuring the characteristic X-rays emitted when alpha particles interact with lunar soil.
- **Laser Induced Breakdown Spectroscope (LIBS):** This rover-mounted instrument utilized laser pulses to vaporize tiny samples of the lunar surface, analyzing the emitted light to determine the elemental composition of the vaporized material.

These advanced payloads, working in concert, provided a comprehensive suite of scientific data that significantly enhanced our understanding of the Moon's composition, thermal properties, and plasma environment.

Preliminary Observations from Chandrayaan-3

At present, the Chandrayaan-3 data have been studied by the Principal investigators from ISRO / Department of Space, and the preliminary science results are under communication with suitable peer reviewed journals.

However, as an interim update, the spectra of lunar samples acquired by the Alpha Particle X-Ray Spectrometer (APXS) and the Laser Induced Breakdown Spectroscope (LIBS), both mounted on the rover, show the presence of all major elements and several minor elements. Abundances of elements show no significant variation over the terrain. All the samples that were analysed by these instruments were within a few tens of meters of radius from the landing site. Temperature evolution of the lunar subsurface as a function of the local time, up to a depth of ~ 10 cm, was measured by the sensors mounted on the ChaSTE probe. Also, during a thermal conductivity experiment, the heater mounted at the tip of the ChaSTE probe was switched on in order to study the heat flow across the depth of the lunar regolith. The RAMBHA-Langmuir Probe onboard the lander has studied the near-surface plasma environment on the Moon, and detected a very low concentration of electron density with a variation over time. The ILSA experiment has catalogued several numbers of signatures of the lunar ground vibration, out of which a fraction was attributed to the events like rover navigation, deployment or operation of payloads etc. In addition, there are a few events noted by ILSA, which are not correlated with such engineering events, and look natural. They are under study.

The exact details of these observations will appear in scientific journals in due course.

India's Mars Exploration: The Mars Orbiter Mission (MOM)

India's Mars Orbiter Mission (MOM), also known as Mangalyaan, stands as a testament to the nation's scientific prowess. Launched in November 2013, the MOM spacecraft embarked on a historic journey, successfully reaching Mars orbit in September 2014. This remarkable feat served two crucial purposes.

Firstly, it represented a significant technological leap, showcasing India's capability to design, plan, and execute a complex interplanetary mission. MOM paved the way for future Indian endeavors beyond Earth, laying the groundwork for even more ambitious space exploration initiatives.

Secondly, the mission aimed to unravel the scientific mysteries of Mars. Equipped with sophisticated instruments, MOM embarked on a comprehensive study of the Martian surface, meticulously analyzing its features, composition, and even its atmosphere, searching for clues about Mars' past and potential for life.

The MOM spacecraft itself was a technological marvel, meticulously designed to withstand the unforgiving conditions of space travel. It had to endure extreme temperature fluctuations, scorching heat during escape from Earth and frigid temperatures around Mars. Additionally, it required robust protection against harmful radiation, including solar flares and cosmic rays.

Operating this mission over vast distances presented unique challenges. The spacecraft needed a carefully designed power system to function efficiently with limited solar energy on Mars. Maintaining stable communication with Earth demanded a powerful long-range system. Precise adjustments and orbital changes throughout the mission were made possible by a dependable propulsion system. Finally, due to the significant time delays in communication between Earth and Mars, the spacecraft needed to operate with a high degree of autonomy, making decisions and taking actions without real-time instructions.

MOM addressed these challenges through automation. Repetitive tasks with predictable timelines were automated, like pre-programmed sequences for crucial maneuvers. Mission planning played a vital role, with ground-based tools ensuring the spacecraft was ready to execute pre-defined actions at specific times.

By successfully overcoming these hurdles and achieving its scientific goals, the Mars Orbiter Mission not only secured its place in space exploration history but also established India as a leading force in this exciting field. MOM served as a stepping stone for future Indian missions, inspiring further exploration of our solar system.

Science from the Mars Orbiter Mission

The Mars Orbiter Mission has returned valuable scientific observations and results on the Martian exosphere, its dependence on the solar forcing, interplay between dust storms and the upper atmosphere of Mars, observations on the hazes, short wave infrared albedo, imaging of the farside of the Martian natural satellite Deimos, to name a few. Following is a brief account of the contributions of India's Mars Orbiter Mission to the advancement of Martian science.

Results on Martian Exosphere and its Local Time Dependence

The Mars Orbiter Mission carried a special instrument called the Mars Exospheric Neutral Composition Analyser (MENCA). This device was a sophisticated gas composition analyzer, the analyzed the thin layer of gas surrounding Mars, known as the exosphere. MENCA focused on measuring the types and amounts of different gases present, particularly focusing on carbon dioxide (CO_2), nitrogen (N_2), and oxygen (O).

MOM's unique orbit brought it very close to Mars at certain points, allowing MENCA to gather data from both the well-mixed lower atmosphere and the more diffuse upper atmosphere (exosphere). By analyzing observations from four specific orbits in late December 2014, scientists were able to track how the composition of the Martian atmosphere changes with altitude.

It was discovered that carbon dioxide is the dominant gas up to an altitude of about 270 kilometers, after which atomic oxygen takes over. Additionally, the average temperature in the exosphere was estimated to be around 271K. These initial findings, focusing on the Martian evening hours near sunset, provided valuable information for refining models that explain how gases escape from Mars' atmosphere.

It's important to note that these observations were made during a period of moderate solar activity and near Mars' closest approach to the Sun. This specific time and location were chosen because they are known to experience the most significant atmospheric changes according to computer simulations.

Detection of Highly Energetic Argon Atoms

Scientists are constantly studying the thin upper atmosphere of Mars and the region beyond, also known as the exosphere, to understand how it behaves and interacts with the rest of the planet. The Mars Exospheric Neutral Composition Analyser (MENCA) onboard India's Mars Orbiter Mission (MOM) played a crucial role in this research.

By analyzing data collected during four specific orbits in December 2014, scientists focused on the element argon (Ar) present in the Martian exosphere. They found that the number of argon atoms reaches a maximum of around 5×10^5 per cubic centimeter at an altitude of about 250 kilometers. Typically, the density of particles in the exosphere decreases with increasing altitude, but in two specific instances, the rate of decrease was much slower than expected, suggesting a much higher temperature in that region, exceeding ~400K (as against the typical temperature of ~275K).

Interestingly, these findings align with observations made by another spacecraft, NASA's Mars Atmosphere and Volatile Evolution (MAVEN) mission. Both sets of data suggest the presence of a large number of argon and carbon dioxide atoms with much higher energy than expected in the upper reaches of the Martian atmosphere, a region called the upper exosphere.

The study also revealed the presence of unexpected variations in the density of particles within the exosphere, resembling waves. These "waves" seem to be connected to the presence of the hot, energetic argon and carbon dioxide. Scientists believe that a process called pickup ion-induced heating might be responsible for creating these energetic particles.

Another interesting discovery is that these phenomena, including the hot argon and the "waves," can occur regardless of the Martian seasons or the amount of sunlight reaching the planet. While the exact cause of these variations is still under investigation, scientists believe that the dissipation of energy from waves in the Martian thermosphere (the layer below the exosphere) might play a role on certain occasions.

These findings offer new insights into the complexities of the Martian atmosphere, revealing unexpected phenomena that challenge our current understanding. Further research is needed to fully understand the mechanisms at play and their implications for the overall Martian environment.

Results on Dust Storm effects on Martian Upper Atmosphere

Understanding the upper atmosphere of Mars is crucial to understand the escape of its atmosphere to space. To gain deeper insights, NASA's Mars Atmosphere and Volatile Evolution (MAVEN) mission and India's MOM took up coordinated observations to simultaneously observe the Martian upper atmosphere during a specific period.

Between June 5th and 29th, 2018, MAVEN observed the morning side of Mars, while MOM observed the evening side. Both spacecraft detected a significant increase in the density of neutral particles within the upper thermosphere (150–220 km) of Mars. This increase coincided with the development of a massive dust storm raging in the lower Martian atmosphere. Interestingly, the density increase was more pronounced on the evening side compared to the morning side, and it peaked when the dust storm reached its maximum intensity.

Scientists believe these observations reveal how the Martian thermosphere is affected by the dust storm. The dust particles in the lower atmosphere absorb sunlight, which heats them up. This heat then radiates outwards, warming and expanding the upper thermosphere. Additionally, the analysis suggests that the way the thermosphere cools down is different on the morning and evening sides. Collisions between oxygen (O) and carbon dioxide (CO_2)

molecules are responsible for cooling the thermosphere, and this process seems to be more efficient in the morning hours.

These observations showcase the interplay between dust storms and the upper atmosphere of Mars, highlighting how sunlight, dust, and atmospheric gases interact to influence the Martian environment.

Observations on Martian Cloud, Dust, Ice, and haze

The Mars Colour Camera has captured detailed images of the Martian north pole, focusing on the Martian clouds and dust, atmospheric dynamics, and the changes in the polar ice.

While studying Martian Clouds and dust, MCC has observed the presence and movement of water-ice clouds and dust particles in the Martian atmosphere, particularly how dust gets lifted and transported. The instrument has also provided important information on atmospheric dynamics, especially on how weather patterns and atmospheric processes work on a regional and local scale around the north pole, specifically focusing on storms and heat distribution. The instrument has also studied the changes in the North polar ice over time, including the influence of warmer regions near the pole.

This research has involved creating a detailed mosaic of the north pole using MCC data collected between December 2015 and January 2016. This analysis revealed different types of weather fronts occurring at the north pole, including curved, straight, and spiral patterns. Scientists are able to track the movement of these fronts to understand atmospheric behavior in that region.

The Mars Colour Camera has also captured over 30 images of high-altitude clouds between September and December 2014, revealing some fascinating details. These clouds were found at incredibly high altitudes, ranging from 43 to 91 kilometers above the Martian surface, and stretched horizontally across vast distances, sometimes exceeding 1200 kilometers. Analyzing the reflected sunlight from these clouds, scientists determined that they are primarily composed of water ice particles, with some dust particles mixed in. Interestingly, one event even showed a cloud made of carbon dioxide (CO_2).

Scientists believe these high-altitude clouds likely form during or after dust storms on Mars. Strong winds lift dust and water ice particles high into the atmosphere, creating these wispy clouds. This explanation is supported by the timing of the observed clouds coinciding with known dust storm events. Additionally, deep atmospheric circulation patterns and changes in the Martian boundary layer height and dust content further strengthen the dust storm connection. Studying these high-altitude clouds helps us understand the composition and dynamics of the Martian atmosphere, including the influence of dust storms and other processes that shape the Martian environment.

Furthermore, the MCC has measured the amount of sunlight reflected from the north polar surface in different colors (red, green, blue). This allows researchers to differentiate between various surface features, such as ice-covered areas, dusty regions, and clear surfaces. By studying how this reflected light changes over time, scientists can gain insights into the seasonal variations and surface composition of the north pole, including areas like Korolev crater and Olympia Mensa.

The Mars Orbiter Mission has also reported about bright hazes observed within Valles Marineris during the mid-southern spring season on Mars. This observation was made by the Mars Colour Camera (MCC) onboard the MOM. The observations revealed that the valley was consistently hazy. A thick layer of haze was observed on orbit 34, followed by a period of relative thinning on orbit 49. Interestingly, the thick haze reappeared eight days later on orbit 52.

Furthermore, the research team employed stereo images captured by MCC on December 5th, 2014, to measure the optical depth of the Martian atmosphere as a function of altitude above the opposing northern and southern walls of Valles Marineris near the Coprates Chasma region. Utilizing the "stereo method," optical depth was estimated through contrast comparisons within the stereo images.

Optical depth measurements were also conducted for the southern wall of Valles Marineris. However, in this case, the optical depth remained relatively constant with decreasing altitude.

Short-wave infrared (SWIR) albedo of Mars

Studying the short-wave infrared (SWIR) albedo of a planetary body like Mars holds significant importance for understanding its surface features, processes, and climate. Variations in SWIR albedo can reveal surface features like craters, volcanic plains, and dust deposits. By studying these albedo variations, scientists can gain insights into geological processes that have shaped the planetary surface over time. For example, areas with low SWIR albedo might indicate the presence of fine-grained dust or specific minerals, while high albedo regions could suggest exposed bedrock or ice deposits.

Furthermore, studying the global distribution of SWIR albedo helps scientists understand the radiative processes that influence the planet's climate and energy balance. Albedo plays a crucial role in regulating a planet's energy balance. Regions with high albedo reflect more sunlight back into space, contributing to a cooler overall temperature. Conversely, areas with low albedo absorb more solar energy, leading to localized warming. This analysis provides valuable insights into the climatic processes that govern the planet.

The MOM has derived the SWIR albedo of Mars from data collected by the Methane Sensor for Mars (MSM) instrument, during the period of October 2014 to February 2015. The mission has revealed the distribution patterns of low and high albedo regions across the Martian surface using the generated MSM apparent SWIR albedo map.

Based on the MSM apparent SWIR albedo values, three distinct classes are defined: high, intermediate, and low albedo. Interestingly, these classifications exhibit a clear correlation with elevation on the Martian surface.

Furthermore, these observations presented the variation of weekly average apparent albedo over three specific regions – Syrtis Major, Daedalia Planum, and Valles Marineris – throughout the observation period. This data provided insights into the temporal variations of albedo within these specific Martian regions.

Imaging of the Far-side of Deimos

The Mars Orbiter Mission achieved yet another notable feat by capturing images of the far-side of Deimos, one of Mars's two moons. This accomplishment is significant because Mars and Deimos are tidally locked, meaning the same side of Deimos always faces Mars. Consequently, most Martian orbiters, positioned between Mars and Deimos, only observe the Mars-facing side.

MOM's highly elliptical orbit transcends Deimos' path, granting it a unique vantage point to capture the previously unseen far-side. This observation, made possible by the Mars Colour Camera (MCC), marks the first time in over three decades that the far-side of Deimos has been imaged by a Martian orbiter.

The captured images were used to create a high dynamic range (HDR) product, revealing surface features distinct from the known Mars-facing side. This observation aligns with recently proposed models of Deimos' shape, further confirming the success in capturing the far-side.

Furthermore, the analysis suggested a slight variation in Deimos' magnitude between the near and far sides, prompting further investigation into potential surface characteristic differences. This observation has sparked scientific interest in understanding the far-side in greater detail, paving the way for future research endeavors. This observation opens doors for further exploration and a more comprehensive understanding of Deimos and the Martian system.

ISRO has released an atlas of Mars with the pictures captured with the MCC instrument onboard MOM. It can be accessed from https://www.issdc.gov.in/docs/mr1/mars-atlas.pdf

The Aditya-L1 Mission

Studying the Sun is imperative in solar system exploration, as it is the prime mover of every process of the solar system. Studying the Sun also offers a unique advantage compared to other stars due to its close proximity. By observing our Sun, we gain valuable insights into the processes within the other stars in our Milky Way galaxy and even beyond. However, the Sun is a dynamic star; it exhibits various eruptive phenomena, releasing immense amounts of energy into the solar system as particles and photons. If these solar outbursts are directed towards Earth, they can disrupt the near-Earth space environment in several ways.

Spacecraft, communication systems, and even astronauts can be affected by such disturbances. Understanding these phenomena beforehand is crucial for taking necessary precautions. Additionally, the Sun's extreme thermal and magnetic activity provides a natural laboratory for studying processes that cannot be replicated in earthly labs.

The Sun continuously influences Earth with radiation, heat, and a constant flow of particles and magnetic fields. This flow of particles, primarily high-energy protons, is known as the solar wind and fills almost the entire solar system. The solar magnetic field also permeates the solar system alongside the solar wind. Both the solar wind and explosive eruption of particles like

Coronal Mass Ejections (CMEs) can significantly alter the nature of space near planets.

For instance, when a CME interacts with Earth's magnetic field, it can trigger magnetic disturbances that can disrupt the functioning of satellites and other space assets. This is why understanding space weather, the changing environmental conditions in space around Earth and other planets, is crucial, especially as we rely more and more on technology in space. Studying near-Earth space weather also sheds light on how space weather behaves on other planets.

India's Aditya L1 mission is the country's first space-based observatory dedicated to studying the Sun. This spacecraft orbits the Sun at a special point called the Lagrange Point 1 (L1), roughly 1.5 million kilometers from Earth. This unique position allows Aditya L1 to continuously observe the Sun without any interruptions or eclipses, providing a significant advantage for studying solar activity.

Equipped with seven advanced instruments, the spacecraft observes the Sun's photosphere, chromosphere, and outermost layer (corona) using electromagnetic and particle detectors. Four of these instruments directly observe the Sun from this special vantage point, while the remaining three study particles and fields directly at the L1 point.

Aditya L1 aims to answer crucial questions about the Sun, including:

- **Coronal heating problem:** One of the biggest mysteries is understanding how the Sun's corona, the outermost layer, reaches temperatures millions of degrees higher than the underlying photosphere. Aditya L1 seeks to unravel the mechanisms responsible for this intense heating.

- **Initiation of CMEs, flares, and near-Earth space weather:** These powerful solar events can have significant impacts on Earth. Aditya L1 aims to understand the triggers behind these events and how they affect our planet's environment.

- **Coupling and dynamics of the solar atmosphere:** Studying how the different layers of the Sun interact and influence each other is crucial for understanding the Sun's overall behavior.

- **Solar wind distribution and temperature anisotropy:** The solar wind doesn't flow uniformly in all directions, exhibiting variations in temperature and density. Aditya L1 aims to map these variations and understand the underlying processes.

By studying the Sun through Aditya L1, scientists hope to gain a deeper understanding of these phenomena:

- **Understanding anisotropies:** The solar wind and other phenomena exhibit anisotropies, meaning their properties vary depending on the direction of measurement. Studying these variations is crucial for a comprehensive understanding of the Sun's behavior.

- **Solar cycle:** The Sun undergoes cycles of activity, with periods of high and low solar activity. Understanding the mechanisms behind these cycles is a key objective of Aditya L1.

Aditya L1 carries a suite of seven sophisticated instruments, each playing a specific role in understanding the Sun's behaviour:

- **Visible Emission Line Coronagraph (VELC):** Studies the solar corona and the dynamics of CMEs.
- **Solar Ultra-violet Imaging Telescope (SUIT):** Images the Sun's photosphere and chromosphere in near-ultraviolet light and measures variations in solar irradiance.
- **Aditya Solar wind Particle EXperiment (ASPEX) and Plasma Analyser Package for Aditya (PAPA):** Study the solar wind, energetic ions, and their energy distribution.
- **Solar Low Energy X-ray Spectrometer (SoLEXS) and The High Energy L1 Orbiting X-ray Spectrometer (HEL1OS):** Analyze X-ray flares from the Sun across a wide range of X-ray energies.
- **Magnetometer:** Measures the interplanetary magnetic fields at the L1 point.

All these instruments were developed indigenously by various Indian research institutions, showcasing the country's growing expertise in space science and technology.

While Aditya L1 focuses on studying the Sun from the L1 point, other vantage points like Lagrange Point 5 (L5) offer valuable perspectives for understanding Earth-directed CMEs and assessing space weather. Additionally, the Sun's polar regions remain relatively unexplored due to the technological challenges of achieving suitable spacecraft orbits. Studying the Sun's polar dynamics and magnetic fields is believed to be crucial for understanding solar cycles. Furthermore, polarization measurements of solar radiation at different wavelengths are necessary to comprehend various processes occurring within and around the Sun.

As India delves deeper into the realm of solar exploration, these additional perspectives will be crucial for unlocking the secrets of our nearest star and its profound influence on our planet and the solar system.

While there are immense possibilities in the field of solar system exploration, we must build a pool of professionals who will contribute to the domains of science, technology and engineering, towards the exploration of the solar system.

As a joint effort of ISRO and Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital, the Aditya-L1 Support Cell has been set up to act as a community service centre. The Aditya-L1 support cell provides tools and documentation required to understand, download and analyse the data from ISRO's data archives. To know more about the Aditya-L1 support cell, visit https://al1ssc.aries.res.in/

Planetary Exploration Data

Planetary science thrives on the data collected by a multitude of robotic and orbital missions venturing across our solar system. These missions gather a wealth of information on planetary environments, compositions, and geological processes. This data, encompassing imagery, spectroscopy, and various in-situ measurements, serve as the bedrock for scientific discovery. However, the raw data hold limited value unless properly archived, standardized, and readily accessible to researchers worldwide. This section presents the critical roles played by the Indian Space Science Data Centre (ISSDC) and the International Planetary Data Alliance (IPDA). We'll explore how ISSDC meticulously preserves and disseminates data from India's space missions, while IPDA fosters international collaboration and ensures the long-term usability of planetary data through standardized archiving practices. By examining these organizations, we gain a deeper understanding of the infrastructure that underpins scientific progress in our ongoing exploration of the solar system.

Indian Space Science Data Centre (ISSDC)

Established in 2008 as a part of the Indian Space Research Organisation (ISRO), the Indian Space Science Data Centre (ISSDC) serves as a critical repository for scientific data gleaned from India's space exploration endeavors. Situated within the Indian Deep Space Network (IDSN) campus in Bangalore, ISSDC fulfills a two-fold mission: archiving and disseminating this invaluable information for the benefit of the global scientific community.

The archiving function of ISSDC ensures the long-term preservation of scientific data collected by Indian space missions. The Centre meticulously ingests, processes, and curates this data, adhering to internationally recognized standards like the Planetary Data System (PDS). This meticulous approach guarantees the integrity and usability of the data for present and future scientific inquiry.

In this context, it is imperative to tell a few words about PDS. The Planetary Data System (PDS), spearheaded by NASA, acts as a critical global archive for a treasure trove of information gleaned from robotic and orbital missions exploring our solar system. Functioning not just as a long-term repository, PDS plays a vital role in standardizing data archival across participating space agencies. This meticulous approach, with its emphasis on consistent formats and documentation, ensures datasets are universally accessible and interpretable for future generations of scientists. The PDS itself encompasses different facets, including data archives for specific mission types (atmospheres, geosciences, etc.), software tools to aid data processing and analysis, and a comprehensive library of documentation to guide researchers in understanding and utilizing the archived information. This multi-pronged approach safeguards the scientific legacy of space exploration and empowers future generations to unlock the secrets encoded within the data.

Beyond archiving, ISSDC actively promotes the dissemination of this scientific wealth. Following an initial restricted period, the data is made accessible to a wider audience. Researchers across the globe are granted access through the internet, fostering international collaboration and propelling scientific discovery. This openness extends even to the general public, igniting a passion for space exploration within the citizenry.

The significance of ISSDC lies in its role as a cornerstone for future scientific progress. By meticulously preserving this data, the Centre ensures a rich resource for researchers to build upon. This archived knowledge paves the way for further exploration and investigation, empowering researchers to delve deeper into the mysteries of the cosmos.

Furthermore, ISSDC fosters a spirit of collaboration within the international scientific community. By sharing this information, researchers from India and across the globe can work together, leveraging their combined expertise to unlock the secrets of the universe. This collaborative approach holds immense potential for scientific breakthroughs, propelling our comprehension of the universe to ever-greater heights.

ISSDC can be accessed through the URL: https://www.issdc.gov.in/

International Planetary Data Alliance (IPDA)

After having discussed about ISSDC, it is necessary to discuss about the International Planetary Data Alliance (IPDA). IPDA serves as a vital resource for the solar system mission data from all the space agencies in one place. Established in 2006, this collaborative alliance brings together space agencies worldwide with a shared objective: ensuring the quality, accessibility, and interoperability of planetary data.

IPDA doesn't maintain its own central repository. Instead, it functions as a network, fostering cooperation between existing planetary data archives operated by individual member agencies. This collaborative approach leverages the strengths of each archive while promoting the development and implementation of consistent data standards. A key feature of IPDA is its commitment to the PDS data format for standardization. By encouraging member archives to adopt PDS, IPDA ensures that data from diverse missions across the globe can be easily accessed, understood, and compared by researchers.

The IPDA website (https://ipda.jpl.nasa.gov/) serves as a central hub for information about the alliance's activities, member organizations, and the PDS standards. Here, researchers can explore best practices for data archiving, discover tools and resources, and stay abreast of ongoing IPDA projects that aim to further enhance the accessibility and usability of planetary data for the global scientific community. India is also a member of the IPDA, and the Indian space mission data may also be accessed through IPDA.

Ethical Aspects of Solar System Exploration

As our capabilities in space exploration continue to advance, so too does the need for a robust and comprehensive ethical framework to guide our interactions with the celestial bodies within our solar system. This framework, encompassing various principles, aims to ensure responsible exploration that minimizes harm and fosters scientific discovery for the benefit of all humanity.

Planetary Protection: Preserving Pristine Environments

Planetary protection, a cornerstone of ethical space exploration, focuses on preventing the forward and back contamination of celestial bodies. Forward contamination refers to the unintended introduction of Earth-based organisms to other planets or moons, potentially jeopardizing the potential for indigenous life or compromising the scientific integrity of pristine environments. Back contamination, conversely, concerns the potential for extraterrestrial organisms, if present, to be brought back to Earth and pose a threat to our own biosphere.

International agreements like the Outer Space Treaty and the Committee on Space Research (COSPAR) Planetary Protection guidelines establish protocols to minimize the risk of contamination. These protocols include rigorous spacecraft sterilization procedures, careful selection of landing sites, and the implementation of strict quarantine measures for returned samples.

Sustainable Exploration: Preserving Resources for Future Generations

Sustainable exploration emphasizes minimizing the long-term impact of our activities on the solar system. This includes responsible resource utilization, minimizing the generation of space debris, and ensuring the long-term viability of celestial environments for future scientific endeavors.

Sustainable practices involve carefully considering the extraction of resources from planetary bodies. While resource utilization may be necessary for future space settlements or scientific research, it should be done with minimal disruption to the natural environment and with a focus on long-term sustainability. Additionally, minimizing the generation of space debris, such as discarded spacecraft components, is crucial to prevent the creation of hazards for future missions and potential interference with scientific observations.

Yet another example is the need for guidelines for preserving the pristine nature of the scientifically significant zones like the lunar

Permanently Shadowed Regions (PSRs), far-side of the Moon, to name a few.

Scientific Integrity and Collaboration

Maintaining scientific integrity throughout the exploration process is paramount. This involves open data sharing, transparency in research methodologies, and collaboration among nations and space agencies. Sharing scientific data and findings allows for the broader scientific community to contribute to the understanding of our solar system and fosters international cooperation in space exploration endeavors.

Ethical Considerations for Potential Extraterrestrial Life

The potential discovery of extraterrestrial life, whether microbial or intelligent, presents a significant ethical challenge. We must be prepared to approach such discoveries with utmost caution and respect, prioritizing the preservation of any potential life forms and their environments. This necessitates the development of clear ethical guidelines for interacting with extraterrestrial life, ensuring that any actions taken do not compromise their existence or their potential for further evolution.

Importance of Solar System Exploration: The Answer beyond Science

If someone asks you what is the benefit of exploring the solar system (as against the ones that have immediate applications or outcomes – like communication, remote sensing, navigation), and speaking merely about the expansion of knowledge is not convincing as an answer, this section needs a careful read.

While it is true that the inherent human desire to quench the thirst for knowledge is the major driving force behind space exploration, the importance of venturing into our solar system extends far beyond mere scientific curiosity. It is an endeavor that holds immense potential for national pride, capacity building, international relevance, as well as economic prosperity.

National Pride and Capacity Building:

In the realm of international relations, space exploration serves as a powerful symbol of a nation's technological prowess and scientific advancement. It demonstrates a nation's commitment to pushing the boundaries of human knowledge and its ability to undertake complex and ambitious endeavors. This, in turn, fosters national pride and elevates the country's standing on the global stage.

Furthermore, the pursuit of space exploration necessitates the development of sophisticated technologies, skilled personnel, and robust scientific infrastructure. This national capacity building process has a ripple effect, strengthening the country's technological base and fostering innovation across various sectors. It empowers universities, research institutes, and industries to develop cutting-edge technologies that have applications not only in space exploration but also in fields like medicine, communication, navigation, material science, forensics, to name a few.

International Relevance and Global Space Economy:

Engaging in solar system exploration positions a nation as a key player in the global space economy. Collaboration with other spacefaring nations on joint missions, data sharing, and technological advancements fosters international partnerships and strengthens diplomatic ties. This collaborative approach not only accelerates scientific progress but also expands the scope of exploration and discovery.

The booming space industry offers big opportunities for countries with the right skills and infrastructure. This goes beyond just building and launching spacecraft. Nations can also provide crucial services like satellite communication, monitoring Earth from space, and even space tourism. By actively participating in these areas, a country can play a significant role in the global space economy.

Strength Respects Strength

In the international arena, "strength respects strength." A nation's capacity for space exploration serves as a testament to its scientific and technological prowess, earning the respect and recognition of the global community. This fosters a sense of self-reliance and opens doors to potential collaborations and partnerships with other advanced nations.

Spin-offs with Societal Value:

The technologies developed for space exploration often have far-reaching societal benefits. Advancements in materials science, robotics, miniaturization, and communication technologies, originally driven by the demands of space missions, have found applications in various fields, from medical diagnostics and disaster management to environmental monitoring and sustainable energy solutions.

The importance of solar system exploration thus transcends the mere pursuit of knowledge. It serves as a catalyst for national pride, capacity building, international relevance, and economic prosperity. By actively engaging in this endeavor, a nation positions itself as a leader in the global scientific community, reaping the benefits of technological advancements and contributing to the betterment of humanity.

Summary

This book has embarked on a systematic journey of the understanding of the solar system, science of its formation, diversity of its members, and the ongoing quest to unravel its mysteries. We explored how advancements in technology, particularly space-based observations, have revolutionized our understanding of these celestial bodies.

We delved into the scientific criteria that define a planet, distinguishing them from asteroids, comets, and other celestial bodies. The unique characteristics of each planetary body were explored, including their orbits, mass, size, temperature, rotation, shape, magnetic fields, surface composition, internal structures, and atmospheres.

Furthermore, we examined the profound influence of the Sun on Earth, highlighting the intricate interplay between solar radiation, heat, and the constant flow of particles that shape our planet's environment. The concepts of weather, space weather, and planetary space weather were discussed, emphasizing their interconnectedness and impact on various celestial bodies.

Equipped with this foundational knowledge, we explored the realm of space exploration, outlining the different techniques employed to study the solar system. We discovered why space-based observations are often preferred and how meticulous planning and execution are crucial for successful space science missions.

Thereafter, we discussed about India's significant contributions to solar system exploration, highlighting the Chandrayaan series of lunar missions, and the Mars Orbiter Mission (MOM). We explored the scientific discoveries made by these missions and India's dedicated solar observatory, the Aditya-L1 mission.

Understanding the vast amount of data collected through planetary exploration missions is crucial. The book, therefore, introduced the Indian Space Science Data Centre (ISSDC) and the International Planetary Data Alliance (IPDA), underscoring the importance of data sharing and collaboration in the exploration of the solar system.

As we conclude this journey, we are left with a deeper appreciation for the multiple facets of the solar system and the ongoing quest to understand our place within it. This book serves as a springboard for further exploration, igniting curiosity and inspiring the young minds to continue unravelling the mysteries of the solar system.