THE LUNAR SAGA

Let's know our Moon better

ABSTRACT

Targeted to the high school students, this book provides a brief description of the Earth's Moon, covering the scientific aspects of its evolution, current understanding, and future scopes of exploration.

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Lunar Science

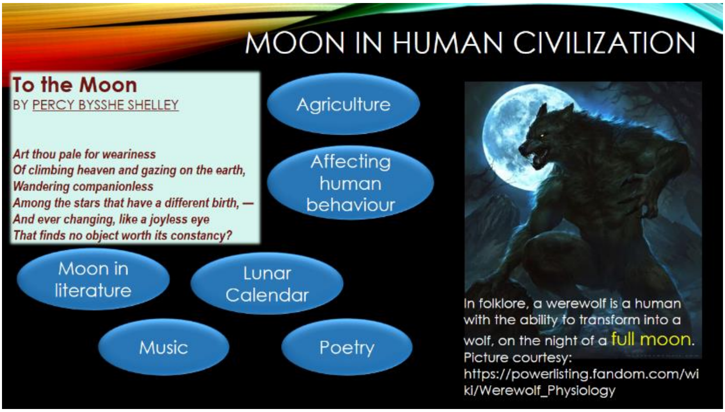
Contents

Moon in Mythology

Moon has been one of the oldest companions of humankind through its journey of origin and evolution, and its strong influence on humankind is documented in the mythologies of almost all known civilizations. In Indian mythology, for example, Moon is considered a deity, and the ancient Indian text, the *Rigveda*, prays to the Moon deity to unveil his mystery to humankind through intellect and wisdom. Ancient Indians used to worship both Sun and the Moon, and the urge for unveiling the mystery of the Moon, as mentioned in the *Rigveda*, is recognized by today's planetary scientists as an efficient way to understand the solar system.

In the mythological depictions, Moon has been personified as male and female deities. For example, the Greek goddess Selene, the Roman goddess Luna, and the Chinese goddess Chang'e, all are female deities. Certain civilizations personified Moon as a male deity, such as Sin of the Mesopotamians, Mani of the Germanic tribes, Tsukuyomi of the Japanese, Igaluk/Alignak of the Inuit, and, the ancient

Indian deity Chandra. Interestingly, many of the Moon missions have derived their names from the mythological lunar deities.

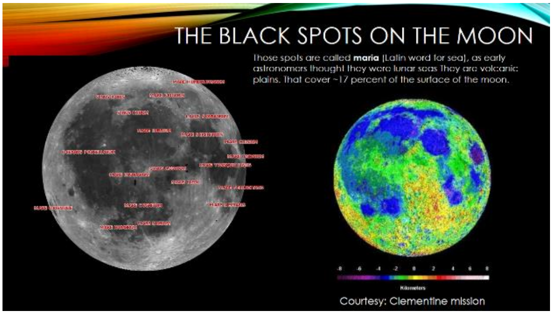


Moon in Human Civilization

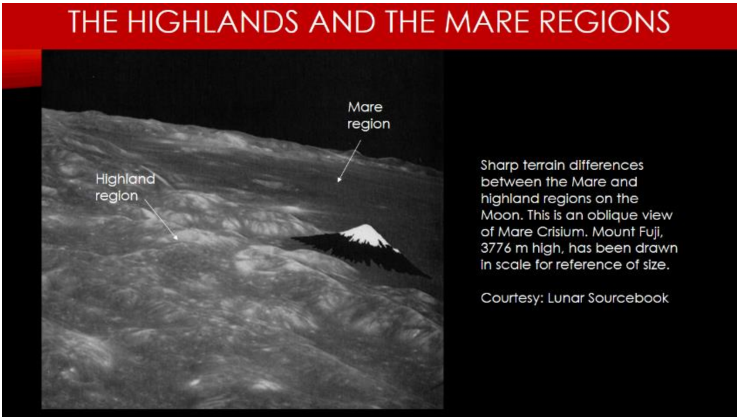
Beyond the realm of mythology, Moon has been a time-keeper since the days of yore, when there was neither clock nor calendar, and thus had an immense influence on the almanac and agriculture; and the lunar calendar is still in use. Moon has inspired our literature, influenced our mood and psyche, and hence has been an inseparable entity of humankind through the ages. Moon has inspired emotions like romance, and even fear, through the association of the behaviour of demonic characters with Moon. Agriculture, low and high tides of sea and ocean bodies, and even the responses of the human body are tuned to the rhythm of the Moon.

The Dark Spots on the Moon

Sky-gazers, during ancient time, used to depend on whatever was observable through bare eyes, and the prominence of the dark patches on the surface of the Moon provoked their imagination. Some of them discovered the resemblence of the patches with rabbit, some with human face. The invention of the telescope in the early seventeenth century had pushed the horizon of observations dramatically; the birth of astronomy helped mankind to view things from a larger perspective. A few years ago, we celebrated the 400th anniversary of Galileo's first public presentation of his telescope. Even a few months before Galileo, on 26 July 1609, the English scholar Thomas Harriot pointed his 'Dutch trunke' at the Moon, which was an optical telescope, that helped him to prepare a sketch of the Moon.



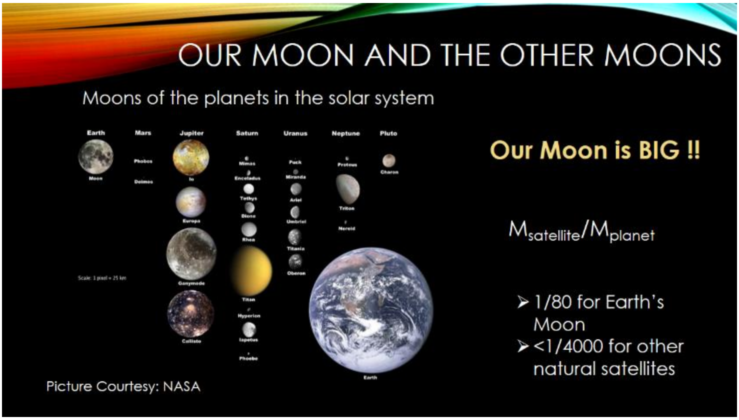
Even in those days, the Moon's surface was classified into two distinct features, the dark regions, and the relatively brighter regions. The prominent dark regions on the Moon's surface appeared smooth enough to resemble ocean surfaces. The dark regions, thus, were called 'Maria', which meant 'ocean'. Later, lunar missions equipped with instruments to study the undulations on the Moon's surface could accurately find out the heights and depths of the crests and troughs. The Maria regions were observed to be comparatively flat, while the other regions were referred to as 'highlands' because of their elevation. Thanks to the missions to Moon; today we know that the Maria or Mare regions are volcanic plains that cover ~ 17 percent of the surface of the moon.



Thanks to the missions to Moon; today we know that the 'Maria' or 'Mare' regions are volcanic plains made of a material called Basalt. In the picture, which is captured from a satellite around the Moon, you can see the clear distinction between the 'Maria' and 'highland' regions. While the highlands resemble a series of hills or mountains, the 'Maria' or the 'Mare' region looks like a water body (say, a pond) in the picture. This is due to the fact that the molten (liquid) lava of volcanic origin, which used to fill those areas during the formative days of the Moon, settled gravitationally with time, which helped them level out the big scale undulations, much like the smooth chocolate layer over your cake that was made to settle under gravity and solidify upon cooling. In this picture, a sketch of the Mount

Fuji is superimposed, in scale, on the highlands region, just to serve as a reference for the sake of comparison.

The Uniqueness of our Moon



Moon, as we know, is the only natural satellite of Earth. We use the adjective 'natural' in order to distinguish it from the 'artificial' satellites which are made by humankind to rotate around the Earth with the mandate of communication, imaging, remote sensing, and navigation, to name a few. In our solar system, we have an inventory of eight planets and one dwarf planet called Pluto. Some of the planets, as well as Pluto, have their natural satellites. In a few cases, there is more than one natural satellite for a planet. However, there is a striking fact that makes Earth's Moon distinct among the other natural satellites in the solar system. While the other natural satellites of the solar system are a few thousand times lighter than their respective central planets, Moon is only about eighty times lighter than the

Earth. So, as you can guess, the Moon is substantially massive to have significant gravitational influences on Earth, you may guess a few of them.

Major influences of the Moon on Earth

As the mass of the Moon is substantial as compared with that of the Earth, Earth and Moon have contributed mutually to their relative motion. In science, it is referred to as a two-body problem, where both the entities have substantial contributions to their collective dynamics. For the Earth-Moon system, this had a few major effects, which shaped the scenario we see today.

First, Moon is believed to have gravitationally stabilized the orbit of the Earth with respect to its wobble, which was substantial during its initial years of formation. Thus, Moon's gravitational influence has facilitated an equitable climate on Earth. Had the wobble of the Earth not been subsided by the gravitational effects of the Moon, Earth would have experienced extreme temperature conditions.

Secondly, In addition to this, the tidal effects due to the gravitation of the Moon has reduced the spin of the Earth from very fast (~ 2 to 5 hour) to the present ~24-hour period. Imagine what would have been the state of our biological clock had Earth really span this fast today. Whether we would have existed may also be debated.

Thirdly, it is believed that it was the Lunar tides brought marine life from seas, where life presumably originated, to land, which evolved into land species.

Comparison between Moon and Earth

MOON AND THE EARTH

Picture Courtesy: nineplanets.org

Moon experiences temperature extremes:
- Day side temperature: ~120 deg C
- Night side temperature: ~ -180 deg C
- Minimum temperature recorded in permanently shadowed regions: ~ -240 deg C

	Earth	Moon
Mean Radius	6371 km	1737.1 km
Mass	5.9×10^{24} kg	7.3×10^{22} kg
Mean Density	5.51 gram cm^{-3}	3.34 gram cm^{-3}
Surface gravity	9.807 m s^{-2}	1.622 m s^{-2}
Surface escape velocity	11.2 km s^{-1}	2.38 km s^{-1}
Atmospheric density	~10^{19} atoms per cc	~10^{5} atoms per cc (lunar day) ~10^{3} atoms per cc (lunar night)
Global magnetic field	YES (~40,000 nano Tesla)	NIL; patches of mini-magnetospheres are present

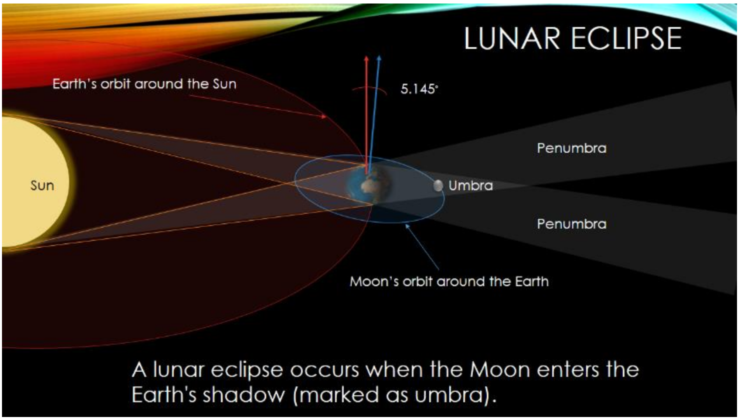
Having compared the Moon with Earth in terms of its mass, let us discuss a few more differences between the Moon and Earth. Moon is popularly known as an airless body, as it does not have a thick envelope of atmosphere surrounding it. This is practically correct when you have to rule out the possibility of landing on the Moon with a parachute (which requires sufficient buoyancy, and hence, enough air molecules to make the parachute descend slowly), but planetary scientists have quantified how much 'airless' the Moon is. While Earth has about 10^19 (i.e. nineteen zeros after one) air atoms and molecules in a volume of one cubic centimeter, Moon has only ~10^5 air atoms and molecules during its day (i.e. when the Sun shines in Moon's sky), and ~10^3 air atoms and molecules during its night (i.e. when there is no Sun in Moon's sky).

Also, on Earth, Nitrogen molecules account for about ~78% of the air atoms and molecules, while the molecular Oxygen accounts for ~ 21%, while the rest are Argon, Carbon Dioxide and other trace constituents, a proportion which is maintained day and night. As you know, atmospheric pressure has a direct proportionality with the number of air atoms and molecules in a given volume of space; the more the number of air atoms and molecules in a given volume of space, the more the atmospheric pressure is. On Moon, however, not only there is a factor-of-hundred difference in the atmospheric pressure during the lunar day and lunar night, but the composition of the air atoms and molecules also changes diurnally. The composition of the Moon's atmosphere and its variability is a matter of active research even today.

Another major difference between Earth and Moon lies in their surface temperature. We are familiar with the temperature variation on the Earth's surface. In the case of the Moon, the lunar day may experience a surface temperature of around 120 degrees Centigrade, while the lunar night side may experience a temperature of about -180 degrees Centigrade. Thus, the day-to-night side temperature difference on Moon is about 300 degrees Centigrade.

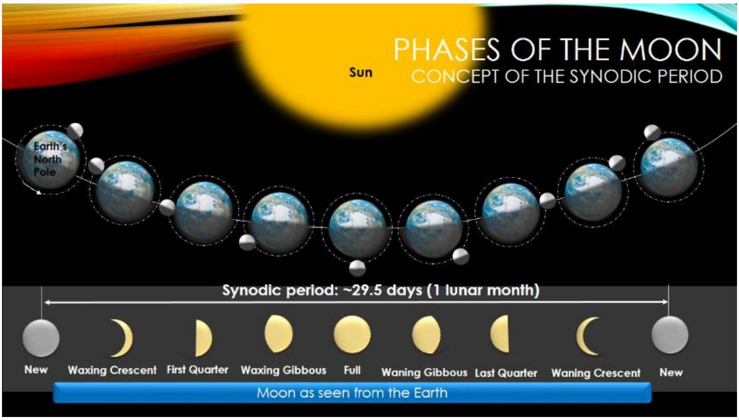
Yet another major difference between the Moon and Earth is that, while Earth has a global magnetic field (which we call the geomagnetic field), the Moon is devoid of such a global magnetic field. Instead, Moon features patches of small localized regions on its surface, typically with a feature size of a few hundreds of kilometers in diameter, which are shielded by magnetic fields, which are individually much weaker than the magnetic field of the Earth. These patches of localized magnetic fields are known as 'mini-magnetospheres'. Like the way we express length in meter, mass in kilogram, and time in second, magnetic field is often expressed in Tesla. When it comes to having a feeling of magnetic field strength, you may consider that a strong refrigerator magnet has a magnetic field of about 10 milli Tesla (milli Tesla means 0.001 Tesla). While the value of Earth's magnetic field near its surface is often approximated as ~35,000 nano Tesla (nano Tesla means 0.000000001 Tesla), the typical magnetic field of a mini-magnetosphere on the Moon is about 100 nano Tesla.

Lunar Eclipse



An interesting astronomical event, which was even noticed by ancient human beings, is the lunar eclipse. A lunar eclipse occurs when Earth's shadow falls on the Moon. A necessary condition for the lunar eclipse to take place is that, the Earth should be in between the Sun and the Moon. You may think that this condition is simple, and is met once in every month, and hence the lunar eclipse should be a monthly affair. However, that does not happen in every month because there is another condition needs to be fulfilled. The condition is that the Sun, Earth, and he Moon need to be perfectly aligned so that the shadow of the Earth is cast on the Moon. This perfect alignment does not happen every month since the Earth's orbit around the Sun is not in the same plane as the Moon's orbit around the Earth. The Earth's orbit around the Sun, which is also called the 'ecliptic', is tilted with respect to the orbit of the Moon around the Earth, by an angle of ~5.145 degree.

Phases of the Moon: The Concept of Synodic Period



While the occurrence of a lunar eclipse is a matter of satisfying a set of conditions, the transformation of the appearance of the Moon through its different phases is a relatively common spectacle.

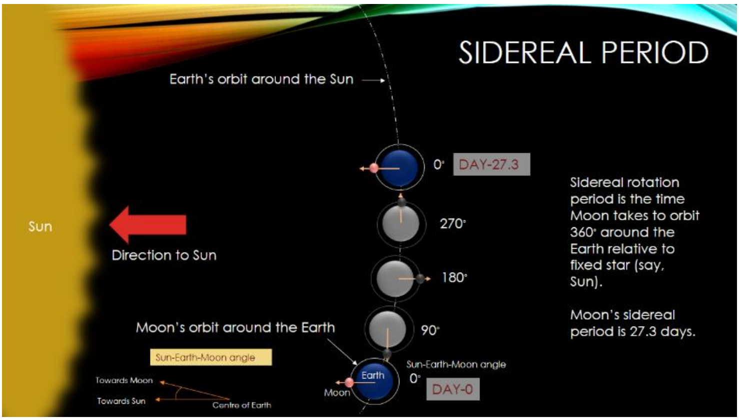
Like the Earth experiences day and night, the Moon also has a day side and a night side, as the Sun always illuminates half of the Moon while the other half remains dark. However, not necessarily we can see, from Earth, the illuminated side of the Moon completely. The fraction of the illuminated side of the Moon visible to us changes as the Moon travels through its orbit around the Earth, which gives rise to the lunar phases.

To understand the different phases of the Moon, it is important to appreciate that while the Earth rotates around the Sun, the Moon rotates around the Earth. All that matters in determining the phase of the Moon visible from Earth is the Sun-Moon-Observer (on Earth) angle, which is also called the phase angle. This picture demonstrates the occurrence of different phases of the Moon.

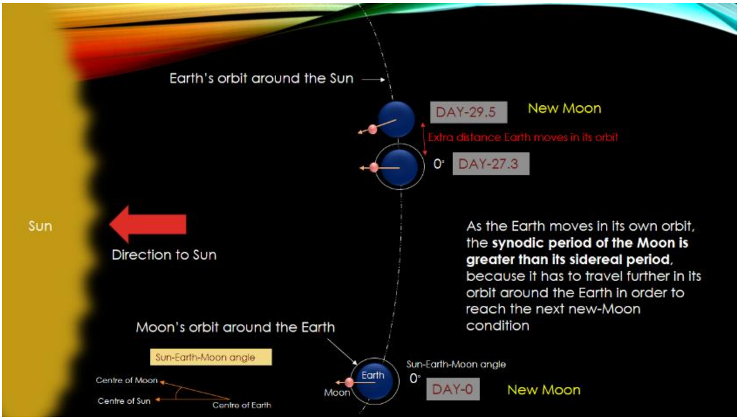
If you observe the Earth down from the sky above its North Pole, the Moon's orbit will look face-on to you, and the Moon will be seen rotating anti-clockwise around the Earth along its orbit. In this picture, I have shown nine positions of the Moon around the Earth's orbit. In all these nine positions, the phase angle is different. In the bottom panel, I have shown the corresponding phases of the Moon. On the left-most side, the new Moon is seen. During the New Moon phase, the entire lunar surface seen from the Earth is in darkness. Thereafter, it progresses through different phases named as Waxing Crescent, first quarter, Waxing Gibbous, Full Moon, Waning Gibbous, last quarter, Waning Crescent, till the next New Moon phase arrives. The adjective 'Waxing' is used to indicate that we are progressing toward the Full Moon phase, while the adjective 'Waning' indicates the progress toward the New Moon.

The time elapsed between two subsequent new Moons (which is also the same time between subsequent full Moons) is known as the Synodic period, which is also known as a lunar month, amounting to 29.5 days.

Motion of Earth and Moon Relative to the Sun: The Concept of Sidereal Period



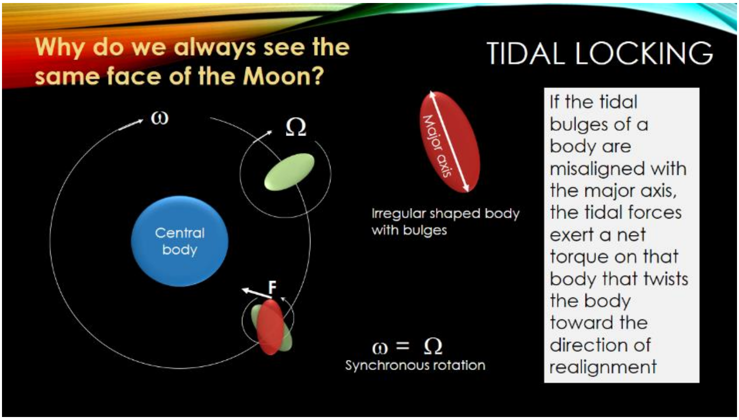
Apart from the Synodic period, Moon's motion with respect to the Sun and Earth gives rise to the concept of the Sidereal period. The sidereal rotation period is the time Moon takes to orbit 360◦ around the Earth relative to a fixed star (say, Sun). Moon's sidereal period is 27.3 days. However, the completion of one sidereal period by the Moon does not ensure the repetition of its phase (i.e. one New Moon to another New Moon). The Moon has to spend almost 2 Earth days of extra time in its orbit to catch up with the completion of its phase cycle. This happens because while the Moon completes one sidereal rotation, the Earth also advances in its orbit around the Sun, and it calls for that extra movement of the Moon along its orbit around the Earth in order to achieve the necessary phase angle to complete the phase cycle.



To summarise, as the Earth moves in its own orbit, the synodic period of the Moon is greater than its sidereal period because it has to travel further in its orbit around the Earth in order to reach the next new-Moon condition.

Tidal Locking

Having discussed about the lunar phases, let us now turn our attention to the fact that we see only one side of the Moon from Earth. This may lead to an impression that the Moon doesn't spin at all. Of course, it is not the case, and we will spend some time to understand the reason behind this.



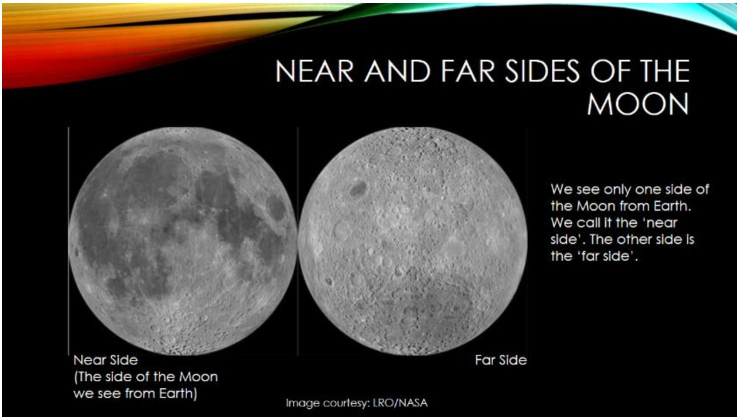
As you know, like Earth, the Moon also spins about its own axis. The major difference is that the spin rate of the Moon is much slower than that of the Earth; one lunar day is equivalent to approximately 14 Earth days. The point to be noted is that, the spin rate of the Moon about its own axis is such that it always shows a particular side to the Earth, which may be identified with the familiar pattern of the dark patches of the Mare regions, although it may be seen in different orientations depending on the latitude on the Earth from where the Moon is being observed.

It may be noted that due to the gravitational attraction between two bodies, there may be deformation in the geometric shape of both of them, leading to two bulges on opposite sides of each body. These bulges are referred to as 'tidal bulges'. The front side tidal bulge is caused due to the gravitational attraction, while the rear side tidal bulge is caused by the inertial effect that opposes the gravitation-induced displacement of the fluid.

If the tidal bulges of a body are misaligned with the major axis, the tidal forces tend to twist the body toward the direction of realignment. As this process continues, it results into a synchronism between the spin and orbital rotation frequencies.

That is why we end up seeing the same face of the Moon from Earth.

Nearside and Farside of the Moon



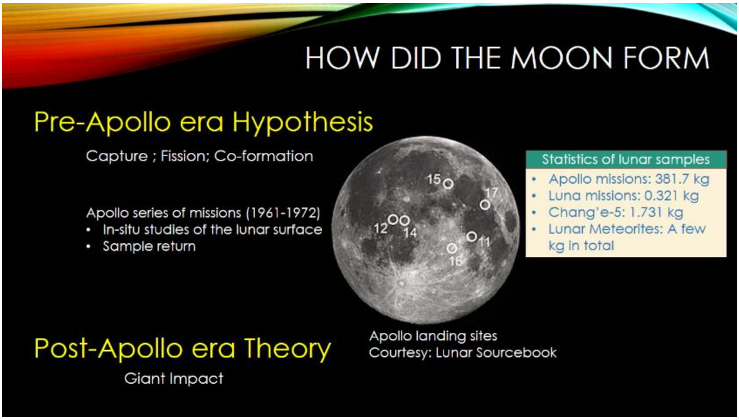
As the spin and orbital rotation rates of the Moon are equal, from the Earth we see only a particular side of the Moon, referred to as the 'Nearside'. The other side, which is not visible from the Earth, is referred to as the 'Farside'. Note that, as the Moon spins about its own axis, both the near and far sides of the Moon experience day and night.

With the progress of technology, humankind is getting more dependent on radiowave communication. May it be satellite communication, radiowave broadcast from mobile phone towers, or emission of radiowaves from electromagnetic devices, humankind is responsible for more and more emission of radiowaves, a part of which is propagated to space. These human-generated radiowaves often interfere with scientific observations of space, which need environments that are free from human-generated radiowaves. At this juncture, it is pertinent to mention that the farside of the Moon, as it always faces away from the Earth, is devoid of the human-generated radiowave interference. Certain astronomical observations in radio frequency wavelengths, that otherwise get contaminated with the human-generated radiowaves, can be conducted from the lunar farside. Scientists, therefore, find enormous potential to set up scientific observatories in the farside of the Moon.

Birth of the Moon

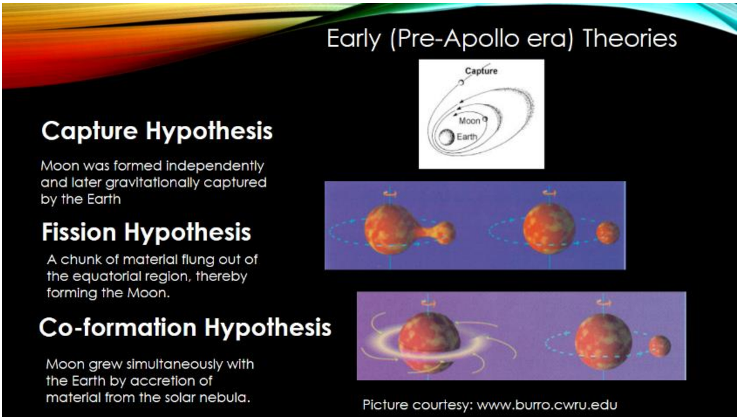
So far, we have discussed the observable attributes of the Moon. As our discussion progresses, we will take it forward towards an overall scientific understanding of the Moon. In this journey, the first aspect we are going to discuss is the formation of the Moon.

The scientific inquisition of humankind probed to answer one of the most fundamental questions of the solar system science, i.e. how was our Moon born? Initially, there were three hypotheses, viz. (i) Capture hypothesis, (ii) Fission hypothesis, and (iii) Co-formation hypothesis. These three hypotheses proposed three completely different possibilities about the formation of the Moon. We will briefly discuss what those hypotheses were all about, and why there were inconsistencies in them. At this juncture, let me tell you that all the three hypotheses had to be discarded once the lunar samples were made available on Earth, for laboratory analyses.



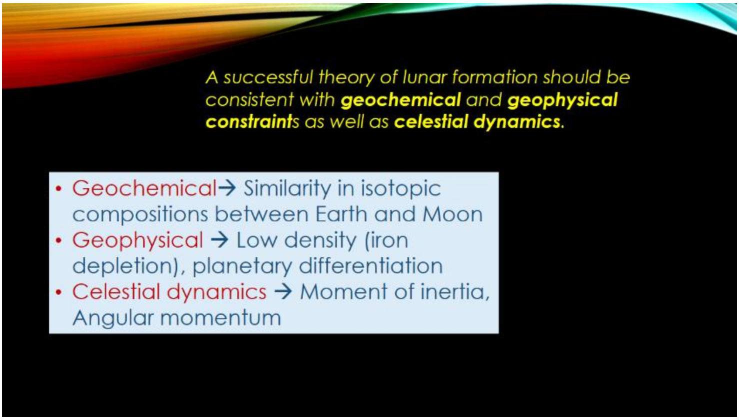
As you are aware, the period 1961 to 1972 was an important era in the history of lunar exploration, as the National Aeronautics and Space Administration (NASA), United States of America, sent the Apollo series of missions to the Moon. A few of the Apollo missions could return lunar rock samples back to the Earth for laboratory analyses. The Apollo missions, altogether, brought back 381.7 kg of lunar samples to the Earth. The Soviet Luna missions have also brought back 0.321 kg of lunar samples. The laboratory analysis of the lunar samples provided insight into their geophysical and geochemical properties.

Before discussing the presently accepted theory on the formation of the Moon, it is important to briefly discuss the three hypotheses which were predominating during the pre-Apollo era.



The capture hypothesis suggested that the Moon was formed independently, and later gravitationally captured by the Earth. The fission hypothesis, on the other hand, suggested that the rapidly spinning Earth became rotationally unstable while it was still molten, and thus a chunk of material flung out of the equatorial region, thereby forming the Moon. The third hypothesis, known as the Co-formation hypothesis, suggested that Earth and Moon formed and grew simultaneously by accreting materials from the early solar system.

All these three hypotheses had some problem or the other. The problem with the capture hypothesis was that, had it been a case of capture of the Moon by the Earth, the latter would have been captured in a bigger orbit. It also did not explain the lesser density of the Moon than the Earth, as well as the iron depletion in the Moon. The fission hypothesis also had a problem in substantiating that the Earth-Moon system really had sufficient angular momentum to fling out a chunk of material from Earth against the viscosity. The co-formation hypothesis could not explain the isotopic ratio similarities with Earth, iron depletion in Moon, and the Earth-Moon angular momentum.



Thus, all these hypotheses were discarded based on the laboratory analyses of the lunar samples.

Thus, it was understood that the theory of the formation of the Moon should be consistent with the geochemistry, geophysics, consistent with the properties of the returned samples, as well as celestial dynamics. It is easy to guess what we mean by celestial dynamics; what we mean is that a successful theory of the lunar formation has to be consistent with the presently accepted value of the angular momentum of the Earth-Moon system. It also has to be consistent with the dynamics of molten and semi-molten bodies, and the tidal effects acting on both Earth and the Moon. I will spend some time explaining what insight the geophysical and geochemical analyses of the lunar samples provided.

The analysis of the Geophysical properties of the lunar samples gave rise to the understanding of their densities ('density', defined as 'mass per unit volume' in Physics, refers to how heavy a given volume of material is; for example, one cubic centimeter of iron is heavier than the same volume of wood, and hence the density of iron is greater than that of wood). This, in turn, provided inputs to the theories that suggested that Moon is a 'differentiated planetary body'.

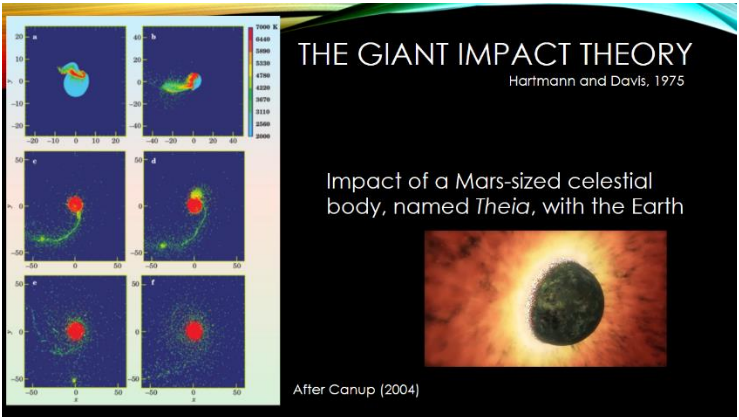
What is a 'differentiated planetary body'? A differentiated planetary body is one where there has been a process of natural sorting of its building materials (while still in molten form) with respect to their relative densities; i.e. the denser materials sank down due to gravitational pull towards the centre of the body, while the lesser dense materials floated up thereby forming the upper surface of the body.

While the geophysicists were busy analyzing the physical properties of the lunar samples, the geochemists were concentrating on their chemical composition. The geochemical analyses of the lunar samples provided inputs on what is called the 'isotopic compositions' of certain elements within it. Here, we will spend some time understanding what are isotopes, what is meant by isotopic composition, and how are they important.

What are isotopes? As you know, an atom comprises a nucleus at its centre, with negatively charged electrons revolving around it. The nucleus comprises positively charged protons and neutrons (which are electrically neutral). The identity of an atom depends solely on the number of protons in its nucleus, which also attributes an 'atomic number' to the element. . As for example, an Argon-40 atom consists of 18 protons and 22 neutrons in its nucleus (22 plus 18 makes 40, and hence the name Argon-40), and thus, its atomic number is 18. If two atoms differ only by the number of neutrons they contain, they are called isotopes. For example, Argon-36 contains 18 protons and 18 neutrons in its nucleus. In both cases, the Argon atoms contain 18 protons, which define its identity as an Argon atom, with atomic number 18. What makes them different is their number of neutrons. Hence, Argon-40 and Argon-36 both belong to the Argon family, but they are isotopes of each other.

The next question is what isotopic ratio is, and how are they important in space sciences? In nature, the isotopes of any element are available in a certain proportion. The ratio of abundances of one isotope to the other is called the isotope ratio. Let us cite an example. In the stream of atoms originating from the Sun, the ratio between the two isotopes i.e. Argon-40-to-Argon-36 ratio (called the isotopic ratio of Argon 40 to 36) is about 10-4. On Earth, this ratio is about 285, much higher than the solar value. Thus, the difference in the isotopic ratio of Argon-40 and 36 suggests that there must have been some event responsible on Earth, which is not happening in the Sun. It is attributed to the radioactive processes within the Earth that make the Aron-40 to 36 ratio higher than the solar value. Argon is merely an example, in nature, several atoms have their isotopes, and the isotopic ratios suggest fascinating scientific facts about the planetary bodies. Geochemists analysed the lunar samples in their laboratories and studied the isotopic ratios of certain elements, and compared these ratios as observed on Earth. They were surprised to observe striking similarities in certain isotopic ratios that are found both in Earth and the lunar samples.

The Giant Impact Theory



Next, we will discuss how all these conditions were made to fulfil in shaping up an acceptable theory of the formation of the Moon. To do that, we have to spend some time on the discussion about the initial era of the solar system.

The solar system is believed to have experienced chaotic dynamics of colliding debris during its initial days of formation. Impacts between the celestial bodies and the left-over materials in the solar system were common. Based on geophysical and geochemical evidences as we have discussed, it is believed that about 4.5 Gy (Billion years) ago, while the Earth was still in its molten form, it was impacted by a Mars-sized rock, often referred to as Theia, and a part of the proto-Earth was ripped off. As a result of the impact, the metallic cores of both the bodies coalesced in the Earth while the materials ejected out of the impact were gravitationally bound to the Earth. Accretion of these impact-generated fragments formed the proto-Moon (say, the early form of the Moon), rotating around the Earth. This is known as the giant impact hypothesis on the origin of the Moon.

Evolution of the Moon

Moon has undergone significant evolution since its formation, and no known form of life was present on Earth to have witnessed its dramatic transformations. Not only the bulk of the Moon has undergone evolution, but its atmosphere, as well as the orbit around the Earth have also significantly evolved. Here, we will discuss all the three evolutionary aspects of the Moon.

Evolution of the Bulk Moon

The giant impact hypothesis suggests that the Moon was completely or at least partially molten in its early formation stage, which was known as the Lunar Magma Ocean (LMO). You may visualise the LMO as a molten sphere of lava, radiating out its heat to space. During the process of losing the heat, and subsequent solidification of the molten magma, the low-density materials (aluminum-rich plagioclase rock anorthosite) buoyantly floated up, while the heavier material sunk beneath. This process is called 'differentiation'.

Thus, the upper crust of the Moon became rich in lighter minerals, like plagioclase feldspar (CaAl2Si2O8), while the deeper part of the crust and the mantle are rich in heavier minerals, like (Mg, Fe)SiO3 (pyroxene) and (Mg, Fe)2SiO4 (olivine). It is suggested that in the first ~ 1000 years of the formation of the Moon, about 80% (by volume) of the LMO was solidified, with the process of complete solidification of the magma had been gradual that taking another few tens of millions of years.

As the top surface of the molten Moon started solidifying first, its density increased, which lead to an 'overturn', i.e. the solidified outer part sank below while the lighter molten region rose up in level. This process is known as 'mantle overturn'.

As a result, much of the iron- and titanium-bearing material sank to greater depth with a possible exception of some titanium-bearing materials, which did not participate in the process of overturning, During the gradual solidification of the molten magma, different minerals are believed to have crystallized in a sequence, within the magma, determined by the chemical composition and pressure. Last in the sequence of crystallization were Potassium (K), Rare Earth Elements (REE), and Phosphorus (P), collectively known as KREEP, which became progressively abundant in the magma as the crystallization process continued.

During that era, impacts on the planets by the solar system debris were common. Such impacts created the big basins (such as Imbrium, Crisium, Serenitatis, etc.) with upturned rims on the Moon. The lunar samples returned by Apollo provided the timing of the basin formation, which dated back to the Late Heavy Bombardment (LHB), about 3.8 to 4 Gy ago. Many of the impacts created fissures (cracks) on the lunar surface, through which hot mantle material rose to the surface of the Moon. The impact basins were filled with molten lava, which crystallized to form the basalt rock. The composition of the basalt rock varied since they were a result of the magma from different depths of the lunar interior. Basalts are dark, fine-grained volcanic rocks, and they formed the large, smooth, and dark regions visible on the lunar surface, known as lunar Maria.

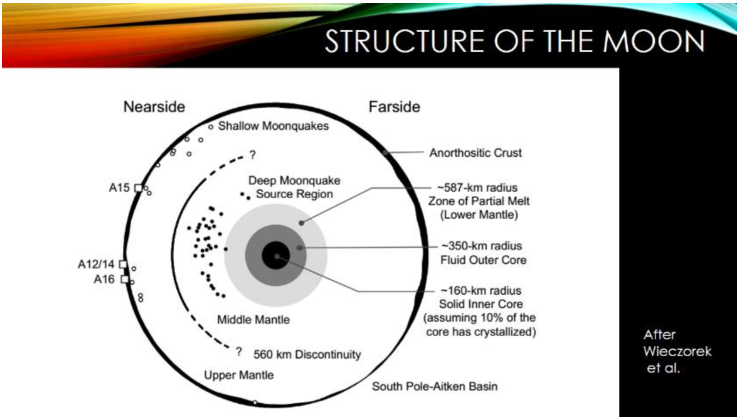
As you can guess, the evolution of a celestial body requires energy. Any evolution process is dramatic in the beginning, and slows down with time. When it slows down, a question that naturally emerges is that, whether the celestial body is still active?

Some of you might have heard about the ‘activity’ of a planetary body. ‘Activity’ refers to any form of manifestation of its internal energy, which may be in the form of a volcanic eruption, causing its resurfacing, or quakes. As you may guess, the evolution of any celestial body greatly depends on its internal energy. As we have discussed the process of evolution of the bulk Moon, a question that arises naturally is that, whether Moon has stopped evolving? Chandrayaan-1 mission has revealed that there is evidence of recent volcanism on the Moon, which happened in the past 100 million years. Yes, 100 million years is categorized as 'recent' in the geological scale, where we speak of billions of years of timescale.

The activity of the Moon, in turn, helped to have an idea on its international structure. Signatures of lunar volcanic eruptions, seismic waves, resurfacing, gravitational anomalies, all of them speak about the structure of the Moon.

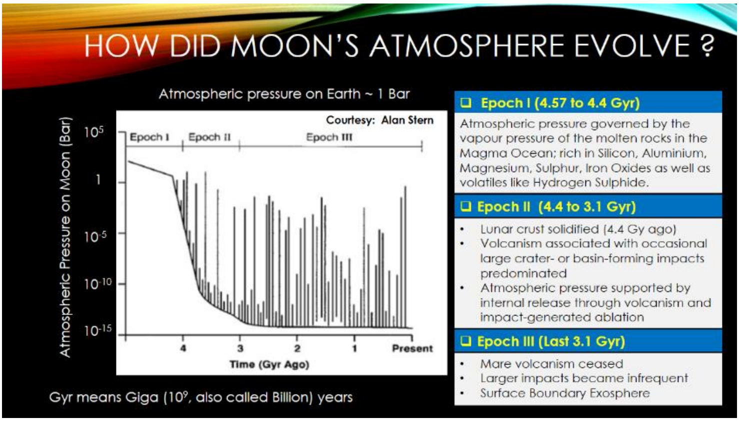
Presently, after integrating all these kinds of scientific information, we have come to an understanding of the structure of the Moon. Thanks to the several space missions that have provided valuable inputs which helped arrive at the present model of the structure of the Moon.

This picture presents a schematic diagram of the internal structure of the Moon as per our current understanding. Moon has a solid inner core, which might have a radius of about 160 km; how much of it has been crystallized is yet to be known. Over the solid inner core, there is a fluid outer core which is believed to be extended up to ~ 350 km. The zone of partial melt, or the lower mantle, extends up to the radius of ~587 km. Over that, there is a zone of mantle; and over the mantle, there lies the crust of the Moon, which is about 40 to 60 km in thickness.



At this juncture, I would like to draw your attention to a few features that are evident from this picture. First, the lunar crust has variations in thickness that are the result of impact cratering events. Secondly, the existence of a seismic discontinuity at a depth of ~560 km is known from the seismic wave observations during the Apollo missions. Geologically, seismic discontinuities are the regions where seismic waves behave differently compared to the surrounding regions due to difference in physical or chemical properties. Thirdly, you may notice the spatial distribution of the deep and shallow moonquakes. The model also suggests the existence of a partially molten region beneath a depth of about 1150 km, and the existence of a molten outer core with a radius of ~350 km. Assuming that the liquid core is partially crystallized, a solid inner core is also likely to be present. This picture assumes an arbitrary core crystallization of 10% by volume, which suggests an inner core radius of about 260 km. It is likely that the 560-km seismic discontinuity is a global feature of the Moon; however, that cannot be confirmed until we have more systematic measurements of the seismic waves covering more area of the far and near sides of the lunar surface.

Evolution of Moon's Atmosphere



Not only had the bulk Moon had undergone an evolution, the lunar atmosphere also evolved dramatically since the formation of the Moon. Today when we say 'Moon does not have an atmosphere', we mean that Moon is an airless body that has no envelope of air atoms and molecules surrounding it. During the initial days of the Moon, the situation was otherwise; the early Moon featured an atmosphere that was a few hundred times thicker than that on Earth today.

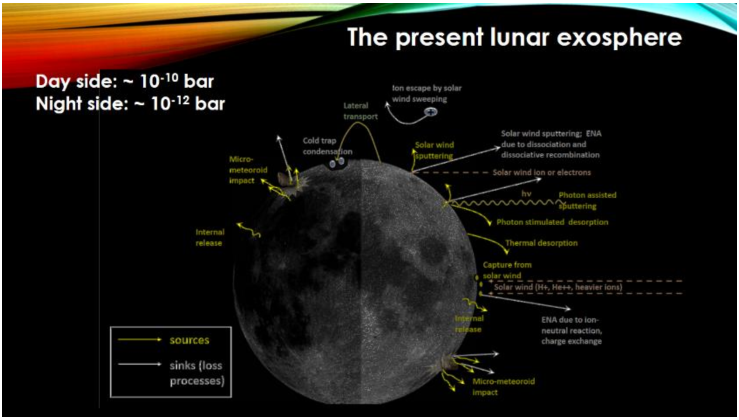
During the period 4.57 to 4.4 Giga years ago (from today), which we call epoch-I while discussing the evolution of the Moon's atmosphere, the atmospheric pressure on the Moon was governed by the abundance of the atoms and molecules that evaporated from the molten rocks in the Magma Ocean. The early lunar atmosphere, therefore, was rich in Silicon, Aluminium, Magnesium, Sulphur, Iron Oxides as well as volatiles like Hydrogen Sulphide.

Subsequently, about 4.4 Giga years ago, the lunar crust solidified. That was the epoch-II, which was from 4.4 to 3.1 Giga years ago. During that time, the Moon experienced frequent volcanism as well as occasional large crater- or basin-forming impacts. In the picture, the spikes represent the enhancement of the atmospheric pressure because of the impacts. Thus, during epoch-II, the lunar atmospheric pressure was supported by internal release through volcanism and impact-generated ablation.

The last 3.1 Giga years (till today) are referred to as the epoch-III in the evolution of the lunar atmosphere. During that time, the Mare volcanism ceased, the larger impacts became infrequent, and hence, there were no significant sources of the lunar atmosphere, as were present during the first two epochs. This, the Moon is left as an airless body.

Let us get to the quantitative aspects of the matter. Currently, the Moon is known to have what is known as a 'surface boundary exosphere'. In any planetary atmosphere, the uppermost part has a very smaller number of atoms and molecules. As a result, the atoms and molecules rarely undergo collisions among themselves.

Such a condition of rarefied atmosphere is called 'exosphere'. While in the case of Earth, the exosphere begins at an altitude of ~550 km, in Moon the exospheric condition starts right from its surface. Hence, the term 'surface boundary exosphere', which means that Moon has an exosphere which is bounded by its surface on one side.



The lunar neutral exosphere is a result of a dynamic equilibrium between several sources and sink processes. The term 'dynamic equilibrium' means that the source and sink processes both are active but they balance the effect of one another.

The 'source' processes are the ones that are responsible to contribute atoms and molecules to the Moon's atmosphere. The 'sink' processes are the ones that are responsible for the loss of the atoms and molecules from the lunar atmosphere, as well as their trapping so that they no longer contribute to the lunar atmosphere. The major source processes that contribute to the lunar atmosphere are solar wind capture (some of the ions emanated from the Sun are captured by the Moon, subsequently neutralized), thermal desorption (the process of sublimation of the atoms from the uppermost layer of the lunar surface), photon-stimulated desorption (desorption that is stimulated by the photons from Sun), Internal release (atoms that are released from Moon's interior due to volcanism or seepage through cracks), Impact vapourization (vapourization of the meteorites as well as the lunar surface material after an impact), and sputtering (the process of ejection of a species from a lattice site in the upper few monolayers of a surface, due to the injection of a discrete impulse of energy).

The major sink processes of the lunar exosphere are thermal escape (which occurs when the thermal energy of an atom exceeds the gravitational binding energy; it is applicable for Hydrogen and, to a certain extent, Helium in the Moon's atmosphere), ionization loss (neutral atoms are ionized by striping off of outer electron(s), or attachment of a positive charge with a neutral, and subsequent loss to the space due to the influence of the fields associated with the solar wind) and condensation (trapping of the atoms in a condensed form, thereby not allowing them to be in a gaseous state).

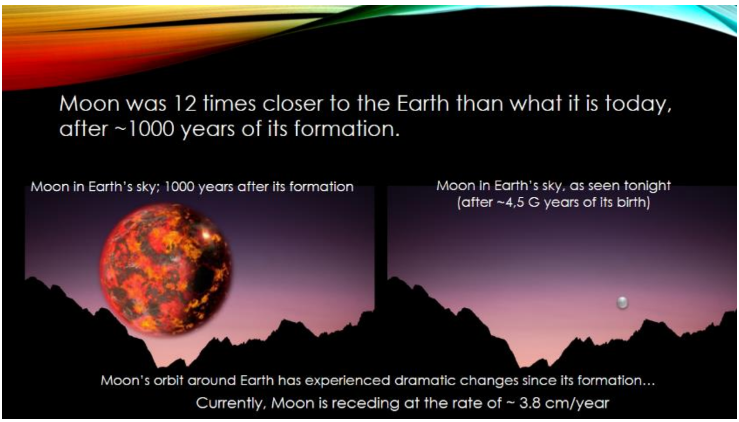
As a result of these processes, Moon's dayside has around 10^5 atoms per cubic centimeter, while the nightside has 10^3 of them.

Evolution of the Moon's Orbit

While speaking about the evolution of the Moon, we have, so far, spoken about the gradual transformation of the bulk Moon from a molten ball of lava to a solid celestial object, and the transformation of the dense lunar atmosphere to a tenuous surface boundary exosphere.

You will be surprised to know that the orbit of the Moon around the Earth also has undergone a dramatic transformation. Would you believe if I tell you that there was a time when the Moon used to appear twelve times larger than what is appears today from the Earth. But, nobody was there on Earth to have witnessed such a spectacular view of the Moon.

This is because, the first cellular forms of life appeared on Earth about 2000 million years ago. The unicellular organisms became multi-cellular life forms in the course of evolution, and by the time of 500 million years, invertebrates were there on Earth. Homo sapiens on Earth came about 0.2 million years ago. But that giant Moon what we are referring to was there about 4.5 Billion years ago, almost after 1000 years of the formation of the Moon. Obviously, there was nobody who witnessed the giant Moon in the Earth's sky.



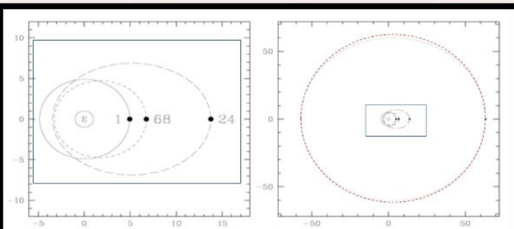
Then the question that arises is that, how did we know about such a transformation? Thanks to the computer simulation techniques, which helped simulating the celestial dynamics of the Earth, Moon and the Sun, and arrived into these results.

Just imagine, how spectacular it had been. Remember that after 1000 years of its formation, the Moon was not a completely solidified object; rather, it was a spherical molten bulk of lava. In this picture, I have attempted to visualize how the Moon would have appeared in the night sky of the Earth after 1000 years of its formation. For the sake of comparison of the sizes, I have shown a picture of the present night sky in the right-hand side. Today, the Moon is about 3.8 lakhs of kilometers away from the Earth; whereas, after 1000 years of its formation, the Moon was about 31 thousand kilometers away from the centre of the Earth, i.e. at about 24.8 thousand kilometer altitude from the Earth's surface. It may be interesting to note at this juncture that the geostationary satellites we send today are placed at about 36 thousands of kilometers above the Earth. Thus, the altitudes of the Moon after 1000 years of its formation, and that of the orbits of geostationary satellites are comparable!

You will be further surprised to note that the journey of the Moon from 25 thousand kilometer distance to 4 lakh kilometer distance from the Earth has not happened monotonically. It means that sometimes the Moon was closer to the Earth, and sometimes at far. Today's orbit of the Moon around the Earth is almost circular.

Many-a-times, during the evolutionary journey of 4.5 billion years, the orbit of the Moon has been elliptical. As you know, an ellipse is a geometrical figure with eccentricity greater than, but lesser than 1. Circle has an eccentricity of zero, while as the eccentricity approaches one, the circle becomes more and more elongated (i.e. more elliptical). In the next picture, I will present a table that would show how did the eccentricity of the Moon's orbit, as well as the semi-major axis varied over time.

Time after formation of the Moon (years)	Eccentricity (more eccentricity, more elliptical)	Semi-major axis (in terms of Earth radii)	Orbital period (hours)
1,000	0.01	4.9	15.2 (0.63 day)
24,000	0.60	8.6	35.3 (1.47 days)
68,000	0.35	5	15.7 (0.65 day)
4.5 billion	0.05	60.3	655.7 (27.3 days)



After Emil Noordeh and Patrick Hall and Matija Cuk, 2012

Left: Evolution of Moon's orbit after 1k, 24k and 68k years; Right: Moon's orbit today in dotted line

A thousand years after the formation of the Moon, the semi-major axis of the ellipse of the Moon's orbit was 4. times the Earth's radius (Earth's radius can be approximated as 6360 km for quick calculations). After twenty-four thousand years, the orbit became more elliptical, while the semi-major axis became 8.6 times the Earth's radius. After sixty-eight thousand years, the ellipticity of the orbit reduced a bit, still, it did not become a circle, and the semi-major axis became 5 times the Earth's radius. Today, the eccentricity of the Moon's orbit is about 0.05, close to zero, and the orbit is nearly circular.

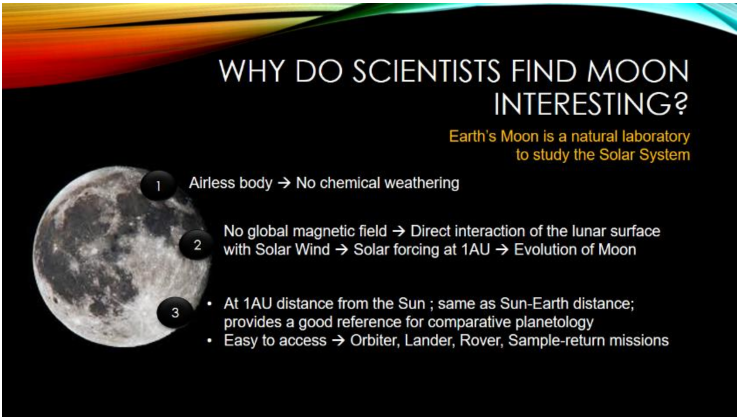
You will also be surprised to note that the orbital period of the Moon has varied a lot during the process of evolution. From a fast-rotating object with an orbital period of 0.63 Earth-day, it now has a period of 27.3 Earth days. In between, the tidal locking process has taken place, as we have discussed sometime back.

This entire dramatic evolution of the Moon's orbit has been attributed to a process, which is known as 'evection resonance', a process, where the Sun, Moon, and Earth, three of them collectively contributed to their dynamics. The physics of evection resonance is beyond the scope of this present deliberation; interested people may refer to the literature mentioned in this picture.

Why do Scientists Find Moon Interesting?

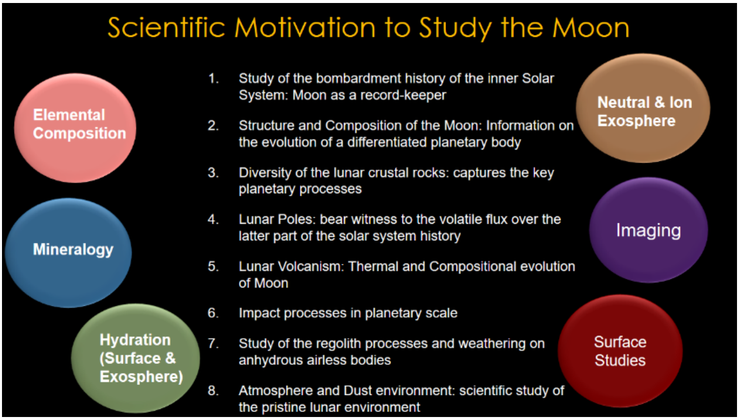
The Moon, today, presents enormous scientific potential for the humankind.

Today, scientists have identified the Moon as the record-keeper of the solar system, and hence, the celestial body that can provide clues on the early solar system (thereby enabling us to understand the evolution of the solar system). Being an airless, non-magnetic celestial body, the Moon is also a natural laboratory that can be used to study the interaction of the solar wind and fields with the planetary surfaces. Being at the same Sun-Earth distance, it also provides a good reference for studying the effects of the Sun at 1 AU (Astronomical Unit) distance. To add to these advantages, Moon is amenable to the orbiter, lander/rover, and even sample return missions. To sum up, Moon provides the scientific community an opportunity to under the inner solar system; both in terms of its evolution and its present status.



Coming to the aspect of using the Moon as a proxy to understand several aspects of the solar system, we will briefly present an overview of the scientific questions that may be addressed once the Moon is studied extensively.

As Moon is considered the record-keeper of the solar system, it can be used to study of the bombardment history of the inner Solar System. The structure and composition of the Moon provide information on the evolution of the differentiated planetary bodies of the solar system. Moon also provides insight on the diversity of the lunar crustal rocks. Also, the lunar poles are the witness to the volatile flux over the latter part of the solar system history. Study of the lunar volcanism provides clues on the thermal and compositional evolution of Moon. The study of the craters on the lunar surface offers opportunity to understand the impact processes in planetary scale. Moon also provides opportunities for the study of the regolith processes . The list is not complete, and the Moon is the single celestial body that may offer the scientific community a plethora of valuable information on the origin and evolution of the solar system.



Quite intuitively, these motivations have inspired several missions to explore the Moon. The missions have collectively studied the aspects of atmosphere and ion studies, lunar surface chemistry, chemical mapping, lunar dust analysis, lunar geophysics, meteoroid studies, radiation environment studies, soil mechanics studies, solar wind studies, to name a few.

Successful Missions to Moon

If you carefully follow the types of the space exploration missions flown by the humankind, you will see that they fall under different categories based on the exploration platforms, like orbiter missions (where we send orbiters around the celestial bodies of interest), lander missions (where we make the scientific instruments, mounted on a lander module, to land on the surface of the celestial body), rover missions (where the scientific instruments are mounted on automobiles that are made to move on the surface of the celestial body), and flyby missions (where the spacecraft passes by a celestial body for observation, while it is *en route* to study some other celestial body of prime interest).

The first lunar mission was a flyby mission named Luna-1, which was sent in 1959 by the then USSR. That was the time when two powerful space forces were competing to send missions to the Moon, i.e. Russia and America. The entire decade of the 1960s was full of lunar expeditions by these two countries. While Russia had its Luna and Zond series of lunar expeditions, America had its Ranger series.

In the decade of the 1960s, Russia had two more feats in its credit, i.e. achieving the first lunar lander mission in 1966, which was Luna-9, as well as placing the first orbiter around the Moon, which was Luna-10, in the same year.

The series of lunar explorations continued. The first flight of the Surveyor lunar lander series of the US was sent in 1966. There was, as US initiative, the Lunar Orbiter series of orbiter missions as well. The Surveyor and the Lunar Orbiter series from the US, and the Luna and Zond series from Russia went on exploring the Moon.

The US had a remarkable feat in the lunar exploration when it accomplished the first crewed orbiter mission Apollo-8 to Moon in 1968. Apollo-10 followed soon after that, in 1969. On 20 July, 1969. the first lunar lander landed on Moon with crews onboard. It was the historic Apollo-11 mission. In order to commemorate that great event in human history, the United Nations have announced 20 July as International Moon Day (IMD).

The history of lunar exploration noted another remarkable feat in 1970, when the Russian Luna-16 mission returned lunar samples. It was followed by another dramatic feat when the US demonstrated the first crewed rover on the lunar surface in 1971, during the Apollo-15 mission.

In 1990, lunar explorations were resumed, this time by Japan, through its Hiten flyby/orbiter mission. That was, in fact, the first intervention from any Asian country in lunar exploration.

In the second phase of the lunar exploration, which started in 1990s, Asian countries like Japan, China and India contributed significantly. China sent its first mission to Moon Chang'e-1 (pronounced as Chan-gey-1), which was an orbiter mission. The first mission to Moon sent by India was Chandrayaan-1, which carried an orbiter and an Impactor, called the 'Moon Impact Probe'. It may be noted that the Moon Impact Probe was the first human-made object from Asia to have been sent to the lunar surface for scientific studies.

In last one-decade, lunar missions have studied the Moon extensively with respect to its surface, exosphere, as well as its internal structure through gravity anomaly measurements. India's Chandrayaan-2 mission was flown in 2019. Although the lander did not succeed to complete its mission, the orbiter is actively studying the Moon. The Chang'e-5 mission sent by China has been successful to return lunar samples.

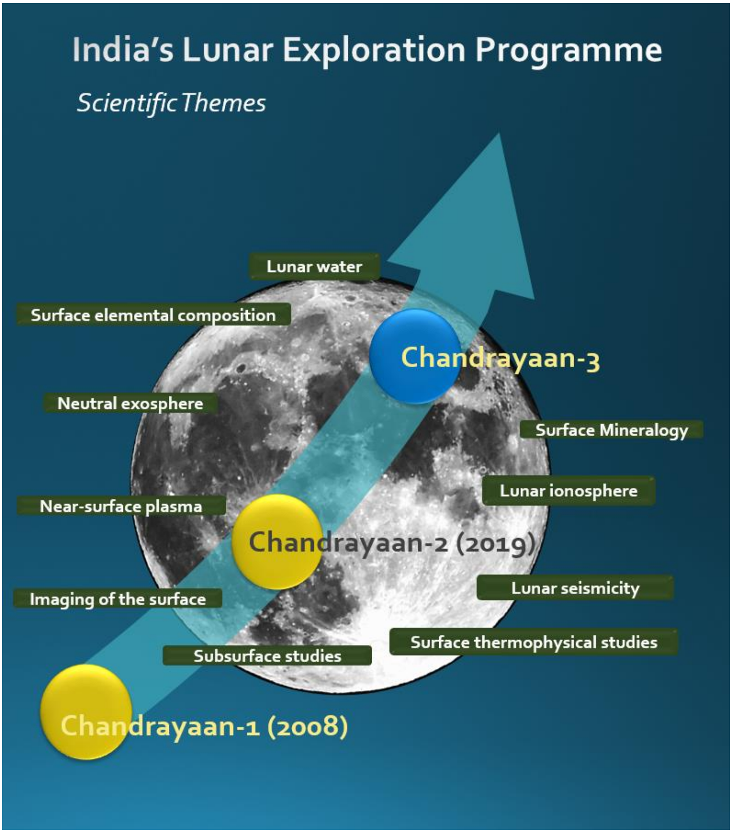
Presently (2022), the missions that are active to study the Moon are the Lunar Reconnaissance Orbiter (LRO) of US, Chandrayaan-2 orbiter of India, and the Chang'e-4 lander plus Yutu-2 rover of China.

India's Missions to Moon

Indian Lunar Exploration Programme

Indian lunar exploration proramme started with the Chandrayaan-1 mission in 2008. The Chandrayaan-1 mission had an orbiter to map the surface topography, mineral, and elemental distribution, study volatiles, and search for surface and sub-surface water-ice signatures. The Moon Impact Probe (MIP), which is a piggyback module onboard Chandrayaan-1, was released from the Chandrayaan-1 orbiter to impact the South Polar Region. Despite its short lifespan of just under a year, Chandrayaan-1 emerged as a successful mission with several discoveries to its credit.

With the remarkable success of Chandrayaan-1, a more complete follow-up mission was configured. Chandrayaan-2 was designed with an orbiter, lander and a rover to pursue global lunar mapping and initiate in-situ studies in and around the landing site. The hard landing of the lander prevented us from pursuing in-situ science, however, the Orbiter is still active with its scientific payloads onboard, which are conducting remote sensing observations of the lunar surface, as well as in-situ observations of the lunar exosphere.

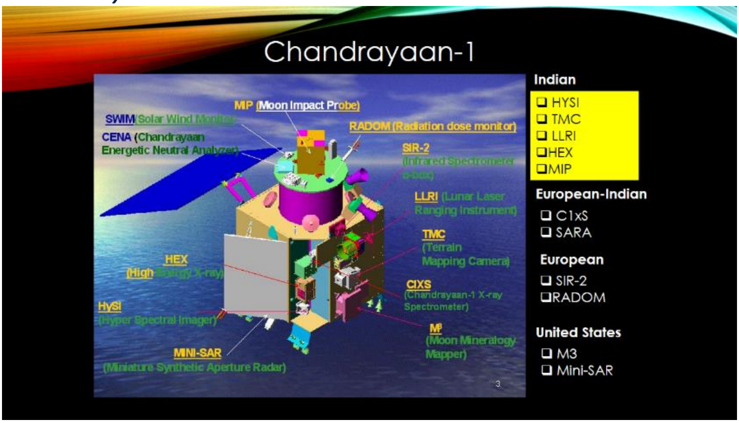


Chandrayaan-2 mission will be followed by Chandrayaan-3, which will demonstrate landing and roving on the lunar surface, and will also complement Chandrayaan-2 orbiter science with in-situ observations.

The Indian lunar exploration programme has also identified scientific problems of the in-situ study of surface/ sub-surface Water/water-ice and other volatiles at Poles, as well as the direct study of the permanently shadowed and permanently illuminated regions at the higher latitudes and poles of the Moon, as the next set of targets.

In brief, we will now discuss the Chandrayaan series of missions.

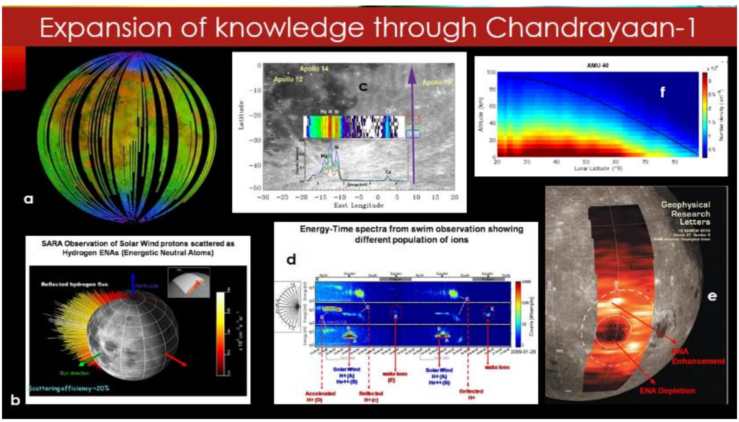
Chandrayaan-1



The Chandrayaan-1 mission, which was the first mission of the Indian lunar exploration programme, carried scientific instruments for conducting high resolution remote sensing observations of the Moon. It had a suit of eleven scientific instruments from India, as well as several other space agencies and international institutes. In that sense, Chandrayaan-1 was an elegant example of international cooperation in space exploration.

The mission was equipped with hyper-spectral imaging technology in the UV-VIS-NIR region using three imaging spectrometers, which, along with a low energy X-ray spectrometer provided mineralogical and chemical composition of the lunar surface at high spatial resolution. The mission also had a terrain mapping camera that provided high resolution three-dimensional images of the lunar surface. In addition to surface-imaging, Chandrayaan-1 also carried a laser ranging instrument to provide lunar altimetry information. Three payloads – a high energy X-γ ray spectrometer, a sub-keV atom reflecting analyser, and miniature imaging radar were used for the first time for remote sensing exploration. Which were meant to investigate on the transport of volatiles on the lunar surface, presence of localized lunar mini-magnetospheres, and possible presence of water ice in the permanently shadowed lunar polar region respectively. A radiation dose monitor was also carried by Chandrayaan-1, which provided valueable information on energetic particle flux en route to the moon, as well as in the lunar orbit.

Chandrayaan-1 also carried the Moon Impact Probe (MIP), which carried an imaging system, a radar altimeter and a quadrupole mass spectrometer. MIP was released from the spacecraft to impact near the lunar South Pole.



Coming to a few significant discovery class of findings from Chandrayaan-1 mission, the panel (a) depicts the Moon in a colour code, where the purple and blue colour zones near the lunar poles indicate the abundance of water-ice on the lunar surface. This interesting result has come from the Moon Mineralogy Mapper (M3) payload of the Chandrayaan-1 mission. It detected the signature of Hydroxyl radical (OH) through the analysis of the reflected solar spectrum from the lunar surface. The presence of OH was attributed to the possible presence of water-ice molecules on the lunar surface near the Polar Regions. Another instrument called Chandra's Altitudinal Composition Explorer (CHACE), which was a part of the Moon Impact Probe, detected signatures of water molecules in the lunar exosphere. It was a disruptive discovery in lunar science, as it was previously believed that Moon was as dry as a bone. The Chandrayaan-1 mission has changed that perspective.

The panel (b) represents another significant science result from the Chandrayaan Energetic Neutral Analyser (CENA) device of the SARA instrument onboard Chandrayaan-1. As you are aware, Sun emits stream of charged particles at an average speed of ~400 km/s, which comprises charged particles (ions and electrons). This stream of charged particles is called Solar Wind. The solar wind comprises ~96% protons, ~4% He++ (doubly charged Helium ion), <1% heavier ions, and equal amount of electrons. The SARA observations have revealed that around 20% of the impinging solar wind protons are scattered back to space as Energetic Neutral hydrogen Atoms (ENAs). These are called backscattered hydrogen ENAs. The picture in panel

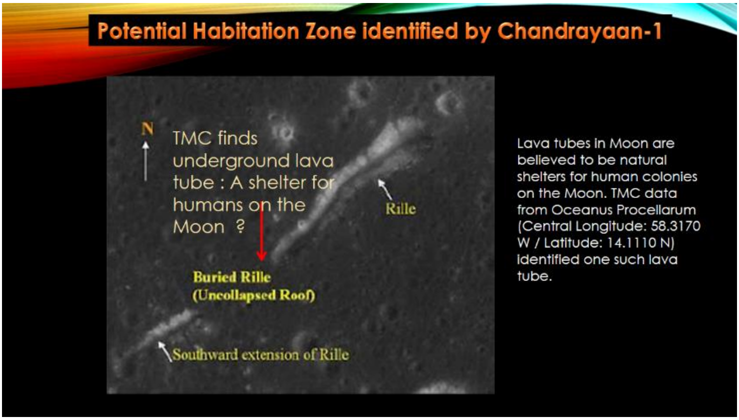
(b) depicts a map of the backscattered hydrogen ENA flux using the data of the SARA instrument. The picture also reveals the dependence of the scattered ENA flux on the solar zenith angle.

The panel (c) depicts a result from the C1XS (pronounced as ‘Kicks’) experiment on board Chandrayaan-2. The C1XS instrument is meant to measure absolute and relative abundances of major rock-forming elements in the lunar crust, like Mg, Al, Si, Ca, Ti and Fe. C1XS measures the X-Ray Fluorescence (XRF) from the lunar rock-forming elements in response to the solar X-ray radiation. In panel (c), XRF signatures of Mg, Al, Si and Ca are clearly seen from the lunar surface. Although not depicted in this picture, C1XS also revealed the first unambiguous evidence of enhanced Sodium on the lunar surface.

The panel (d) depicts yet another interesting result from Chandrayaan-1. It revealed that the physics of the lunar wake region (the region of space under the shadow of the Moon) was not as simple as it was thought. Previously, it was believed that the solar wind cannot reach the lunar wake region. The SARA instrument (to be precise, the solar wind monitor device SWIM, which was a part of the SARA instrument) onboard Chandrayaan-1, however, detected significant proton fluxes in the near-wake region of the Moon. The picture shown in panel (d) are called energy-time spectrograms, which depict the observed ion counts coming from the surface (below the local horizon), (middle) limb (toward the horizon), and (bottom) space (above the horizon). Five distinct ion populations are identified, which are labelled A through E. The protons are detected close to the lunar equatorial plane at a 140° solar zenith angle, that is, ~50° behind the terminator at a lunar altitude of 100 km.

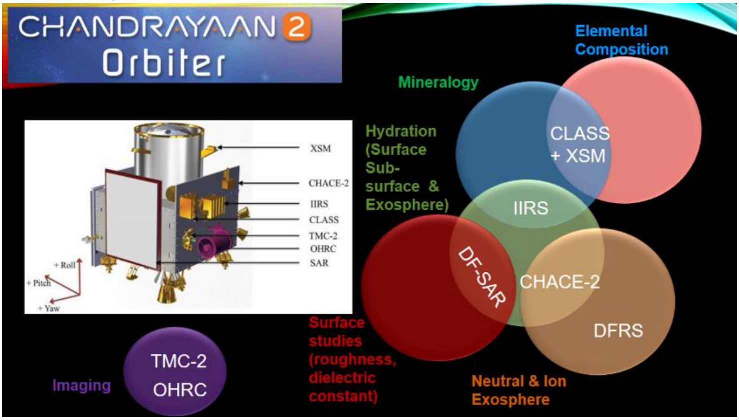
The panel (e) depicts map of scattered hydrogen ENA flux normalised to solar wind proton flux over a mini magnetosphere. The depletion in ENA flux over the mini-magnetosphere region, as well as the enhancement of the ENA flux over surrounding regions is clearly brings out the feature of the mini-magnetosphere. The ENA flux is depleted over the mini-magnetosphere because of the shielding of the solar wind by the patches of magnetic fields (also called magnetic anomalies), which, in turn, cannot give rise to enough ENAs. The ENA-enhanced regions, on the other hand, depict that the solar wind particles which were deflected by the mini-magnetosphere, are precipitated along its contour, thereby giving rise to more ENAs.

The panel (f) depicts the distribution of the Argon-40 gas in the lunar exosphere over the ground trace of the MIP. Although restricted to a single meridian, that was the first-ever measurement of lunar exospheric Argon-40 over bread range of latitudes covering the South Polar Region. Argon-40 is a condensable gas in the lunar exosphere, which originates due to the radioactive disintegration of radiogenic Potassium-40 in the lower crust and upper mantle of the Moon, and seeps out through cracks or orifices. Although no depicted in the picture, the CHACE instrument revealed remarkable science results on the detection of lunar exospheric water vapour signature, distribution of lunar exospheric Neon and molecular Hydrogen; provided indications on the spatial heterogeneity and indications of inter-hemispherical asymmetry of radiogenic activity in the lunar interior; upper limit of the lunar exospheric Helium-4 density under extreme conditions that are no conducive for hosting them.



As the Moon is devoid of any atmospheric veil and intrinsic global magnetic field, it is highly vulnerable to meteoritic impacts, radiations and energetic particles. A possible human settlement on Moon would look forward to a solution to avoid those hurdles. There are a few regions that show the hope of providing safe shelter for the human explorers on the Moon, such as volcanic lava tubes, which are free form the hostile effects. These may be adequate for human settlement which is an important perspective for long term research and development in outer space. Lava tubes are formed when an active low viscosity (lesser dense) lava-flow develops a continuous hard crust due to continuous cooling of its outermost part (the heat from its outer part is radiated to space), which thickens with time, and forms a solid roof above the still flowing lava stream beneath. Often, if the conditions are conducive, an empty flow channel, free from molten magma, is left behind in the form of a cylindrical-shaped tube, known as the volcanic tube. The Terrain Mapping Camera (TMC) onboard Chandrayaan-1 has detected a buried uncollapsed, near-horizontal lava tube, as shown in this picture.

Chandrayaan-2



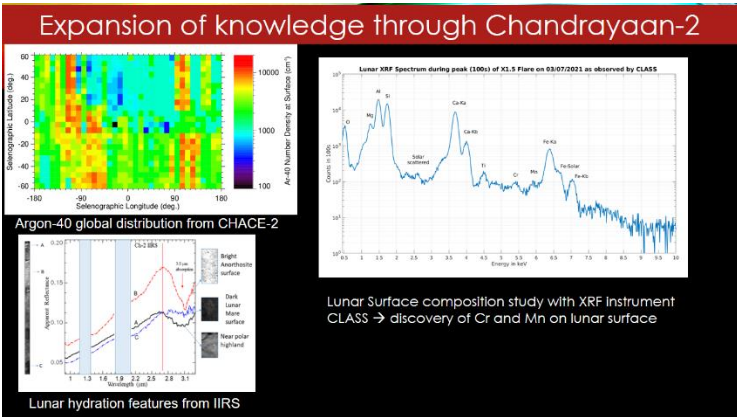
The lessons learnt from Chandrayaan-1 mission prompted the inception of Chandrayaan-2, India's second lunar mission. The Chandrayaan-2 mission was envisaged with an orbiter, lander and a rover, however, the lander suffered hard landing on the lunar surface. The orbiter component of Chandrayaan-2, which is equipped with eight scientific instruments, is still operating, and returning valuable scientific information.

The eight scientific instruments onboard the Chandrayaan-2 orbiter address the aspects of elemental composition, mineralogy, hydration, neutral & ion exosphere, as well as imaging.

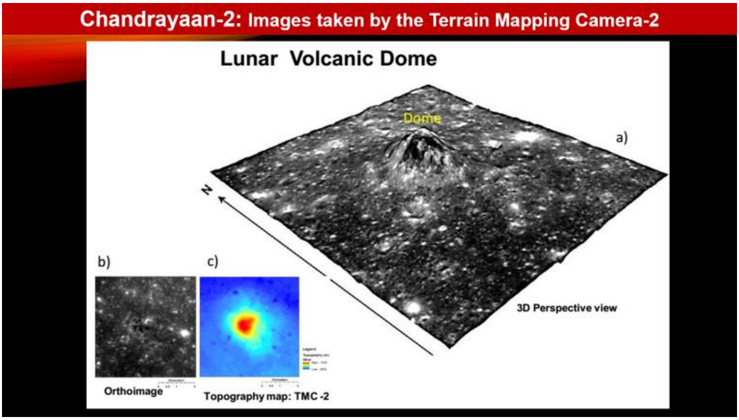
The CLASS instrument onboard Chandrayaan-2 is the follow-up of the C1XS experiment, which is studying the X-Ray fluorescence from the elements and minerals on the lunar surface. CLASS is aided by the X-Ray Solar Monitor (XSM) instrument, which is pointed towards the Sun, and studies the solar X-Ray emission. Thus, while the XSM instrument studies the cause (i.e. emission of X-Rays by the Sun), the CLASS instrument studies its effects (XRF of the lunar surface elements).

The IIRS instrument onboard Candrayaan-2 is an infra-red spectrometer, capable to studying the mineralogy of the Moon, as well as the hydration sigantures on the lunar surface. Taking lessons from the M3 instrument (which was limited to 2.8 micron wavelength, which could not directly capture the water-ice signature, which could have been observed at 3.0 micron) of Chandrayaan-1, the IIRS instrument is equipped to observe up to 5.0 micron wavelength range. Thus, it is equipped to observe both hydration and mineralogy signatures on the Moon's surface.

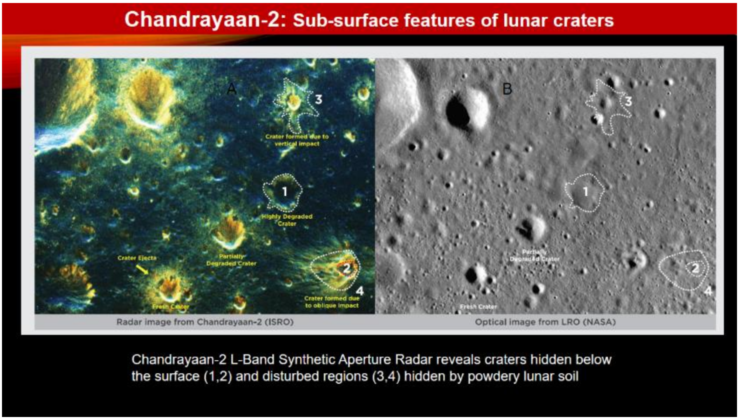
The Dual Frequency Synthetic Aperture Radar (DF-SAR) is studying the sub-surface water-ice; surface roughness and dielectric constant variation of the lunar surface. The CHACE-2 experiment, which is a follow up of the CHACE experiment onboard the MIP in Chandrayaan-1, is meant to conduct in-situ study of the composition of neutral atoms and molecules in the lunar exosphere. Unlike CHACE, which was a single-shot experiment (as it was impactor-borne, and limited to a single lunar meridian), limited to the mass range of 1-100 amu, the CHACE-2 experiment is studying the lunar exosphere on a global scale, with an increased mass range of 1-300 amu. The Dual Frequency Radio Science (DFRS) Experiment is studying of the ionosphere around the Moon. The Terrain Mapping Camera-2 (TMC-2) is engaged in the global imaging of the Moon, with identification of scientifically significant geological features. Another imaging instrument is Orbiter High Resolution Camera (OHRC), which is performing high resolution imaging of lunar surface, with an unprecedented resolution of 25 cm.



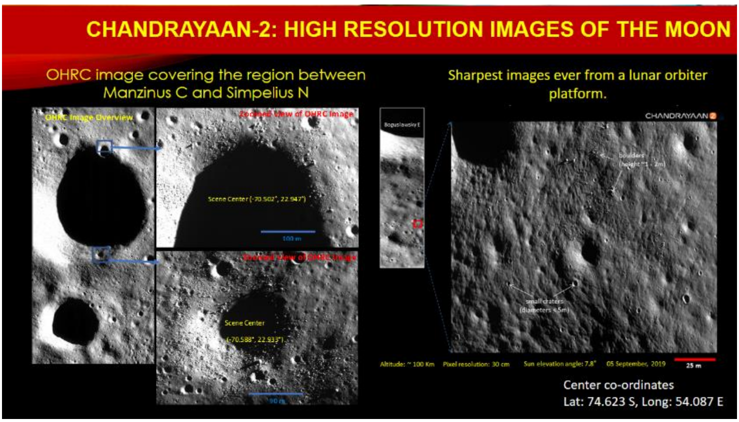
Chandrayaan-2 orbiter is providing high-quality remote sensing and in-situ observations of the Moon with eight scientific payloads on-board; the data are made available to public with more than 2800 worldwide registered users. Chandrayaan-2 science results have provided new insights to the lunar science research, a few of which are depicted in this picture. The major scientific results obtained so far from Chandrayaan-2 orbiter include characterization of hydration features on surface; characterization of young, fresh lunar crater floors; global distribution of Argon-40 in the lunar exosphere; study of the geotail dynamics at lunar distances; detection of minor elements, such as Cr and Mn from the orbiter, and mapping of sodium distribution for the first time.



The Dual-frequency (L and S band) SAR is aimed at providing continuity to the Chandrayaan-1 S- band MiniSAR measurements with enhancements such as L-band for greater depth of penetration (~5-10m i.e twice that of S-band), which will have potential to retrieve scattering from lunar sub-surface. The left panel of the picture depicts the revelation of craters hidden below the lunar surface, and also disturbed regions which are hidden by the lunar regolith. The right panel of the picture presents an image from the LRO orbiter, corresponding to the same region, for comparison.



Coming to the OHRC instrument; as you know, the lunar surface is uneven; there are numerous boulders of different sizes. Boulders can be easily identified using OHRC images due to its very high spatial resolution. Hundreds of boulders, ranging from 1m to 50m in diameter, are distributed within an ejecta close to the crater rim.



These boulders represent the deepest material excavated during crater formation. Boulders on the Moon surface are often found around young impact craters.

Apart from characterizing the landing sites, the OHRC images allow scientists to study boulder populations in the region of interest and help them interpret geologic features and derive geologic history for a region.

Towards Chandrayaan-3

Chandrayaan-3 is meant to soft-land in the southern high latitudes on the Moon. The expected mission life is around 14 Earth days. The Rover and payloads on the lander and rover are similar to the Chandrayaan-2 mission. After landing, the rover will roll out of the lander and perform in-situ observations.

Indian lunar program is science-driven. The scientific objective of the Chandrayaan-3 mission is to study the thermo-physical properties, seismicity, and elemental composition in the vicinity of the landing site. The spacecraft has a landing module with Rover inside the lander and a propulsion module. The propulsion module will remain till100x30 km around the Moon and deploy the lander, which will then use its own propulsion to land on the lunar surface.

Indian Space Science Data Centre

At this juncture, I take this opportunity to tell you briefly about the Indian Space Science Data Centre (ISSDC), which is situated along with India's Deep Space Network (DSN) at Byalalu, in the state of Karnataka. ISSDC hosts the ISRO Science Data Archive (ISDA), which is the repository of all the science data from the Indian science missions. It hosts the data of Chandrayaan-1, Chandrayaan-2, Mars Orbiter Mission, AstroSat, to name a few.

Each mission archive includes raw and reduced data, calibration data, auxiliary data, higher-level derived data products, documentation, and software.

ISDA makes use of the well-proven archive standards of the Planetary Data System (PDS) and follows the International Planetary Data Archival (IPDA) guidelines. By this, ISSDC ensures compliance with the global standards for long-term archival of the data, maintains their usability, and facilitates the scientific community with the high-quality data for their analysis.

Many of you will be happy to know that the data are made accessible to scientists from other institutions and also to the general public. All that you have to do is to visit the website www.issdc.gov.in and register yourself to start using the data. This repository is very useful for the student community as well, in order to receive exposure to the standards of the data archival, different levels of the data, as well as the documentation.

Summary and Future Scope

To sum up, the missions to explore the Moon have collectively given lots of scientific insight in terms of its structure, surface composition, mineralogy, exosphere, as well as its state of activity. These missions have also helped to shape our perspective about the Moon; for example, the discovery of water signatures on the Moon and evidence of recent lunar volcanism revolutionized our impression of the Moon.

The samples collected from the Moon have helped test the existence of, and duration of, the impact processes in the early solar system; studying the correlation between the crater counts and radioactive dating of the collected samples (which is known as crater chronology calibration); testing models of early planetary differentiation, including the effects of giant impacts and

magma oceans; obtaining specific information on the Moon's thermal evolution, and developing a better understanding of the formation and modification of impact-basins

Yet, the missions have raised lots of scientific questions, some of which are the study of the volatile materials in the lunar Polar Regions; detailed study of the Permanently Shadowed and Permanently Illuminated Regions of the Moon; in-situ sample analysis for knowing the ground-truth of the lunar mineralogy, hydration, and astrobiology, to name a few. Also, Moon's far-side is found attractive because of its radiowave-free environment, which is suitable for astronomical observations.

Apart from the scientists, the technologies are also finding the Moon as a potential celestial body with respect to in-situ resource utilization for the generation of propellants from lunar resources. Technology development is in progress to explore the techniques to do civil engineering on Moon. From a larger perspective, Moon is also looked upon as a potential space station to observe the Earth.

While explorations would continue, I hope that this brief presentation could offer you a fairly complete perspective of the Moon, which may motivate you to take up space science as your career. One day your research may also unveil new mysteries of the Moon.