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ÚSTAV JAZYKŮ

LUNAR EXPLORATION AND ROVERS ON THE MOON IN THE 21ST CENTURY

LUNÁRNÍ PRŮZKUM A ROVERY NA MĚSÍCE V 21. STOLETÍ

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Lunar Exploration and Rovers on the Moon in the 21st century

INSTRUCTION:

Exploring the Moon has always been a fascination of mankind since the 20th century. In the space race of the 1960s,, the USA's NASA Apollo missions were successful in landing both men and vehicles on the moon. In the 21st century other countries such as China and India have been even successful in landing rovers to explore the Moon’s surface. The aim of the semester project is to describe the race in exploring the moon and then giving a description of the lunar programs of particularly China and India in successfully landing landers with rovers and exploring Moon's surface. The future thesis will go deeper in examining the technology of their lunar programs, and describing other countries' plans for exploring the moon too.

RECOMMENDED LITERATURE:

Manfred "Dutch" von Ehrenfried, Water on the Moon: Landers and Rovers in the 21st Century, 2022. ISBN: 9798842720187

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Abstract

This thesis focuses on the past and present missions to the Moon. The historical part focuses particularly on the programs of the Soviet Union and the United States involving impactor probes, landers, and the Apollo program. The present section deals with the Chinese Chang'e program, and the Indian Chandrayaan missions. Then, the paper provides a description of the Nova-C lander constructed by Intuitive machines. The last section delves into the upcoming mission of rover VIPER which is under development by NASA. The chapters in this paper provide a comprehensive description of the design of spacecraft, science experiments on board, and the execution of missions.

Keywords

Moon, spacecraft, mission, Luna, NASA, Chang'e, Chandrayaan,

Abstrakt

Tato práce se zaměřuje na minulé a současné mise v oblasti průzkumu Měsíce. Historická část cílí na programy Sovětského Svazu a Spojených Států, které zahrnují nárazové sondy, přistávací moduly a program Apollo. Z hlediska současných misí se práce zabývá čínským programem Čchang-e a dvojicí indických misí Čandraján. Poté se práce věnuje přístávacímu modulu Nova-C konstruovaného společností Intuitive Machines. Poslední sekce se zaobírá nadcházející misí roveru VIPER, který vyvíjí NASA. Kapitoly této práce obsahují ucelený popis konstrukce sond a kosmických lodí, jejich vědeckých experimentů a následnou realizací misí.

Klíčová slova

Měsíc, sonda, mise, Luna, NASA, Čchang-e, Čandraján

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Author’s Declaration

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Academic year:	*2023/24*
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I declare that I have written this paper independently, under the guidance of the advisor and using exclusively the technical references and other sources of information cited in the project and listed in the comprehensive bibliography at the end of the project.

As the author, I furthermore declare that, with respect to the creation of this paper, I have not infringed any copyright or violated anyone’s personal and/or ownership rights. In this context, I am fully aware of the consequences of breaking Regulation S 11 of the Copyright Act No. 121/2000 Coll. of the Czech Republic, as amended, and of any breach of rights related to intellectual property or introduced within amendments to relevant Acts such as the Intellectual Property Act or the Criminal Code, Act No. 40/2009 Coll., Section 2, Head VI, Part 4.

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Brno, May 22, 2024 ---------------------------------------

author’s signature

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I would like to thank my supervisor Kenneth Froehling, M. A., for his valuable advice. I also want to thank my girlfriend, friends, and family who have given me much-needed support while writing this thesis.

Contents

INTRODUCTION

Our solar system is filled with other worlds waiting for exploration. From planets such as Mars, which in the past was believed to have liquid water, a dense atmosphere, and conditions that could support life; to Europa, the moon of Jupiter covered in ice where approximately 22 km beneath the surface is a vast ocean that might support unicellular life; to planets that are inhabitable, such as Venus with its enormous pressure of 92 bar and temperatures rising to 464 °C. It is safe to say that the solar system is an exotic and turbulent place. Those far-off planets and moons are difficult to reach, yet our nearest celestial body, the Moon, is relatively accessible in comparison. Its combination of low gravity with a force of only one-sixth of Earth's, and the lack of atmosphere makes the Moon an accessible place for robotic and manned exploration.

Not even a century ago, lunar exploration was only possible through the lens of a telescope; however, with the advancements in rocketry and computing technologies throughout the 1940s and 50s, it became possible to take a closer look at the Moon through robotic and later manned missions. Generally, lunar missions require large amounts of resources and money, making it difficult to justify these financially unprofitable missions. During the Cold War; however, lunar missions were extensively funded by both the United States and the Soviet Union in a contest for technological superiority, militaristic superiority, and prestige. This was characterized by an increased intensity of lunar missions and rapid development in aerospace technology throughout the so-called Space Race.

Robotic exploration of the Moon began in 1959 with the Soviet probe Luna 2. It was the first success of the series of impactor probes designed to conduct experiments en route and finish the mission by impacting the surface. After taking the lead, the Soviet Union extended it with Luna 3 which captured pictures of the far side of the Moon. After five years, NASA responded with the Ranger program in 1964, a series of impactor probes that took high-definition photographs of the Moon's topography.

A logical step in lunar exploration was a robotic soft landing. This type of mission required a restartable engine to decrease the lander's velocity for a safe landing, which increased the complexity of the mission. Additionally, a precise guidance system was necessary to properly adjust velocity and angle relative to the surface. The first soft landing was achieved in 1966 by the Soviet Luna 9, reassuring their lead. It landed thanks to an innovative airbag system which reduced the complexity and weight of the lander. However, the conventional landing legs implemented by the American Surveyor program were considered more practical for subsequent manned missions.

The ultimate objective of the Space Race was a manned mission to the Moon. Such a venture not only provided gains in terms of science, but it also served as a tool for propaganda and unification of society to achieve a common goal. A manned mission was by far the most challenging type of mission of the time. The weight of the spacecraft significantly increased due to the need for life support systems, space for ubication, and other requirements, therefore, a brand-new rocket capable of launching heavy payloads was required.

Modern exploration of the Moon's surface is being undertaken by new participants such as China, and India. Surficial exploration returned after almost four decades with the Chinese Chang'e 3 program. The mission comprised the rover Yutu and the Chang'e 3lander both designed to conduct experiments on the surface. The Chang'e 4 followed a similar design to Chang'e 3, and it aimed to study the environment on the far side of the Moon. The latest surficial mission conducted by the CNSA was the Chang'e 5 designed to obtain samples from the lunar surface and bring them back to Earth.

Indian lunar exploration began in 2008 with Chandrayaan-1, a combination of orbiter and impactor designed to map the chemical, mineralogical, and photo-geological features of the Moon. The second successful project was the Chandrayaan-3. It is a combination of a lander Vikram and a rover Pragyan. In addition to conducting experiments, the main objective of the pair was a technology demonstration of achieving a successful soft landing and its subsequent operation.

Exploration of the lunar surface is entering a new era that is not solely limited to programs funded by governments but also provided by private companies, the first such mission was achieved in February 2024 by the American company Intuitive Machines with the Nova-C lander. The frontier of lunar exploration is represented by rover VIPER. It is being developed by NASA and aims to study the South Pole using cutting-edge equipment.

This thesis is divided into two chapters. The first chapter covers exploration during the Cold War starting with relatively simple impactors and ending with the American Apollo program. Lunar programs of the Soviet Union and the United States were described and compared. The second chapter is dedicated to modern exploration by China with their three landings, and India with the Chandrayaan-1 and Chandrayaan-3 missions. Additional focus is put on the Nova-C lander and the upcoming VIPER rover that is being developed by NASA. Each mission in this thesis is summarized in terms of its objectives, technical characteristics, and mission execution.

1. THE RACE FOR THE MOON

1.1 The Beginning of The Space Race

October 4, 1957, is considered to be the beginning of the Space Race when the Soviet Union launched the first artificial satellite Sputnik 1 designed by Mikhail Khomyakov. The devices on board were simplistic. The satellite carried two 1 W transmitters for communication. Interestingly, the iconic "beep" signal produced by the transmitters could be captured by ordinary radio receivers. This increased interest and awareness in space flight among people across the world. Electrical devices were powered by three silver-zinc batteries and cooled by one ventilator while covered in a pressurized sphere made of highly polished aluminum. (Krebs, n.d.-a) The satellite did not carry scientific instruments; however, the mission was proof that it is possible to launch a device carrying instruments and remain functioning in extreme conditions in space. The mission lasted 21 days until the spacecraft burned up during its re-entry to Earth's atmosphere.

The aftermath of the mission resulted in global recognition and sparked interest among other countries to launch their spacecraft. The motivation to participate in space flight was high. To provide context, during the 1950s, the world was politically divided. The two most relevant sides were the democratic west and the socialistic east. Throughout the Cold War, each side contested for supremacy, including superiority in various fields such as education, quality of life, the arms industry, and technology, with the exploration of space becoming yet another field in this contest. The result of the Soviet Sputnik mission "caught the United States by surprise" and led to the creation of NASA (NASA, 2023).

1.2 First Space Missions

Background

After the first successful space mission, the newly born space industry experienced a boom in interest among the public and the governments of major countries that increased their investment in space flight. This resulted in numerous scientific accomplishments, notably, the Soviets successfully launched Sputnik 2 carrying the dog Laika being the first biological experiment in space.

The following year of 1958, NASA launched their first satellite Explorer 1. The spacecraft was equipped with a cosmic ray detector which was designed to measure the radiation environment in Earth's orbit leading to the exploration of the Van Allen radiation belt (NASA,2018).

Each successful mission provided the necessary knowledge and experience to the engineers of both contenders and resulted in more complex missions. The objective was to not only accomplish the mission with success but also to secure the distinction of being the first to achieve it. The previously mentioned missions were sub-orbital launches of satellites. In the context of Moon exploration, the first satellites were designed to set a collision trajectory with the Moon and impact it without the intention of a soft landing. However, the so-called impactor missions were compared to sub-orbital flights relatively complex as they required precise computation of trajectory and more fuel to achieve the required velocity.

1.3 Impactors

1.3.1 Luna 1

Objective

Luna 1 was the first probe to successfully perform a fly-by of the Moon. It was the fourth attempt from a series of Luna missions with the code name E-1 No. 4. The objective of the mission was to directly impact the surface of the Moon and study the environment of space during the flight and close approach of the Moon.

Instruments

To perform measurements, the probe was equipped with a Magnetometer, Geiger counter, scintillation counter, micrometeorite detector, and equipment necessary to support the function of the vehicle in the vacuum of space. Mercury-oxide batteries and silver-zinc accumulators provided power to all instruments including one rigid and four whip antennas used for communication with the Earth center. (NASA, 2022-a) The instruments in the probe were protected by a sealed sphere following a design reminiscent of previous satellites.

Launch and Results of Experiments

On January 2nd, 1959, after a successful launch utilized with a modified R-7 rocket, Luna 1 separated from the third stage and traveled on the trajectory to the Moon. The following day, the probe released sodium gas into the vacuum as an experiment on the behavior of gas in the environment. Additionally, this cloud could be observed and tracked by astronomers from Earth (NASA, 2022-a).

Luna 1 mission provided several findings. Contrary to predictions, the magnetometer on board discovered that the Moon does not have a magnetic field. The mission also discovered the presence of solar winds in deep space. Despite the scientific findings, the main objective of directly impacting the Moon was not achieved. The probe overshot the target, with the periapsis of its orbit being approximately six thousand kilometers. Consequently, an inadequately executed maneuver redirected the trajectory of the probe out of the gravitational field of the Moon and Earth, making it the first spacecraft to enter orbit around the Sun. It is believed that the main reason for failure was the fact that the mission was performed manually and due to the delay of signal, the engine did not stop the combustion on time as scheduled (Reichl 2019).

1.3.2 Luna 2

The Luna 1 was therefore only a partial success. The primary goal of the Luna 1 mission was realized with the launch of Luna 2, a probe of a similar design. The spacecraft executed the mission similarly to the previous one; however, this time the engine of the third stage did not overperform, and the impact of the Moon was successful. On September 14, 1959, at approximately 21:02 UT, radio communication ceased which indicated the first direct impact to the Moon (NASA, 2022b). The spacecraft reached an impact velocity of 3.3 kilometers per second. The spherical body of the probe was adorned with medals of the Soviet Coat of Arms and carried commemorative pennants. The intention was to symbolically scatter the medals and pennants across the surface; however, the impact velocity was so high that the probe likely vaporized upon impact with the Moon (Mitchell, 2008).

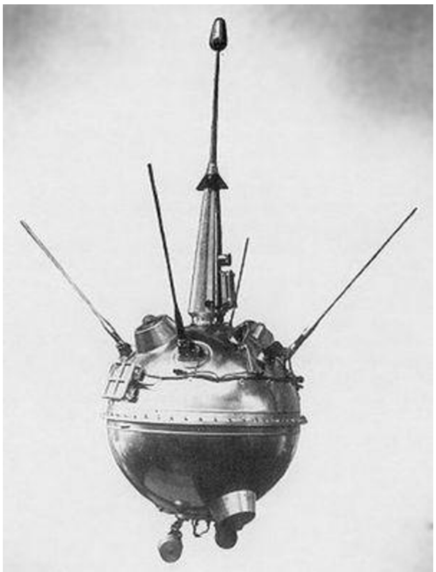

Fig. 1. Luna 2 (Pallardy, n.d.)

1.3.3 Ranger 7

The Ranger program was a series of impactor probes developed by NASA. As a scientific instrument, the Ranger was equipped with six television vidicon cameras. The spacecraft reached the Moon on July 31, 1964, and started fulfilling the objective of the mission by taking high-resolution photographs of the topography of the surface. The results confirmed that the surface of the Moon is relatively smooth over small distances of one meter. Additionally, numerous closely spaced ridges and shallow, elongated to circular craters aligned along rays (Trask, 1970).

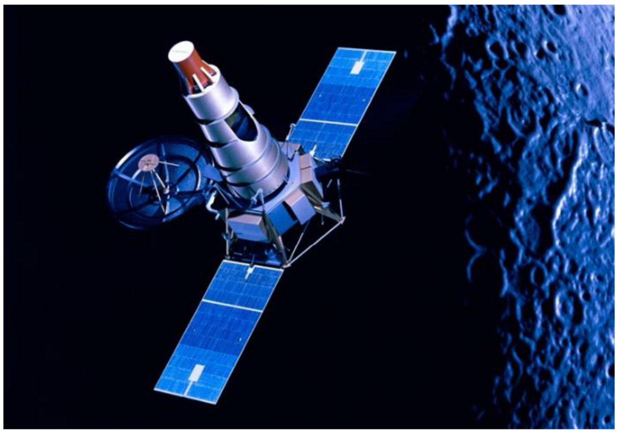

Fig. 2. Ranger 7 (NASA, 2018)

NASA continued with the success with subsequent Ranger 8 and 9 which captured images of different parts of the lunar surface. This data was further utilized in the subsequent Surveyor program to determine an appropriate location for a soft landing.

1.4 Robotic Landers

Achieving a controlled soft landing on the Moon was a logical step after impactor probes. By the early 1960s, both Soviet and American lunar programs had already begun their development of modules and rockets for manned missions; however, researchers were not certain about the plausibility of landing due to the unknown density of the soil, therefore analysis of the surface became one of the main objectives of first landers. Moreover, it was required to test additional maneuvers during the course as well as the terminal guidance system during the landing phase.

1.4.1 Luna 9

The Soviet lunar exploration program designed Luna 9 which introduced an innovative approach to landing on the Moon. The spacecraft comprised two parts: an automatic lunar station for the landing and a flight stage mounted below the station for the course stage. The lunar station was essentially a pressurized metal sphere that weighed 99 kilograms with a diameter of 58 centimeters. The interior was equipped with a radio system, programming device, thermal control system, and batteries to provide electricity for the mission. In terms of scientific equipment, it was equipped with a lightweight panoramic camera and a radiation detector.

In order to land on the Moon, it was necessary to reduce velocity during the flight. This was realized by the flight stage's main retrorocket engine KTDU-5A and four outrigger vernier rockets. Additionally, three nitrogen jets linked with gas bottles were used for maneuverability during descent. The five engines were connected to a pumping system that extracted fuel from the toroidal tank and a 90-centimeter-wide spherical tank containing oxidizer. For the landing phase, the lander was equipped with an airbag system to cushion the impact upon reaching the surface (NASA, 1979).

On January 31, 1966, Luna 9 was launched by Molniya-M rocket from the Baikonur Cosmodrome. Every maneuver was executed correctly including the 48-second combustion of the retrorocket during the course. On February 3, at an altitude of 250 kilometers above the surface, the main breaking phase was initiated. During the descent, a metal rod was extended from the flight stage pointing towards the surface. Upon touching the soil with the rod, it simultaneously activated an ejection system for the lunar station and the airbag system. Following the initial impact, the station experienced several bounces from the ground; however, due to the relatively small impact velocity and the airbag system, the landing was executed softly. The airbags were deflated once the lander became stationary, and the probe opened its four petals to ensure the correct angular position (Christy, n.d.).

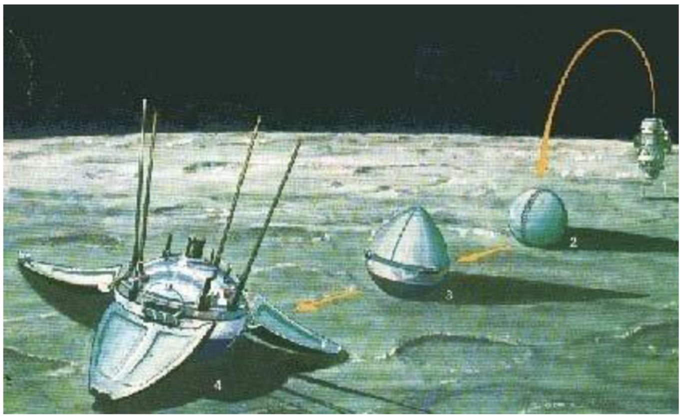

Fig.3. Landing sequence of Luna 9 (Seboldt et al., 2004)

1.4.2 Surveyor Program

The Surveyor 1 was the first iteration of the NASA Surveyor program which focused on robotic landings on the Moon. Out of a total of seven landers launched, five were successful. Although the first landing was achieved by the Soviet Luna 9, the Surveyor used a more practical landing method. Instead of inflatable airbags, the lander used landing legs. Because of the Surveyor program, NASA was able to properly test this method of landing which was later implemented in the design of the Apollo lunar module.

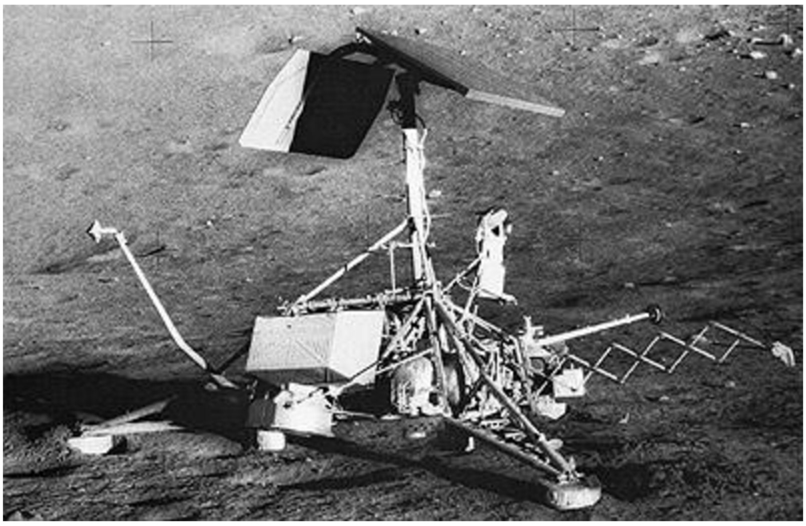

Fig.4. Surveyor 3 (Krebs, n.d.)

According to NASA, it is considered as being the "first true landing". Each lander weighed around 340 kilograms. In terms of dimensions, it was a three-meter-tall vehicle based on a triangular structure with each leg being situated at every corner. Landing pads were fitted with aircraft-type shock absorbers to soften the landing. Star-37 retro-rocket engine was utilized for the main breaking phase and three hydrazine engines for the final landing phase. Surveyor 1 was equipped with one TV camera that provided high-resolution images of the landing site. The tripod design allowed modular mounting of larger scientific equipment compared to Luna 9, which was limited by its small spherical design. The equipment differs with each lander. Surveyor 3 was fitted with a sampling scoop. Surveyor 5 conducted a Vernier engine erosion experiment to determine chemical elements in lunar soil. Surveyor 6 was fitted with a small magnet attached to one landing pad. Additionally, it successfully tested liftoff and re-landing on the surface. Every lander used two solar panels that provided approximately 85 W output and supplied a 24-volt battery (Krebs, n.d.-b).

Mission procedure followed the same principles as the Luna 9 mission. It was necessary to perform a slow-down burn of the retro-rocket engine. After depletion of fuel, the engine was dispensed from the spacecraft to lower landing weight while the other three engines finalized deceleration. The engines were then automatically halted at a 3.5-meter altitude to prevent contamination of the landing site.

1.5 Manned Missions to the Moon

Both NASA and the Soviet Union were actively preparing for manned missions to the Moon simultaneously with robotic missions. However, compared with robotic missions, a manned mission requires a rocket system capable of carrying a significantly larger payload that is necessary to support life in space. As far as the Moon landing is concerned, both sides had a similar approach of sending two separate modules into Lunar orbit: the command module which serves as living quarters for astronauts/cosmonauts while also functioning as a control center, and the landing module responsible for the transport of people from the command module to the lunar surface and back. Both modules must support all necessary human needs such as oxygen, supply of food, a sanitation facility, and living space for the duration of the mission. Additionally, a docking system was required due to the need for separation of the two vehicles.

Presidential Declaration

On September 12, 1962, President John.F. Kennedy stated in his famous speech about the nation's space effort "We choose to go to the Moon". He promised the public that the United States would put a man on the Moon by the end of the decade. The Soviet Union took a different approach and kept its lunar program classified.

1.5.1 Apollo Program

The program was the successor of the Mercury program in terms of crewed flights. Apollo consisted of eleven manned missions. The first four flights tested the spacecraft and its systems. Out of seven missions, six landed on the moon. The first manned mission to the moon was Apollo 8 which orbited around the moon and then returned. Finally, On July 24, 1969, Apollo 11 was the first crewed mission to land on the lunar surface (Wild, 2023). These missions were realized by a combination of three modules.

Command and Service Module

The entire module (CSM) consisted of two distinct units: The command module (CM) in which the crew spent most of the mission, controlled operations of the aircraft, and housed re-entry equipment to Earth's atmosphere, and the service module (SM) which carried most of the consumables such as oxygen, helium, water, and fuel cells. It also carried fuel for the main propulsion system. The combined length of the two units was eleven meters with a diameter of 3.9 meters. The CSM from the Apollo 11 mission weighed 28 801 kilograms (launch mass including propellants). The command module alone (CM) had a mass of 5557 kilograms and the service module (SM) 23 244 kilograms.

The command module

As far as technical description is concerned, the CM was made of an aluminum honeycomb sandwich bonded between sheet aluminum alloys. A docking assembly and a hatch were fitted on the tip of the module to connect the vehicle with the Lunar Module. While fully docked, the crew could internally move between the modules. The bottom part of the CM was equipped with a heat shield made of a brazed stainless-steel honeycomb filled with phenolic epoxy resin as an ablative material. The interior of the CM was divided into three compartments. The forward compartment held three 25.4-diameter main parachutes, two drogue parachutes, and pilot mortar chutes for a return landing on Earth. The aft compartment around the base of the CM housed tanks of propellant, reaction control engines, wiring, and plumbing. The crew compartment was fitted with three couches for astronauts. The access hatch for the crew was located above the seats and a smaller docking hatch was situated in the nose of the module. The crew compartment was equipped with navigation systems, displays, and control systems among other systems used by the crew. The module offered five windows for rendezvous maneuvers and overall orientation. For maneuverability, the CM used twelve nitrogen tetroxide/hydrazine thrusters.

The Service Module

The Service Module had an additional four such thrusters. The main engine mounted on the back called the service propulsion system (SPS), was a gimbal-mounted restartable hypergolic liquid propellant engine with a power output of 91 kN. This module contained three 31 hydrogen-oxygen fuel cells generating 28 volts. In terms of fuel storage, two tanks with cryogenic hydrogen combined with two tanks with cryogenic oxygen supplied the SPS. Two helium tanks mounted in the central cylinder were used for pressurization. Furthermore, radiators for the power system were located at the cylinder's upper part with the environmental control radiator panels spaced around the bottom (NASA, 1969a).

Lunar Module

The Lunar module "Eagle" was designed for operations both on the Moon's surface and its orbit. 15 103 kilograms heavy vehicle (including propellants) was separated into two stages: the ascent and descent stage. The ascent stage weighed 2445 kilograms without fuel and was constructed to contain 2376 kilograms of propellant. The descent stage had a dry mass of 2034 kilograms and carried 8248 kilograms of propellant.

Descent stage

During the descent phase, the two stages were connected via a docking system and operated as a unified system. The lower part of the descent stage was an octagonal prism with a diameter of 4.2 meters. The landing mechanism comprised four extendable landing legs mounted on the sides of the octagonal structure providing ground clearance of 1.5 meters. To enable the astronauts to cover the distance from the landing module to the surface, the vehicle was equipped with a ladder in addition to a small platform between the hatch and the ladder. In terms of the propulsion system, the landing was performed by a single 45 kN engine mounted on the bottom. This engine was powered by two tanks of aerozine 50 and two tanks of nitrogen tetroxide oxidizer. The descent stage additionally contained storage for various experiments for extravehicular activity.

Ascent stage

The ascent stage was an irregularly shaped unit mounted on top of the descent stage. The interior was pressurized enabling the astronauts to work, eat, and sleep without a spacesuit. The compartment was fitted with two hatches: one designated for EVA (Extravehicular activity) and the other for moving astronauts from the Landing Module to the Command Module. In terms of communication, all antennas (rendezvous antenna, parabolic S-band antenna, and two VHF antennas) were mounted along the top of the stage. Two triangular windows were fitted for visual orientation; however, their size was limited due to weight-saving. Regarding the interior equipment, the walls were allocated for the control console and two more control panels. To perform the ascent, the stage was fitted with a smaller 15 kN engine paired with a singular fuel and oxidizer tank. The main difference was that this engine was fixed and could not alter the direction of thrust, therefore steering was realized by the reaction control system (four RCS thrusters). After completing all activities on the lunar surface, the two astronauts boarded the LM and initiated the engine of the ascent stage which then separated with the descent stage, leaving it on the surface (NASA, 1969b).

Fig.5. Illustration of docking maneuver of the ascent stage with the Command and Service Modules (NASA, 1969)

2. MODERN EXPLORATION

Orbital exploration by ISAS and ESA

Orbital exploration of the Moon resumed in 1990 with the Hiten probe, the first launch of the Japanese Institute of Space and Astronautical Science (ISAS). The main objective of this mission was the double lunar swing-by experiment and deployment of a small sub-satellite into lunar orbit. The probe conducted additional experiments such as aerobraking, optical navigation, utilization of a fault-tolerant computer, and detection of micro-meteorites (Uesugi et al., 1991). Japan was after the Soviet Union and the United States the third country to send a probe to the Moon.

In 2003, the European Space Agency (ESA) launched SMART-1 which tested its electric propulsion system and other deep-space technologies. It also demonstrated various innovative mission control techniques. In terms of exploration of the Moon, the probe utilized three pieces of equipment: A d-CIXS X-ray telescope to study chemical elements in the lunar surface, an SIR infra-red spectrometer to chart minerals of the surface, and lastly AMIE, An ultra-compact electronic camera to study the terrain in near-infrared light (ESA,n.d).

Modern exploration of the surface

In terms of exploration of the surface using landers and rovers, the intensity plummeted after the Apollo program. The Soviet Union failed to create the heavy launching platform necessary for manned lunar missions. The N-1 rocket was an equivalent of the American Saturn V. The Soviet rocket underwent four flight tests, all of which were failures. The second flight test on July 3, 1969, resulted in the destruction of the launch pad which was a major setback for the program. Consequently, the streak of failures together with lack of funding and overly complicated design of the rocket ultimately resulted in the cancelation of the program and Soviet efforts for manned missions to the Moon. Due to the lack of a direct competitor, it became difficult to maintain funding for expensive lunar programs. This resulted in a significant decline in government spending for NASA and together with the loss of public interest, the final three missions (Apollo 18, 19, and 20) were canceled.

In 1976, The Soviet robotic lander Luna 24 conducted a robotic lunar sample return mission which was the last lunar surface mission for 37 years. In 2013, the Chinese Lunar Exploration Program (CLEP) broke this long-lasting streak with the Chang'e 3 mission described in chapter 2.1.2.

2.1 Chinese Moon Program

2.1.1 Chang'e 1 & 2

Chang'e 1

Chang'e 1 was the first lunar mission conducted by the CNSA. It was an orbiter whose primary objective was to gain experience and test the technology necessary to perform missions to the Moon. Additionally, there were scientific objectives to capture 3D stereo images of the surface, analyze the distribution of elements, examine the thickness of lunar soil, and evaluate helium-3 occurrence. The probe also studied the environment along the path between the Earth and the Moon.

The cubic-shaped probe weighed 2350 kilograms. Chang'e 1 carried eight scientific instruments that corresponded to 130 kilograms of science payload: a stereo camera system to map the surface in visible wavelengths, an interferometer spectrometer imager for multispectral imaging of the Moon, a laser altimeter for topography measurement, a gamma ray and an X-ray spectrometer to analyze the composition and radioactive components of the Moon, a microwave radiometer to map the thickness of regolith, and lastly a high energy particle detector and solar wind monitor to study space environment. Two solar panel arrays were used to provide power to the spacecraft (NASA, 2005).

The status of the mission

The probe was launched on October 24, 2007. It was set to an impact trajectory with the moon on March 1, 2009. The mission lasted 495 days, which exceeded its planned lifespan of approximately four months. 1.37 Terabytes of raw data were retrieved from the probe which was processed into four Terabytes of science data. The mission achieved a series of scientific results by analyzing the gathered data (Ouyang et al., 2010). Chang'e 1 mission was successful and set the foundations for future missions conducted by the CNSA.

Chang'e 2

Chang'e 2 was designed as a backup probe in case of a potential failure of Chang'e 1. Nevertheless, there were some differences. In comparison, Chang'e 2 featured an improved camera system with a resolution of 10 meters at 100 kilometers altitude and 1.5 meters at 15 kilometers altitude. Its objective was to take high-resolution images of the lunar surface which will be used to select the landing site for the upcoming Chang'e 3. Additionally, this mission was composed of additional objectives not related to the Moon exploration such as engineering tests of the Sun-Earth Lagrangian Point L2 and a fly-by of asteroid Toutatis (Krebs, n.d.-c).

The probe was launched on October 1, 2010, on a Long March 3C booster. It was sent into a 12-hour elliptical lunar polar orbit on October 6. The orbit was adjusted to a 100-kilometer altitude for scientific purposes. After completion of its lunar activity, the spacecraft entered L2 point on August 25, 2011. Chang'e 2 then left orbit on April 15, 2012, to fly within 3.2 kilometers of asteroid Toutatis and capture close-up images while moving at a speed of 10.7 kilometers per second (NASA, n.d.-a).

2.1.2 Chang'e 3

Chang'e 3 was the first mission of the Chinese Lunar Exploration Program (CLEP) to land on the Moon. The landing system comprised two distinct parts: the LLV (Lunar Soft-Landing Vehicle) and the Lunar Surface Exploration Vehicle (rover Yutu)

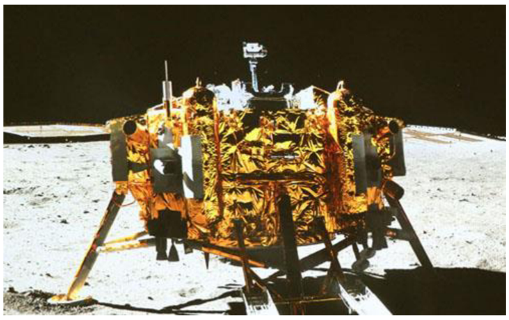

Fig.6. close-up picture of the lander taken by Yutu (Xinhua, 2013a)

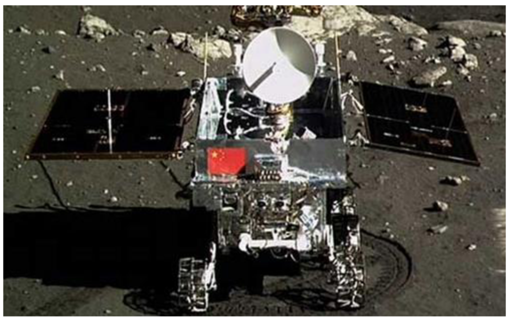

Fig.7. photo of Yutu rover taken by the Chang'e 3 lander (Xinhua, 2013b)

Lander

The lander had a mass of 1200 kilograms with four landing legs which provided a vehicle span of 4.76 meters with a ground clearance of 0.83 meters. It comprised various equipment for orientation and analysis of the lunar environment:

The Descent Camera was located at the bottom part of the lander and was used for the examination and selection of potential landing site at altitudes between two to four kilometers. The camera was designed to be small and lightweight with the capacity to withstand high levels of radiation and vibration. Additionally, it included automatic focusing capabilities.

MastCam was positioned at the top of the mast of the LLV and was used for the survey of the landing area. The camera was also designed to provide multi-color photos and videos of the surface and the operating Yutu rover.

LUT (Lunar-based Ultraviolet Telescope) was used to observe celestial objects from an atmosphere-free environment. The automated telescope mounted vertically on the lander is the first observatory on another celestial body.

Extreme Ultraviolet Imager (EUV) was located on the upper side of the lander. This instrument provided images of the Earth's ionosphere in extreme ultraviolet regions. Moreover, it investigated space weather forecasting and ionosphere studies. It could track Earth automatically and cover a 15-degree field of view in the operational wavelength of 30.4 nanometers. Its objective was to observe Earth's plasmasphere. It was the first camera of its kind to operate on the Moon.

Yutu

The rover had a mass of 120 kilograms. The body was rectangular and was fitted with solar panels for energy production. Additionally, it featured a robotic arm that held parts of the instrument payload. The rover was designed for a three-month-long operation. Since solar power is its only source of energy, the rover featured a sleep mode that deactivated most functions to preserve power during long lunar nights. The movement was realized by a six-wheeled main and sub-rocker-bogie suspension system. Yutu rover was fitted with the following equipment:

PanCam - was located at the topmast of the rover. Its objective was to obtain 3D imagery of the lunar surface for the survey of the terrain, its geological features, and structures. It was additionally used as a monitoring device for the operational status of the lander. It had both manual and automatic focusing ability.

GPR (Ground penetration radar) - was mounted on the bottom part of Yutu. Its objective was to measure the depth of the lunar soil and measure its structural distribution together with lava tubes, magma, and sub-surface rock layers.

VNIS (VIS/NIR imaging spectrometer) - a specialized spectrometer located beneath the top deck of the rover. Its objective was to analyze the composition of the lunar surface through imaging in the visible and near-infrared wavelengths. The protection was provided by an anti-dust accumulation system to repel dust particles which could affect its function.

APXS (Alpha Particle X-Ray Spectrometer) - used for measurements of the composition and distribution of elements on the lunar surface. It could observe the scattered X-rays from the bombardment of alpha particles on selected rocks. It was mounted on the robotic arm of the rover (Kramer, 2016).

The status of the Mission

The spacecraft was launched on December 2, 2013. It was placed into an eccentric polar lunar orbit on December 6. On December 14, Chang’e 3 initiated its landing procedure. During the descent, the spacecraft started collecting scientific data. The lander successfully landed 430 meters east of the crater in northwestern Mare Imbrium. The day after landing, the Yutu rover initiated its separate operation on the surface. Yutu covered 114 meters. In terms of science data, its collecting started during the descent phase. The mission is expected to stay active on the surface for twelve months (Li et al., 2015).

2.1.3 Chang'e 4

The Chang’e 4 is the second lander and rover developed by the CNSA. It is essentially the same system as the Chang’e 3. This mission was intended as a backup mission. However, due to the success of Chang’e 3, the Chang’e 4 was modified for new purposes. The major difference is the science payload and landing location on the far side of the Moon.

Lander

The lander shares the same structure and landing platform as the LLV in the Chang'e 3 mission and comprises the following scientific payload:

Landing Camera (LCAM) - The device is mounted to the bottom of the spacecraft and provides black-and-white visualization of the surface during the descent phase.

Terrain Camera (TCAM) - a color camera on the topmast of the lander. It is designed for observation of the surface and Yutu-2 rover. TCAM provides 360 degrees of coverage.

Low Frequency Spectrometer (LFS) - It is used to study low-frequency radio emissions from the Sun and Moon. Emissions from the Earth are blocked due to the location of the landing.

Lunar Lander Neutrons and Dosimetry experiment (LND) - This experiment was contributed by the German University of Kiel and was designed for dosimetric measurement of radiation in the environment. Data from this experiment will contribute to our knowledge of long-term exposure to radiation for future human missions. Additionally, the LND analyses particle fluxes and their changing patterns on the far side of the Moon (Wimmer-Schweingruber et. al., 2020).

Biological Experiment Payload (BEP) - is the first micro-ecosystem on the Moon. This experiment was conducted in a compartment under atmospheric pressure. It comprised three types of seeds (potato, arabidopsis, rape), fly eggs, yeast, and 18 milliliters of water. Light was provided through a light guide tube (Xie et al., 2023).

Yutu-2

Being based on Yutu 1, it shares the same equipment such as chassis, solar panels, and other components. The major difference is the absence of a robotic arm and different payload which is as follows:

Panoramic Camera (PCAM) - a system of two-color cameras which provide 360 degrees of visual coverage.

Lunar Penetrating Radar (LPR) - used to examine the layers of material under the surface by sending and receiving radio signals. It is designed to map the subsurface up to 300 meters below the surface. (Yirka, 2023) This enables the rover to analyze layers of material that were once lava, thereby studying the early stages of the Moon.

Visible and Near-Infrared Imaging Spectrometer (VNIS) - is used to detect and analyze the composition of minerals on the lunar surface. It is based on the VNIS of Chang'e 3 mission. This version received a software update.

Advanced Small Analyzer for Neutrals (ASAN) - is a compact mass-resolving energetic neutral atom analyzer. Its objective is to measure energetic neutral atoms. The atoms were investigated using an electrostatic analyzer (Wieser et al., 2020).

Landing site & Queqiao 1

The landing site of Chang'e 4 mission is the Von Kármán crater which is located in the southern hemisphere of the far side of the Moon. Such a location prevents direct communication access between the Earth and the spacecraft. It is therefore necessary to establish connection through a satellite that can transfer signals from the landing site to the Earth Center.

This problem was solved by Queqiao 1, a relay communication satellite on the Earth-Moon L2 Lagrange point. It is equipped with a 4.2-meter deployable antenna which provides four 256 kBps X-band links with the lander & rover and one 2 MBps S-band for connection with Earth (Krebs, n.d.-d).

The status of the mission

Queqiao 1 was launched on May 21, 2018, and was successfully inserted on the L2 point becoming the first satellite to provide communication coverage of the far side of the Moon. The lander and Yutu-2 launched on December 8, 2018, and landed in the Von Kármán crater on January 3, 2019 (Li et al., 2021). As of 2024, both the lander and rover are still operating on the surface exceeding their planned length of mission of twelve and three months respectively.

2.1.4 Chang'e 5

The Chang'e 5 is the latest mission conducted by CNSA designed to land on the Moon and return samples for analysis on Earth. The spacecraft was a combination of four sub-systems: a service module, a lander, an ascender, and an Earth re-entry module (returner). Each sub-system contributed to achieving the main objective. Lander ensured soft landing and mining of regolith, gathered material was transferred to ascender which set to orbit to dock with returner and performed the second transfer of material. Returner docked with the service module and then set towards Earth. In the final phase, the two systems decoupled, with the returner reentering the Earth (Kramer, 2020).

Subsystems

The service module was a vital part of the whole system. It was equipped with solar panels to power the onboard batteries. Furthermore, it provided uplink and downlink communication with the Earth Center. A throttleable propulsion system of the service module enabled the whole system to perform correction in trajectory, orbital maintenance, overall propulsion capabilities on lunar orbit as well as the final trans-Earth injection burn on the journey back together with the returner.

In terms of the returner, it was a scaled-down and repurposed version of the Shenzhou module used for human spaceflight missions. To endure re-entry, the subsystem was protected with a heat shield able to withstand speeds up to eleven kilometers per second. Additionally, the returner was equipped with a parachute and thrusters to control orientation relative to Earth during reentry to achieve safe re-entry. Moreover, trusters altered the reentry path to reach the desirable landing location.

The lander had a dry mass of one metric ton. With oxidizer and fuel, the weight increased to 3 800 kilograms. The landing module was derived from the lander used in the Chang'e 3 mission. The lander was modified to carry an ascender and a coring drill instead of a rover. The drill was designed to collect multiple samples in depths of two meters. After drilling, the material was then stored in a protective tube made of Kevlar and transferred to the ascent module.

The delivery of samples from the lander to the orbiter (service module) was provided by the ascent module. To achieve this task, the subsystem was equipped with a spring that ejected the ascender from the lander into a safe distance to ignite its main engine. Rendezvous with the service module was accomplished using sensors, and laser range finder adopted from the Shenzhou module. The docking itself was achieved by three claws, spaced 120 degrees apart, that firmly locked the ascender with the service module (Kramer, 2020).

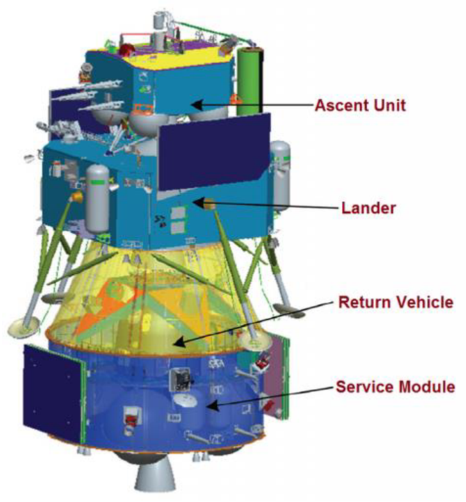

Fig. 8. The four subsystems of Chang'e 5 during travel configuration (Blau, n.d.)

In terms of the additional payload, the Chang'e 5 was fitted with a Panoramic Camera (PCAM) for observation of surroundings and a landing Camera (LRPR) for the landing sequence. Furthermore, the spacecraft carried a visible and near-infrared Lunar Mineralogical Spectrometer (LMS) used for analysis of the lunar soil. This task was also fulfilled by the Lunar Regolith Penetrating Radar or LRPR (NASA,2020).

Status of the mission

Change' 5 was successfully launched on November 23, 2020. It executed two planned correction maneuvers in the following two days. The spacecraft reached lunar orbit on November 28 after the seventeen-second-long ignition of its engine. The following day, while orbiting at an altitude of two hundred kilometers, the landing procedure started with the decoupling of the descender (lander and ascender). The lander successfully landed in the Mons Rumker region. Most of the activities, and experiments on the surface occurred within the first forty-eight hours.

The lander performed fifteen sampling runs of drilling and scooping. The mission extracted 1.731 kilograms of lunar regolith. The samples were placed into the ascender, which lifted off on December 3 and docked with the orbiter two days later. The cargo was inserted into a sealed container. This was the final task of the ascender which subsequently decoupled from the orbiter and was deorbited. After five days, the return journey was initiated. The service module separated from the returner and started its secondary objective for observation of the Sun in the L1 point. The returner successfully landed on December 17, in the autonomous region of Inner Mongolia in north China, completing the main objective (NASA,2020).

2.2 Indian Moon Program

2.2.1 Chandrayaan-1

The first Moon mission conducted by ISRO was the Chandrayaan-1. It was a combination of two modules, an orbiter, and an impactor with a combined weight of 1380 kilograms. The main objective was to obtain a detailed mapping of the surface's chemical, mineralogical, and photogeologic properties. To achieve the set objectives, the spacecraft carried eleven scientific instruments, five of which were produced domestically and six imported. The following list provides a description of onboard instruments and their objectives:

Terrain Mapping Camera (TMC) - used for the preparation of a three-dimensional atlas with high spatial and elevation resolution. It featured panchromatic spectral region of 0.5 to 0.85 micrometers and measured the reflected solar radiation from the surface.

Hyper Spectral Imager (HySI) - its objective was to scan the mineral composition of the lunar surface using mapping in 64 contiguous bands in the VNIR. Tele-centric refractive optics were used for scanning the surface.

Lunar Laser Ranging Instrument (LLRI) - used to determine the range between the spacecraft and the Moon via a laser rangefinder. A pulse of light was directed towards the surface. Part of the light was reflected towards the spacecraft, and by measuring the round-trip travel time, it was possible to determine the relative distance.

High Energy X-ray Spectrometer (HEX) - its objective was to detect radioactive emissions and describe lunar terrain in terms of chemical and radioactive composition. Additionally, HEX studied the possibility of water presence near polar regions.

Moon Impact Probe (MIP) - the 35-kilogram heavy impactor was intended to decouple from the orbiter and set itself to an impact trajectory using a small propulsion motor. Decoupling occurred at an altitude of a hundred kilometers. This event was followed by a controlled twenty-five-minute-long descent. Its main objective was to demonstrate controlled descent while gathering and sending data. Experience from the maneuver was utilized in the Chandrayaan-3 lander mission. The impactor was equipped with a radar altimeter to measure the relative altitude to the surface, a video imaging system provided by an analog CCD camera, and a mass spectrometer used for the measurement of the composition of particles in the environment near the surface. The impactor was sending data every four seconds until impact.

Chandrayaan-1 X-ray Spectrometer (C1XS) - was used to conduct high-quality X-ray spectroscopic mapping of the surface. The experiment was aimed at studying the abundance and distribution of materials such as Aluminum Magnesium, and silicon. The C1XS studied the evolution of lunar soil together with the Moon.

Mineralogy Mapper (M3) - the M3 differed in specifications compared to the C1XS. It utilized a high throughput push-broom imaging spectrometer for the measurement.

Near Infrared Spectrometer (SIR–2) - this spectrometer was particularly designed to study crater formation on the Moon, space weathering, and localization of minerals suitable for upcoming exploration on the surface via landers.

Sub keV Atom Reflecting Analyzer (SARA) - imaged the surface using low energy neutral atoms in the energy range of 10 eV to 3.2 keV for imaging the magnetic anomalies, interaction of solar wind with the surface, and overall composition of permanently shadowed areas. These areas were also studied by Miniature Synthetic Aperature Radar (Mini SAR) designed to increase the overall ability of the spacecraft to detect water at a depth of a few meters.

Radiation Dose Monitor (RADOM) - was used to measure radiation in an environment near the lunar surface. It conducted numerous measurements of particle flux, deposited energy spectrum, and doses of radiation at given altitudes. Data from this instrument was used for the evaluation of shielding requirements for future manned missions.

The status of the mission

The Chandrayaan-1 was launched on October 22, 2008, and successfully reached the projected 100 x 100 km orbit above the surface. Upon reaching the given orbit, the Chanrayaan-1 started conducting experiments on board. It was the first spacecraft to detect Hydroxyl and water molecules on the lunar surface. Additionally, the spacecraft provided detailed mapping of the surface. It studied lava tubes and discovered evidence of lava vents that were only approximately one hundred million years old. After completion of experiments, the spacecraft was raised to a 200-kilometer orbit to decrease the temperature of the system. On August 29, 2009, the control center lost communication with the spacecraft; however, the set objectives were achieved which resulted in the successful termination of the mission (ISRO, n.d.).

2.2.2 Chandrayaan-3

The Chandrayaan-3 was the backup mission of the Chandrayaan-2 which failed to land on the Moon. The configuration consists of a Lander Module called Vikram (LM), rover Pragyan, and a Propulsion Module (PM), which transported the two spacecraft to a proximity of 100 kilometers above the lunar surface. The objective of the mission was to achieve a safe landing at the South Pole, deploy the rover, perform a demonstration of roving, and conduct experiments with the delivered payload (ISRO,2023).

Propulsion Module (PM)

This module of a prismatic shape weighed 2148 kilograms and its main objective was to ferry the Lander Module from GTO (Geostationary Transfer Orbit) to the final lunar polar circular orbit and separate the Lander. It was equipped with a single 440 N engine. A rectangular solar panel provided power for the system. The PM was connected to the LM through an IMA cone. Telemetry of the module was provided by a TTC antenna. Additionally, the PM had one experimental payload called SHAPE (Spectro-polarimetry of Habitable Planet Earth) which is aimed at studying spectro-polarimetric signatures of Earth in near-infrared (NIR) wavelength (ISRO,2023).

Lander module (LM)

The LM is a two-module configuration that accommodates the rover inside. The Lander Vikram follows the shape of a prism that weighs 1752 kilograms. For its landing sequence, the bi-propellant propulsion system facilitates four nozzle engines that produce up to 800 N of thrust. The engine used MMH + MON3 as fuel and was accompanied by an additional eight engines for maneuverability. All engines were throttleable. The module was fitted with landing legs, a rover ramp for the deployment of Pragyan, and an X-Band antenna for communication (ISRO,2023).

Scientific equipment on board of the lander Module:

Radio Anatomy of Moon Bound Hypersensitive Ionosphere and Atmosphere (RAMBHA) - to study the temporal evolution of electron density in the Lunar ionosphere.

Chandra's Surface Thermophysical Experiment (ChaSTE) - measured the temperature of the topsoil around the polar region on the Moon.

The Instrument for Lunar Seismic Activity (ILSA) - uses six high-sensitivity accelerometers to measure ground vibrations generated by impacts, quakes, and other events.

LASER Retroreflector Array (LRA) - a passive instrument used to precisely determine the location of the lander.

Pragyan Rover

In comparison to Yutu, the Pragyan is a relatively small rover that weighs only 26 kilograms. It is based on a six-wheeled rocker-Bogie chassis. Most of the electronics are protected inside a warm electronic box, housing the differential, rover hold down, and solar panel hold down. In terms of exterior equipment, it was fitted with one rectangular solar panel and faced perpendicularly to the rover when extended. Rx/Tx antennae were located on the top of the extended solar panel. These were used exclusively for communication with the Lander Module. For orientation, the Pragyan used two navigation cameras facing forward direction (ISRO,2023).

Scientific equipment on the Pragyan Rover:

LASER Induced Breakdown Spectroscope (LIBS) - to investigate the chemical composition of the Moon's surface through elemental analysis by subjecting materials to concentrated laser pulses produced by the device.

Alpha Particle X-ray Spectrometer (APXS) - to determine the elemental composition of lunar materials (AI, K, Mg, Si, and Fe).

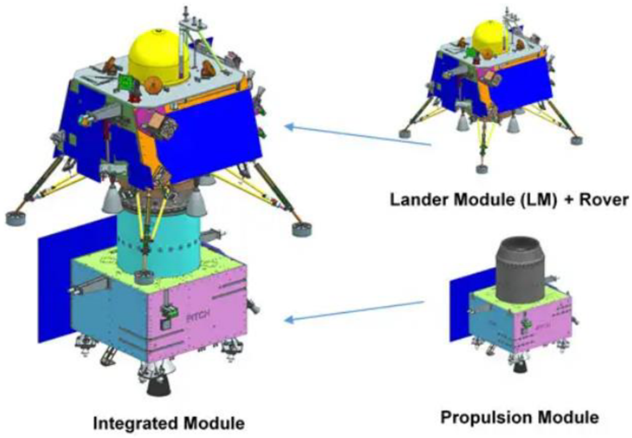

Fig. 9. Visualization of Chandrayaan-3 modules (ISRO, 2023)

The status of the mission

According to the report by the Ministry of Information and Broadcasting of India, the Chandrayaan-3 was launched on July 14, 2023, by the LVM3 M4 launching vehicle. It executed four orbit-raising maneuvers between July 15 and July 25 before its final TLI (Trans Lunar Injection) on August 1. The spacecraft achieved an elliptical orbit of 164 kilometers apoapsis and 18 074 kilometers periapsis. The orbit was consequently reduced to 151 by 179 kilometers. On August 17, the propulsion module separated from the rest of the vehicle which then initiated two separate deboosting phases to reach an altitude of 25 kilometers above the surface. The final powered descent was planned for August 23. The Chandrayaan-3 successfully landed with the message "I reached my destination, and you too".

On the surface, the Pragyan rover drove from the ramp on August 24. Throughout the rest of the month, the lander and rover conducted various experiments with their payload:

ChaSTE - measured the temperature of the topsoil to a maximum depth of 10 centimeters.

LIBS - confirmed the presence of Sulphur (S) through in-situ measurements.

APXS -detected the presence of minor elements (Sulfur, Aluminium, Silicon, Calcium, and Iron)

ILSA -measured ground vibrations produced by Pragyan's roving.

RAMBHA-LP - measured plasma content near the surface.

On September 4, both Lander and Rover achieved their objectives and finished their activities and were put in "sleep mode". Most of the systems were shut down to preserve electricity. The awakening of the pair was expected around September 22; however, the ISRO was unable to establish communication with both vehicles and therefore declared the mission complete (MOIBGOI, 2023).

2.3 Private Sector

Traditionally, spaceflight was funded by the governments of each representative country. The accessibility of these missions is constrained by the high cost per kilogram of payload delivered into orbit. This, however, has changed in recent years with the arrival of Falcon 9, a two-stage rocket, produced by private company SpaceX. From the economical perspective of rocket construction, the propulsion system is typically the most expensive part of a rocket. The Falcon 9 is the first rocket with the ability to land and reuse its first stage containing nine out of a total of ten engines. This enables SpaceX to significantly lower the price for their customers, including government contracts and contracts from private companies. Together with the help of NASA, numerous private companies are developing their spacecraft including lunar landers. The following chapter will focus on the first successful lunar landing conducted by the private company Intuitive Machines and its Nova-C lander.

2.3.1 Nova-C lander

The lander was intended to deliver payloads provided by NASA and other contractors to the lunar surface. Apart from its main objective of payload delivery, the lander should demonstrate precise landing technology. In terms of scientific objectives, the mission aimed to study space weather interaction with the lunar surface and provide radio astronomy capabilities (NASA, 2024).

As far as the construction of the lander is concerned, according to the press kit published by the company, the spacecraft follows a hexagonal shape, is 4.3 meters tall, and 1.6 meters wide. The spacecraft was equipped with six landing legs providing a span of 4.6 meters. The spacecraft weighed 675 kilograms and was capable of delivering up to 130 kilograms to the lunar surface. It was powered by fixed solar panels on the roof and sides of the lander. The landing was achieved using a 3D-printed engine powered by a mixture of liquid oxygen and liquid methane (Marshall,2024).

Payload

In terms of NASA's onboard instruments, Nova-C carried ROLSES (Radio Observations of the Lunar Surface Photoelectron Sheath). Its objective was to measure the electron plasma in the lunar environment by using a low-frequency radio receiver system. Moreover, it observed radio sources from the Sun and planetary objects. The instrument measured radio environment in the 10 kHz – 30 MHz range.

LRA (Laser Retro-Reflector Array) is an array consisting of eight retro-reflectors. It will be used as a precise landmark for guidance and navigation for future missions in the region.

In terms of instruments intended for the descent phase, NDL (Navigation Doppler Lidar for Precise Velocity and Range Sensing) provided velocity and range measurement by using lasers. SCALPSS (Stereo Cameras for Lunar Plume-Surface Studies) was used for the analysis of dust scattering created by the propulsion system as it approached the surface.

LN-1 (Lunar Node 1) was a small CubeSat intended to provide S-band radio navigation to increase efficiency and precision of future lunar landings.

Lastly, the RFMG (Radio Frequency Mass Gauge) used radio waves to measure the amount of propellant in Nova-C's tanks. This gauge tested high-precision monitoring to increase the fuel economy of spacecraft.

The lander also carried payloads of private companies. The first was provided by the International Lunar Observatory Association. Their ILO-X is a dual-camera system, one wide field, and the other narrow field. Its objective was to conduct astronomy and capture the first images of the center of the Milky Way from the lunar surface.

In terms of visualization of the surroundings, Eaglecam, created by Embry-Riddle Aeronautical University, is a camera designed to capture third-person images of the lander. The camera was intended to deploy before landing at an altitude of thirty meters above the surface.

The rest of the commercial payload was intended for sponsorship, symbolic, and artistic purposes. Columbia sportswear tested Omni-Heat Infinity, a thermal reflective fabric tuned according to the standards of the aerospace industry, Jeff Koons created a group of sculptures to celebrate human curiosity and desire to achieve. Lastly, Lunaprise, organized by Galactic Legacy Labs, serves as a database for the preservation of human knowledge (Marshall,2024).

Fig. 10. Nova-C lander (Pearlman, 2023)

The status of the mission

The IM-1 launched on 15 February 2024, on the Falcon 9 rocket. The lander started its operation in a 185 by 60,000 kilometer orbit around the Earth. After the translunar injection and a correction maneuver, the Nova-C was put on a circular orbit at an altitude of one hundred kilometers above the Moon. The landing was completed on February 22. It landed in a Malapert crater on a slope of approximately twelve degrees. The lander miscalculated its velocity and experienced a “rough-soft” landing, during which a part of the landing gear sustained damage upon impact. This resulted in the Nova-C bouncing from the surface and then tipping over. Currently, the spacecraft is resting at an angle of thirty degrees relative to the horizon. Nevertheless, the science payloads were able to operate; however, due to the inappropriate angle of solar panels, the lander lost power supply on February 28, ending the mission (NASA, 2024).

2.4 Near future of lunar exploration

The future of the exploration of the Moon is highly influenced by the Chandrayaan-1 mission which, as already mentioned in the chapter on Indian exploration, found evidence of water presence near the permanently shadowed craters at the South Pole. Various agencies are now aiming to study the region for additional evidence.

Confirmation of water presence would open new possibilities. Molecules from H_2O can be split into hydrogen and oxygen which could be utilized for the production of rocket fuel, oxygen, and water for future colonies on the Moon. The following chapter will focus on a promising project that is scheduled to launch at the end of 2024.

2.4.1 Griffin Mission and rover VIPER

Griffin Mission developed by NASA is an upcoming mission of a roving vehicle to operate near the south pole of the Moon. According to NASA, the spacecraft will launch using a Falcon Heavy rocket provided by SpaceX. The main objective of the mission is to study regolith and its potential presence of water and other volatile substances. The mission will additionally focus on the origin of water and its distribution on the Moon. The gathered data will be used for upcoming missions aimed at the extraction of water from the soil. Furthermore, the mission serves as a technology demonstration for operations in the extreme environment of the lunar South Pole, which is characterized by rugged terrain, extremely low temperatures, and changing lighting conditions. The spacecraft will test power generation technologies and storage capabilities. Lastly, NASA, through its Commercial Lunar Payload Services (CLPS), will offer dedicated compartments to commercial customers and their payloads (NASA, n.d.-b).

In terms of the description of the vehicle, the VIPER's dimensions are 1.5 x 1.5 x 2.5 meters making it one of the largest robotic rovers intended for Moon exploration. The 430 kilograms heavy vehicle is powered by a solar array with a power output of 450 W. Maximum speed is 0.8 kilometers per hour. The four-wheeled semiautomatic vehicle will be primarily controlled from the Earth Center (NASA, n.d.-b).

Fig. 11. Testing of VIPER rover's wheel movement and rotation (NASA, 2024)

Payload

VIPER will carry scientific equipment to fulfill its objectives. <u>TRIDENT or The Regolith and Ice Drill for Exploring New Terrains</u> will be used to perform drilling at depths of up to one meter. Being developed by Honeybee Robotics, it is a rotary percussive drill that uses both rotational forces to cut the ground and hammer to the soil to improve the overall efficiency of drilling. The drilled material will be accumulated on the surface in the form of a pile. The drilled material will be analyzed by the equipment on the rover (NASA, n.d.-c).

In terms of analysis of surrounding particles, the <u>NSS: Neutron Spectrometer System</u> will focus on the indirect detection of water in the lunar soil. This will be done by measuring alternations in the number and energy of neutrons radiating from the surface. If the neutron collides with hydrogen (a component of a water molecule), it loses a noticeable amount of its energy. These potential shifts will be measured by the NSS.

The next piece of equipment is the NIRVSS: Near-Infrared Volatiles Spectrometer System aimed at studying the hydrogen detected by the NSS. It will determine if the hydrogen belongs to water molecules, solely hydrogen, or other compounds containing hydrogen such as hydroxyl. Furthermore, the NIRVSS will analyze minerals and ices containing carbon dioxide, methane, and ammonia.

MSolo: Mass Spectrometer Observing Lunar Operations will analyze dust that will be lifted after the landing of the vehicle to determine whether the material originated from the lander or the surface. Additionally, Msolo will analyze volatile material drilled by TRIDENT. (NASA, n.d.-c)

CONCLUSION

Humanity started to take a closer look at the Moon at the end of the 1950s. The beginnings of lunar exploration were dominated by the Soviet Union and the United States. The ongoing Space Race allowed both agencies to make large investments in spaceflight.

Prior to robotic missions, the nature of the Moon was not well known. The arrival of scientific equipment on board various probes provided data revealing many aspects of our only natural satellite. New discoveries started with the first lunar mission, the Soviet Luna 1, which proved that the Moon does not have a magnetic field. The Americans also contributed to exploration with the Ranger program which depicted and described topography of the Moon.

As the Space Race progressed and missions became increasingly more ambitious, it became possible to take a closer look at the Moon by surficial missions. The Soviet Luna 9, followed by the American Surveyor 1, were the first spacecraft to achieve a soft landing. Before these landings, scientists were not certain about the density of the lunar soil which raised concerns about the feasibility of landing on the Moon. However, these missions successfully landed, documented the surface properties, and paved the way for future surface exploration missions.

The culmination of the Space Race was a manned landing on the Moon, an objective pursued by both the Soviets and the United States. The Soviet engineers failed to construct their heavy-lift rocket N-1 required for manned missions. Consequently, NASA's Saturn V successfully launched its lunar modules, delivered two astronauts to the surface of the Moon, and achieved not only a victory in the Space Race but also an extraordinary milestone for all of humanity.

The intensity of lunar exploration plummeted after the eleventh Apollo landing due to the lack of competition that had previously justified investment in expensive lunar programs. Intensive exploration resumed in the 2000s with the arrival of new space agencies of China and India. The Chinese Chang'e 3 and 4 missions sent two pairs of landers and rovers with numerous experiments to study yet unexplored locations. The Chang'e 4 was the first lander to land on the far side of the Moon. These missions investigated the chemical composition of lunar soil, measured temperature, studied cosmic rays, performed astronomical observation using a radio telescope, and conducted the first miniature biological experiment on the Moon. The Chang'e 5 lander extracted 1.731 kilograms of lunar regolith and delivered the material back to Earth. It was a purposely sophisticated mission that tested the capabilities of their spacecraft design and set the foundations for future missions.

Indian program contributed to two scientific missions. The first mission Chandrayaan-1 is considered to be one of the most influential missions in modern lunar exploration. The orbiter discovered evidence of water in craters at the South Pole. The bottoms of these craters have not received sunlight for millions of years, potentially hosting ice deposits of water. The second mission was the Chandrayaan-3 mission. It was the first landing in the South Pole region. The mission comprised lander Vikram and rover Pragyan. This pair measured temperature, studied seismic activity, occurrence of plasma, and chemical composition of the surface. The major discovery of Chandrayaan-3 was the detection of Sulphur on the surface. Overall, the findings of the Indian lunar program inspired other agencies to search for water and volatiles near the South Pole.

The year 2024 marked the maiden landing conducted by the private company Intuitive Machines. The objective of the mission was to deliver payload to the lunar South Pole. The success of their Nova-C lander was affected by an inappropriate landing that led to the spacecraft capsizing on its side. This event prevented the spacecraft from receiving enough energy from the solar panels, therefore, the mission was terminated earlier than expected. Nevertheless, the lander was still regarded as successful for delivering payloads from their customers to the South Pole of the Moon.

The future of surficial exploration of the Moon remains focused on the South Pole and the search for water. This will be the main objective of the rover VIPER. Introduced by NASA, the vehicle will explore the bottoms of craters with equipment specially designed for detecting water and other frozen substances. The projected launch is set for the end of 2024, and its potential confirmation of water presence could open new possibilities for future colonies. Potential deposits of water will enhance the value of our only natural satellite by enabling the production of rocket propellants directly on the surface. Future manned missions could utilize water for drinking and split water molecules to create oxygen for breathing. This would make a long-term human presence on the Moon more feasible by reducing the need to transport resources from Earth.

Rozšířený Abstrakt

Tato bakalářská práce se zabývá popisem průzkumných misí, které přispěly k našemu lepšímu pochopení Měsíce. Dokument obsahuje časové spektrum vesmírných lunárních misí. Hlavním cílem bylo detailně analyzovat cíle, technickou stránku vesmírných lodí a provedení jejich letů.

První kapitola se věnuje historickému vývoji průzkumu Měsíce v rámci vesmírných závodů mezi Spojenými Státy a Sovětským Svazem. Po stručném popisu prvních vesmírných sond jako jsou Sputnik 1 a Sputnik 2 kapitola přechází do misí, které se věnovaly samotnému průzkumu Měsíce. Tyto mise byly zpočátku prováděny pomocí takzvaných nárazových sond, které cíleně směrovaly svoji trajektorii vůči Měsíci a sbíraly data během letu až do samotného zničení nárazem. První dva lety této třídy sond byly vyslány Sovětským Svazem. Luna 1, vyslaná v roce 1959, sice svůj cíl netrefila, ale její průlet vedl k objevu, že Měsíc nemá magnetické pole, a také potvrdila existenci slunečního větru. První úspěšný zásah byl zaznamenán Sovětskou sondou Luna 2. Tento úspěch byl jeden z mnoha důležitých milníků v rámci vesmírného závodu. Tento milník dokázaly Spojené Státy splnit až po šesti letech v rámci programu Ranger, jehož sondy byly vybaveny kamerami, které během letu mapovaly topografii Měsíce.

Podkapitola 1.4 se věnuje dalšímu důležitému milníku v rámci vesmírného závodu, a to měkkému přistání přistávacího modulu na Měsíci. V této disciplíně se mezi dvěma rivaly výrazně lišila metoda přistání. Zatímco Sovětská Luna 9 provedla historicky první přistání lidstva na Měsíci pomocí airbagového systému, Spojené Státy implementovaly konvenční způsob přistání užitím tří přístávacích noh. Tyto přistávací moduly patřící do třídy Surveyor byly v porovnání komplexnější a jejich metoda přistání byla vhodná pro implementaci do budoucích přistání s posádkou.

Následující podkapitola 1.5 se zaměřuje na dosud jediný úspěšný program zaměřený na lety na Měsíc s posádkou. V této části jsou mise Apolla stručně shrnuty a převažuje technický popis jednotlivých modulů. Tento druh mise se celkem skládal z tří speciálních modulů, které společně zajistily přepravu astronautů z orbity Země na Měsíční povrch i jejich návrat na Zemi. Prvním modulem byl takzvaný servisní modul

(Service Module), který byl vybavený raketovým motorem, manévrovacími tryskami a zajistil uskladnění paliv a kyslíku. Tento modul byl připojený na velitelský modul (Command Module), ve kterém posádka řídila operace a trávila většinu času mise. Posledním modulem byl modul přistávací (Landing Module), který zajistil přepravu dvou ze tří astronautů na Měsíční povrch. Tento modul byl rozdělen na sestupovou a vzestupovou část. Obě části byly vybaveny vlastním motorem a prostředky nutnými k dosažení cílů mise. Po dokončení všech operací na povrchu se vzestupová část odpojila od zbytku lodě a vzlétla směrem k velitelskému modulu. Posádka tří astronautů byla poté společně přepravena zpět na Zem.

Po sovětské robotické misi Luna 24, která provedla extrakci lunárního regolitu v rámci takzvané sample-return mise, průzkum povrchu pomocí přistávacích modulů a vozítek utichl. Tento typ misí byl obnoven příchodem nových vesmírných agentur Číny a Indie a jejich programů. Kapitola 2.1 se věnuje Čínské agentuře CNSA, která uskutečnila celkem tři přistání. První přistání bylo realizováno misí Chang'e 3. V roce 2013 dopravila mise na Měsíc přistávací modul a vozítko Yutu, díky kterým byly provedeny vědecké experimenty, analýza povrchu a pozorování vesmírných objektů ultrafialovým dalekohledem. V roce 2018 následovala mise Chang'e 4, která byla původně záložní misí v případě selhání Chang'e 3. Následovala tedy podobnou koncepci s upravenými cíli mise. Mise se zasloužila o vůbec první přistání na odvrácené straně Měsíce a také o první biologický experiment provedený na jeho povrchu. Chang'e 5 provedla v roce 2020 pomocí konfiguraci čtyř různých modulů extrakci vzorků z Měsíčního povrchu a dopravila materiál zpět na Zemi k analýze.

Kapitola 2.2 obsahuje shrnutí dvou úspěšných lunárních misí Indické agentury ISRO. V roce 2008 byla vyslána sonda Chandrayaan-1, která analyzovala Měsíční povrch a prováděla mapování topografie z jeho orbity. Sonda byla také vybavená malou nárazovou sondou určenou k uvolnění vrstvy lunárního materiálu jižního pólu, který byl poté analyzován orbitální sondou. Tato mise stála za prvními definitními důkazy výskytu zmražené vody na Měsíci. Další misí byl Chandrayaan-3, která byla určena k průzkumu jižního pólu. Jednalo se o pohonný modul, přistávací modul Vikram a vozítko Pragyan. Je to první mise, která operovala na povrchu jižního pólu Měsíce. Mise Chandrayaan-3 provedla analýzu místního povrchu, měření teploty a seismické aktivity. Mimo vědeckých cílů mise sloužila jako technologická demonstrace měkkého přistání na Měsíci.

Následující podkapitola 2.3 je zaměřená na vstup soukromého sektoru do oblasti průzkumu Měsíce. Jedna z nejdůležitějších metrik pro soukromé společnosti je cena za kilogram nákladu vynesený na orbitu. Tato cena se podařila snížit pomocí ekonomicky efektivních raket konstruované americkou technologickou společností SpaceX.

Tato nově vyskytnutá příležitost byla využita firmou Intuitive Machines, která navrhla svůj vlastní přistávací modul Nova-C. Modul byl částečně financován v rámci projektu CLPS (Commertial Lunar Payload Services), který zavedla agentura NASA. Projekt byl dále financován kontrakty soukromých zákazníků. Cílem této mise bylo dopravit náklad poblíž jižního pólu. Přistávací modul byl vynesen raketou Falcon 9. V únoru 2024 se Intuitive Machines podařilo jako první soukromé společnosti přistát na Měsíci. Při přistávací sekvenci došlo k neplánovanému převrácení modulu na jeho bok, což vedlo k omezení signálu a výroby energie solárními panely. Přesto byla mise prohlášena za zdařilou, jelikož úspěšně dopravila náklad na cílené místo.

Poslední kapitola se zabývá blízkou budoucností Měsíčního průzkumu. Budoucí mise by se měly zaměřovat zejména na oblast jižního pólu. Cílem těchto přistávacích modulů a vozítek bude analýza místního povrchu a pokračování v hledání zmrazených molekul vody a dalších substancí skrytých v nánosech ledu. NASA pro tento účel vyvíjí vozítko VIPER v rámci mise Griffin, která je popsána v kapitole 2.4. Plánovaný start mise je momentálně stanoven na poslední čtvrtletí roku 2024. Aby vozítko splnilo cíle mise, je vybaveno speciální vrtačkou TRIDENT, která je schopná vrtání materiálu do hloubky až jednoho metru. Vyvrtaný materiál bude nahromaděn na povrch a podroben analýze. Vozítko je vybaveno trojicí spektrometrů, které mají zkoumat vyvrtaný materiál a okolní prostředí. Vědecké vybavení se bude zaměřovat na detekci minerálů a ledů obsahující oxid uhličitý, metan a amoniak.

LIST OF FIGURES

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LIST OF ABBREVIATIONS

NASA	National Aeronautics and Space Administration
CNSA	China National Space Administration
ISRO	Indian Space Research Organisation
VHF	very high frequency
RCS	reaction control system
TTC	Telemetry, Tracking and Command
VNIR	Visible and Near-Infrared
LLV	Lunar Soft-Landing Vehicle