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Analysis of the Facilities and State-of-Art Proposals for Deep-Space Exploration

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Abstract:

Deep-space exploration has made significant progress in recent years, with several missions pushing the limits of the knowledge of the solar system. The aims of this study are to analyze recent advances in deep-space exploration, emphasizing significant missions and the cutting-edge instruments they use. The study analyzes the scientific contributions made by the technological facilities and cutting-edge spacecraft used in the major space programs. By examining these programs and instruments, their feasibility in studying planetary surfaces, atmospheres and the wider space environment is discussed. The findings emphasize the critical role of future AI autonomous systems, advancing technological innovations and international cooperation in driving deep-space exploration forward. The significance of this study is that it summarizes the current state of deep-space exploration today and anticipates further advances, and that continued advances in the field of advanced technology will provide a powerful aid to human exploration of outer space and gradually deepen the understanding of the solar system.

Keywords: Deep-space exploration; space missions; technological innovations; AI autonomous systems; international cooperation.

1. Introduction

Since the 1950s, space exploration has gradually emerged as a field of scientific inquiry, initially driven by the Cold War space armaments competition between the United States and the Soviet Union. In 1957, the Soviet Union successfully launched the world‘s first artificial satellite, Sputnik 1, which marked the beginning of human space travel [1]. In the subsequent decades, the United States assumed the vanguard position with the Apollo program, achieving the inaugural human landing on the moon in 1969. In contrast, the Soviet Union concentrated its efforts on unmanned exploration and Mars exploration. These initial achievements established a robust foundation for space exploration and propelled significant advancements in aerospace technology. The evolution of deep-space exploration over the last 50 years may be classified into three stages: a period of competition, a period of silence, and a period of maturity. The period of competition, from 1960 to 1979, was characterized by a mutual demonstration

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of will and strength between the USSR and the United States, during which technology developed rapidly, while the period from 1980 to 1994 was one of silence. A period of maturity began in 1995, with scientific goals as the main driver [2].

In the ensuing decades, space exploration has evolved from a competing U.S.-Soviet endeavor to a global endeavor involving multiple nations and international cooperation. In the mid-1990s, countries such as China, Japan and the European Space Agency (ESA) joined the ranks of spacefaring nations and gradually began research into space exploration. 2021 saw the successful arrival of China‘s first man-made Mars satellite, Astronomy-1, which deployed the “Zhu Rong” [3]. The Zhu Rong rover, a major achievement of China‘s space program, is equipped with a variety of advanced instruments and is designed to study the Martian atmosphere, surface structure, and underground water ice, among other tasks. Meanwhile, China‘s lunar probes Chang‘e-4 and Chang‘e-5, as well as Chang‘e-6, which will be launched in the first half of 2024, have all achieved technological breakthroughs in lunar exploration These include China‘s first unmanned lunar sample return mission with Chang‘e-5 and the world‘s first lunar backside landing and takeoff sampling mission with Chang‘e-6. The U.S. also continues to delve deeper into the field of space exploration, with notable missions including NASA‘s Curiosity and Eternity Mars rovers, which are conducting extensive research on Mars‘ continents, terrain, and trying to find signs of past life [2]. As mission difficulty rises and countries focus on economic efficiency, more and more countries are engaging in international cooperation to accomplish deep-space exploration missions [3]. Thus, China and Russia have proposed the International Lunar Research Station (ILRS), which is intended to serve as a base for long-term lunar research, resource utilization, and technology testing [4]. ESA‘s Jupiter Explorer “JUICE” will explore Jupiter and its moons, studying their atmospheres and topography to find if habitable environments exist, reflecting the close cooperation of European countries in exploring the planet. This is an implication of the cooperation of European countries when it comes to the frontiers of deep-space [5]. Many countries have also examined deep-space exploration with regard to asteroids and small bodies, which are considered to be a part of the evolution of the solar system. Japan has put a focused emphasis in this area with the mission of Hayabusa-2 probe that brought the asteroid “Ryugu” from the moon of Jupiter [6]. “Ryugu”, which has played an crucial role in future research on the composition and development of these asteroids and small bodies in the future [7].

However, as deep-space exploration missions have become more complex over time, it has become especially important to research new technologies to accomplish deep-space exploration missions. By innovating technologies such as spacecraft propulsion systems, communication networks, and automated robotics, one is able to explore more distant objects and accomplish more complex missions. NASA‘s new “NEXT” ion propulsion system has higher power and thrust than traditional chemical propulsion, allowing for power-driven missions with fewer thrusters [8]. In addition, new energy sources such as nuclear energy are also being investigated by national space agencies to allow spacecraft to achieve a wider range of distances in the solar system.

Therefore, against this background, this paper focuses on analyzing and studying some of the cutting-edge instruments and equipment in the field of deep-space exploration in recent years, as well as examining and discussing some of the limitations of present-day deep-space exploration and suggestions for future exploration missions. The format of this paper is as follows. Section 2 introduces the fundamental ideas of deep-space exploration, including propulsion and resource utilization. Section 3 introduces some of the major facilities and instruments used in deep-space exploration missions in recent years. Section 4 summarizes some of the major proposals for deep-space exploration in recent years, including some of the exploration plans and objectives. Section 5 discusses the limitations of the current deep-space exploration technology and the outlook of the future. Section 6 summarizes the results of the study.

2. Concepts of Deep-Space Exploration

Deep-space exploration is the study and exploration of the Moon, other celestial bodies, and space beyond. This field requires highly sophisticated technology and significant resources for in-depth exploration, and it combines planetary science and related specialties such as aerospace technology [9]. These exploration missions often rely on complex and highly sophisticated navigation systems and reliable communication technologies for long-duration interplanetary travel, and they test not only the state-of-the-art technology but also the courage and determination of human beings to explore uncharted territories. Delta-v is an important concept in deep-space exploration, representing the change in velocity necessary for a spacecraft to transition between orbits and derived from calculations of the Tsiolkovsky rocket equation:

$$\Delta v = v_e ln\left(\frac{m_0}{m_f}\right) \tag{1}$$

Here, v_e represents the rocket motor‘s exhaust velocity, m_0 is the spacecraft‘s beginning mass, and m_f is the spacecraft‘s final mass after the fuel has been burned. Therefore, in order to minimize the need for delta-v, many deep-space spacecraft use gravity assist, also known as the gravitational pull of the planets, to change their trajectories, which saves the spacecraft fuel to some extent. Another key concept in deep-space exploration is International Space Resource Utilization (ISRU), a concept that refers to the use of local materials on other celestial bodies to support human missions, which reduces the cost of exploring, building habitation modules, and even space colonization on other celestial bodies, and makes missions much more viable. Mars is extremely rich in resources, with large amounts of water and carbon dioxide, as well as soil rich in minerals. These local resources effectively reduce the amount of materials that need to be transported from Earth, allowing more room to optimize spacecraft and probes, and enabling missions to reduce unnecessary risk as well as increase the life cycle of equipment [10]. As such, ISRUs play a significant role in deep-space exploration programs to colonize the Moon and Mars. Countries including the United States and China are investing heavily in research into ISRU technology, which has broader strategic implications for realizing a sustainable human presence on these celestial bodies [8]. These fundamental concepts of deep-space exploration delta-v and ISRU are critical to future human missions to explore distant worlds. As space technology continues to innovate, these concepts will play a central role in future deep-space exploration missions.

3. Deep-space Exploration Facilities

Contemporarily, a number of site probes in the field of deep-space exploration have been launched by various countries, equipped with cutting- frontier scientific instruments designed to provide significant data for the exploration of celestial bodies in the solar system and over. The following provides a detailed description of several important observatories and the cutting-edge equipment they use. The Parker Solar Probe was launched in 2018, and its primary mission was the study of solar wind and sun’s outer atmosphere. This is the first probe in history to approach the sun, allowing scientists to investigate the dynamics of the solar wind and coronal heating [11]. It is quite important to understand the impact of solar activity on Earth by the scientists’ studies. Several important scientific instruments are included with the Parker Solar Probe. The FIELDS suite, which has a bandwidth of 20 MHz and a dynamic range of 140 dB, makes it possible to measures electric and magnetic fields [12]. For research into the dynamics of the solar plasma, the SWEAP can analyze particles in the solar wind, with proton velocities measured in the range of 139 to 1072 km/s, Ion, electron and particle velocities were measured with different instruments as shown in Table 1. The ISΘIS suite detects energetic particles between 10 keV and 100 MeV, helping to study the acceleration mechanisms of these particles. The detector currently only contains one imager, the WISPR imager, which will be able to provide white-light large-scale images of solar wind, as well as coronal mass ejections (CMEs), once the telescope fields of view of 40°×40° and 58°×58°, respectively.

Table 1. The Instruments in the SWEAP Suite

Name	Type	Particle Measured	Measurement Type	Look Direction
SPAN-Ai	Electrostatic Analyzer + ToF	Ions	3D VDF + mass	Ram
SPAN-Ae	Electrostatic Analyzer	Electrons	3D VDF	Ram
SPAN-Be	Electrostatic Analyzer	Electrons	3D VDF	Anti-ram
SPC	Faraday Cup	Ions and electrons	1D VDF + energy-dependent flow angles	Nadir

Chang’e 5 is the only China’s probe which yet launched in 2020 with the primary mission to collect samples from the lunar surface and returning them to Earth, the overview of the Chang’e 5 mission is shown in Fig. 1. The probe completed China’s first lunar sample return and is of immense importance in understanding the terms of the material makeup and development of Lunar crusts. Mission Chang’e-5, overall turned out to be successful, providing a significant boost to China’s deep-space exploration efforts, as will the upcoming mission launches of Chang’e-6 and Chang’e-7. Some of the sophisticated instruments established on Chang’e-5 are used for the sampling and analyzing of the lunar materials. Lunar Mineral Spectrometer (LMS), to obtain spectra of minerals on the lunar surface with a wavelength range of 480 to 3200 nm and a spectral resolution of 3 to 25 nm, enable the detection of the distribution of minerals within a distance of 2 to 5 meters [12]. The lunar soil penetrating radar or LRPR is used in analyzing features such as the structure of the lunar soil. It can penetrate more than 2 meters into the ground with

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vertical resolution of not more than 5 cm, and its operating frequency is 1 to 3 GHz. Last but not the least, there is a drilling device and a surface sampling device form the sampling system. To guarantee that the layered structure of the collected sample is not disturbed, the drilling device being used enters approximately 1 meter into the lunar soil [13]. The surface sampling device with a robotic arm can take rocks and soil from the surface of the Moon, as shown in Fig. 2. The total rock and soil samples collected weigh approximately 1.5 kg.

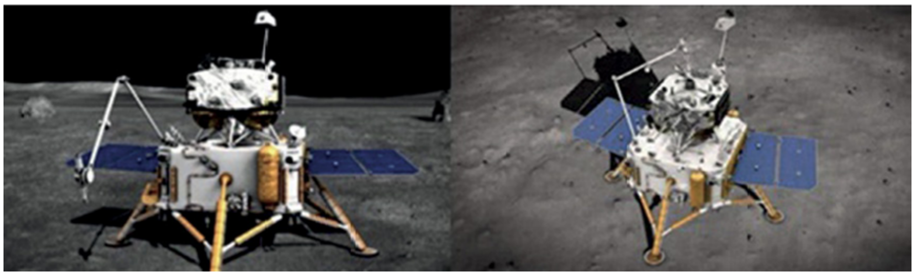

Fig. 1 Chang'e-5 samples the lunar surface using a robotic arm [13].

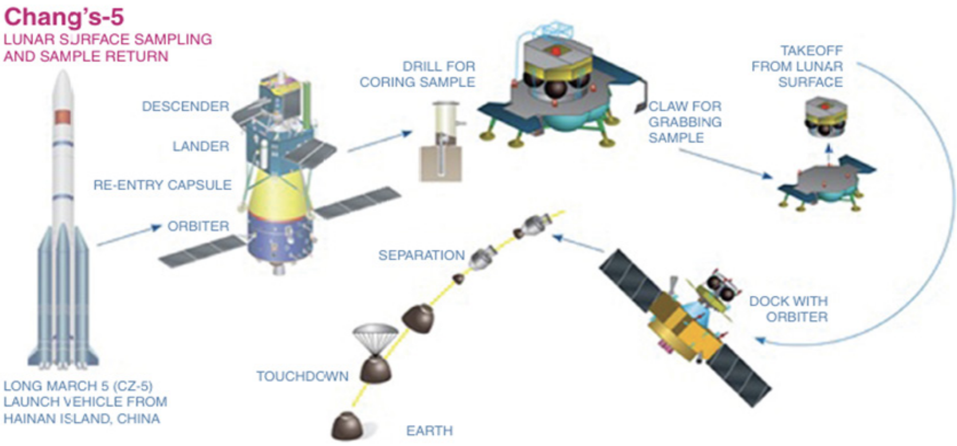

Fig. 2 An overview of the Chang'e-5 mission [13].

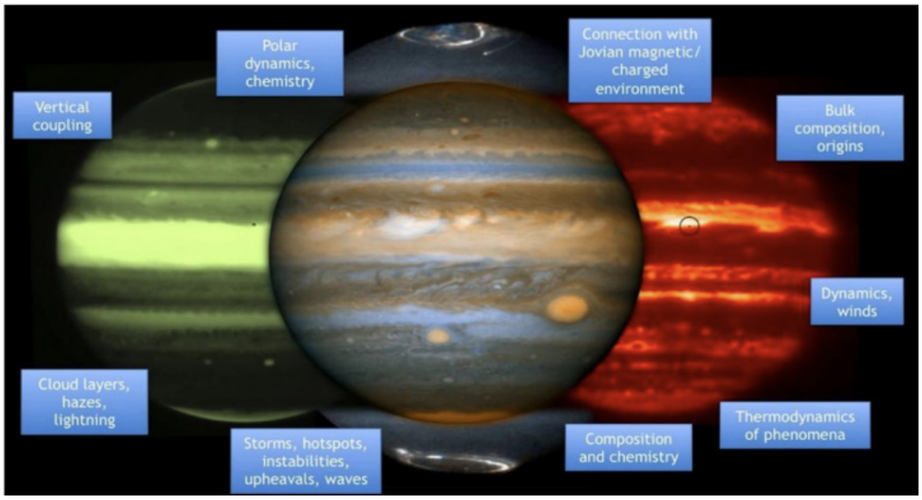

Fig. 3 Examples of the Jupiter science objectives of JUICE [15].

Moving in the year 2022, the European Space Agency (ESA) has sent Jupiter ice satellite explorer to study Jupiter and its three large moons which include Ganymede, Europa, and Callisto [14]. Their ability to host life and geological activity is important for the investigation, which is to search for signs of liquid water environments, i.e., subsurface oceans, beneath the Jovian moons' icy mantles (seen from Fig. 3) [15]. The JUICE probe also has some of the most modern scientific equipment on board. J-MAG magnetometer has a sensitivity of 0.01 nT and, therefore, will provide detailed measurements of Jupiter's magnetic field as well as the magnetic environment and topography of Jupiter and its satellites. The topography and tidal deformation on Ganymede are analyzed using the GALA laser altimeter installed on the spacecraft with 10 cm coverage range, along with a spatial resolution of 25 meters over the coverage area. Due to the ability to resolve vertically at 30 meters, which is needed to identify possible liquid waters beneath the ice, the RIME radar can soundly Ganymede and Europa with energies that probe to a depth of 9 kilometers of ice. Furthermore, the JANUS optical camera takes images of the immense surface of the Jovial moons with a resolution of 2.4 meters and gives detailed analysis.

4. Exploration Proposals

Nowadays, several countries and space agencies have set some important goals for deep-space exploration, and in addition to showing that such goals could be technologically feasible, have refuted claims that space exploration was only possible through unbridled nationalism or militarism. The three major proposals that are described in this section are the United States 'Artemis program, China's Tianwen-1 program, and Russia's ExoMars program which can be considered as key global objectives in the exploration of deep-space.

Artemis program by NASA is the effort to return a man to the moon by 2026 that is one step closer to mankind's journey to Mars [16]. The program has three main phases: Artemis I is an uncrewed flight test that occurred in 2022 to prove the performance of Orion spacecraft and the Space Launch System (SLS) rocket. The subsequent Artemis II mission planned for 2025 will be the first crewed mission around the Moon. Last but not the least, Artemis III will hopefully deliver a man to the moon in 2026 which will indeed be a journey back to the moon after the Apollonian era. Within the Artemis program together with lunar exploration NASA aims to create a long-term research platform at the lunar South Pole to be used for deep-space exploration. The program is based on the model of cooperation with the other countries for the implementation of the project and the United States of America cooperates with the European Space Agency (ESA) for studying service module of Orion spacecraft while, Canada is responsible for robotics part. The important objectives of the Artemis are to prove the prospects of long-term crew existence on the lunar surface and the possible use of local resource with reference to subsequent missions to Mars. NASA also works with private companies through the program, and specifically, those that produce lunar landers and other equipment. This sort of cooperation in the deep-space study can be viewed as a new model of innovative research of the National Space Agency with the ventures involved in space exploration.

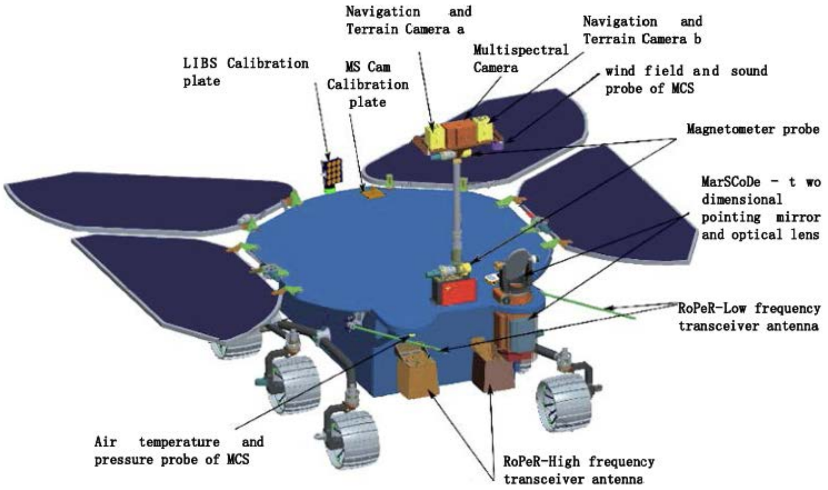

Fig. 4 Positioning of scientific payloads on the rover [17].

China's Tianwen-1 is set to be successfully launched on July 23, 2020 with the help of Long March 5 rocket, i.e., the nation's maiden Mars exploration mission. Now for the first time in history all of the three benchmark objectives including orbiting, landing and surveying Mars have been achieved at once. At May 2021, the Mars rover named "Zhu Rong" landed on the Utopian plain of Mars to explore the red planet and become the second country in the world, after the United States, to execute a soft landing on the planet's surface. Of them, topographic mapping of Mars, investigation of its geophysical characteristics and search for water ice in surface deposits and subsoil are the main scientific goals of Tianwen-1 (depicted in Fig. 4) [17]. High-resolution camera, subsurface sounding radar, its climate detector included in "Zhu Rong" Mars rover are capable of capturing and understanding important aspects of Martian geography and climate, respectively. This mission puts China for the first time in the ranks of the worlds' leaders in deep-space exploration technology and sets the groundwork for future Mars sample return missions [18].

The ExoMars program is a joint space exploration mission of the Roscosmos, the Russian Federal Space Agency and the European Space Agency, that exists for the purpose of searching for life's existence on Mars and the space age history of the planet. The European-Russian mission "ExoMars 2016" launched in March 2016 the Trace Gas Orbiter (TGO) as the first preparation for a multi-satellite Mars exploration program designed to investigate, among other things, trace gases in the Martian atmosphere whose presence might signify biological or geological activity. The second stage of the program was planned for the year 2022, but some technical problems and certain political reasons contributed to a postponement of the program. The purpose of this phase is to launch the "Kazatchok" lander and the "Rosalind Franklin" rover to the Mars. Lander will explore radiation data and the geophysical structure of the Martian upper crust, the rover will look for organic compounds and biosignatures by placing a drill to a depth of 2 meters at the Martian surface [19]. Nonetheless, Russia and the ESA remain extremely determined to move forward with the work that will be required in the future for the finding of more obvious signs of life on Mars.

5. Limitations and Prospects

While significant progress has been made in deep-space exploration, huge drawbacks are also felt in technique, finance, and cooperation. Thus, the development of these areas is the given priority, and it is these that may provide better prospects for the further operations in the framework of deep-space exploration. One important limitation is technological challenges to can be within the particular technological or programmatic implementation of an information system. Extra-terrestrial explorations place emphasis and pressure on the spacecraft to operate for long formative durations in the most active and hostile conditions, so the spacecraft systems need to be very smart and resistant. For example, reliable energy sources are needed for space voyages to Mars and Jupiter's moon, and yet solar energy decreases the farther a spacecraft is from the Sun. Nuclear energy can be a possibility, though they present other problems such as regulatory and technological constraints. Communication systems are not immune to problems of delay, and enhanced techniques are required to optimize the extent of real time suitable for other remote activities.

Cost is still a major factor that poses a challenge to the implementation of the designed and recommended interventions. Any missions to deeper space including the Mars mission by China and the Artemis program by NASA need massive capital to develop, launch and maintain them. Questions on how several Global space organizations are surmounting the dilemma of adopting or advancing their space exploration goals without incurring the high costs have become worrisome. However, while international cooperation, as well as cooperation between States and private individuals, has a significant impact in sharing costs, limited funding remains a problem that cannot be ignored. Additionally, geopolitical tensions present challenges for international cooperation. partnerships between agencies like ESA and Roscosmos have generally been key to the success of joint operations, political turbulence may cause delays or cancellation of missions, as seen in the ExoMars project‘s delay. These cases show that cooperation in deep-space exploration between different organizations on a global scale is very vulnerable.

Going forward, future deep-space exploration missions will rely on human advances in nuclear power, more advanced artificial intelligence, and sophisticated robotics, which will revolutionize future deep-space exploration missions. Spacecraft with AI may have greater autonomy, allowing them to explore and make independent decisions in distant regions of space. International cooperation is still necessary to overcome technological barrier and funding obstacles. In the end, deep-space exploration of the Mars and Moon will provide valuable experience for future human deep-space missions over longer distances, and humans may be able to unlock some of the mysteries of the solar system and beyond.

6. Conclusion

To sum up, this paper analyzes the major facilities and proposals for deep-space exploration in recent years and identifies current limitations and cutting-edge recommendations for the future, focusing on major missions including NASA‘s Artemis, China‘s Astronomy-1, and Russia‘s ExoMars. These missions reflect the rapid advances in national deep-space exploration technologies in recent years, as well as the growing cooperation to explore the Moon, Mars and beyond. The advanced instruments on board spacecraft such as the Parker Solar Probe, Chang‘e 5 and JUICE, which can provide us with important data and details about celestial bodies and expand the understanding of more planetary environments, reflect the great ingenuity of humankind in exploring deep-space and emphasize the importance of international cooperation in space exploration. Looking ahead, advanced propulsion systems and artificial intelligence technology with a high degree of autonomy will make mankind‘s future missions to the Moon and Mars smoother, opening up new possibilities for exploring more positional objects and expanding the scope of mankind‘s future deep-space exploration. The research in this paper is significant because deep-space exploration is going to be the main means by which humanity advances in the future, which will not only improve the knowledge of the solar system and even the Milky Way galaxy, but also provide us with the possibility of living in space for a long period of time, which pushes forward human civilization as well as the advancement of technology.

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