Strategic Study of CAE 2022 Vol. 24 No.4
DOI 10.15302/J-SSCAE-2022.04.023

Research Status and Future Development of Deep-Space Security

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Abstract: With an increase in deep-space exploration activities in the world, alongside increasingly complex exploration environments and tasks, the study of deep-space security issues is of great practical significance. Starting from the basic connotation of deep-space security, this paper briefly describes the research significance and key issues of deep-space security, and discusses the research status and future development of four key deep-space security issues: space radiation threat, planetary protection, space heritage protection, and space legislation. In this study, space radiation is found to have the characteristics of multiple threats sources and high radiation intensity, with research needed from the perspectives of physical protection, biomedical protection, and chemical protection. The challenges faced by planetary protection include pollution and the impact of deep-space spacecraft, with research in this area needed from the perspectives of technology and policy formulation. The protection of space heritage is controversial due to political, cultural, and legal differences among countries in terms of evaluation and protection measures, and research should be carried out from the perspectives of international cooperation, deep-space spacecrafts, and a reduction of human impact. Due to the complex international relations among countries, deep-space legislation makes it difficult for the effectiveness of current laws and regulations to become the consensus of the international community. Thus, research performed from the perspectives of international legislative organizations, domestic research institutions, and the improvement of domestic legal systems is needed.

Keywords: deep-space security; space radiation threat; planetary protection; space heritage protection; space legislation.

1 Introduction

Deep-space exploration refers to the exploration of the moon and distant celestial bodies or spaces [1]. The level of technology used for this type of exploration is related to the ability to safeguard national strategic interests, as well as being an important symbol of national scientific and technological competitiveness. Studies have shown that there may be scarce material resources (e.g. helium-3) on the moon, as well as precious metal mineral resources in the asteroid belt between the orbits of Mars and Jupiter [2]. The development and utilization of deep-space resources may compensate for the shortage of corresponding resources on Earth and provide energy, materials, and other material resources for humans to expand their extraterrestrial living space [3]. In recent years, rapid progress in deep-space exploration technology has further enhanced the feasibility of the human exploration

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Received date: June 26, 2022; **revised date:** July 18, 2022

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Funding program: National Defense Basic Research Program (JCKY2020903B002); National Natural Science Foundation of China (12150007)

Chinese version: Strategic Study of CAE 2022, 24 (4): 240–248

Cited item: Wu Ke et al. Research Status and Future Development of Deep Space Security. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2022.04.023

of deep-space celestial bodies and the environment, as well as the development and utilization of deep-space resources. At present, the world’s main space powers are actively developing deep-space exploration. Owing to increasingly active deep-space exploration and increasingly complex exploration environments, the importance and urgency of deep-space security has become increasingly prominent [4].

Deep-space security mainly involves three aspects: deep-space resources, deep-space activities, and deep-space environmental threats. Specifically, all countries should jointly and peacefully use space resources to: (i) avoid security problems caused by disorderly competition in the field of deep-space exploration [5]; (ii) scientifically perform deep-space exploration activities to avoid microbial infection between extraterrestrial celestial bodies and the Earth; (iii) address the security problems caused by the complex and unknown extreme environmental threats in deep space [6]. Deep-space security focuses on the four key issues, namely space radiation, planetary protection, space heritage protection, and space legislation, with the main space powers carrying out research activities to support the formulation of strategies relevant to these areas. It should also be noted that most existing studies are spontaneous and scattered, focusing only on a certain type of deep-space security issue. As a result, there is a lack of systematic summary, and the work in problem analysis, development status, and future trends is not sufficiently comprehensive. As a pilot research in the field of deep-space security in China, this paper strives to systematically elaborate the basic connotation of deep-space security, clarify the research status, and summarize future trends to provide a basic reference for the formulation of deep-space planning and the overall design of exploration missions.

2 Research significance and key issues of deep-space security

The concept of deep-space security is relatively broad in the aerospace field and has not yet been clearly defined internationally. The United Kingdom published the *National Space Security Policy* (2014), which defines deep-space security as “having safe, assured and sustainable access to space capabilities, with adequate resilience against threats and hazards” [6]. Canada and other countries jointly published the *Space Security Index* (2020), which described deep-space security as “the secure and sustainable access to, and use of, space and freedom from space-based threats” [7]. The *National Security Law of the People's Republic of China* (2015) describes the contents of deep-space security: the state insists on the peaceful exploration and the use of outer space, enhances the ability of safe entry and exit, scientific investigation, development, and utilization, strengthens international cooperation, and maintains the security of activities, assets, and other interests of China in outer space. Based on the above viewpoints, deep-space security appears to mainly refer the reasonable utilization and protection of natural and man-made resources in space; the performance of free, safe, and sustainable space activities; and the ability to effectively warn and respond to various possible deep-space threats.

It is generally believed that deep-space resources, activities, and environmental threats are critical to deep-space security (Fig. 1): (1) Deep-space resources include deep-space assets such as deep-space probes, Earth–moon translation point relay satellites, orbital positions, and spectrum resources, which play an important role in the rational development and utilization of deep-space assets and the rational protection of space heritage; (2) Deep-space activities refer to the ability to freely enter and exit deep space; the core content is to make full use of deep space, such as establishing a deep-space reference system and carrying out various remote sensing or *in situ* scientific exploration missions; and the focus is to prevent the Earth’s organisms from contaminating other celestial bodies and protect the Earth from being contaminated by other celestial organisms; (3) deep-space environmental threats refer to factors that may interfere with or damage deep-space activities and resources, and are divided into natural threats and man-made threats. Deep-space environmental pollution is caused by the development of deep-space activities.

An in-depth study of deep-space security issues, in line with national strategic needs, is of great significance to improving the level of aerospace science and technology and space security assurance capabilities.

3 Key directions and development course of deep-space security

3.1 Space radiation

The main radiation threats to deep-space security are galactic cosmic rays and solar proton events. Space radiation can cause serious radiation damage to astronauts, increasing the risk of central nervous system disease and acute radiation symptoms [7,8]. Furthermore, integrated circuits in deep-space detection equipment are sensitive to radiation. When high-energy cosmic radiation particles penetrate the spacecraft and integrate the protective materials into the sensitive area of the integrated circuit, errors or even permanent damage to the integrated circuit can occur, thus affecting the normal operation of the space capsule and space station equipment.

DOI 10.15302/J-SSCAE-2022.04.023

Therefore, the threat of space radiation is an important factor affecting the implementation of deep-space exploration, especially in the context of manned deep-space exploration missions. Effective space radiation protection is necessary to ensure the health of astronauts and the smooth implementation of deep-space exploration missions.

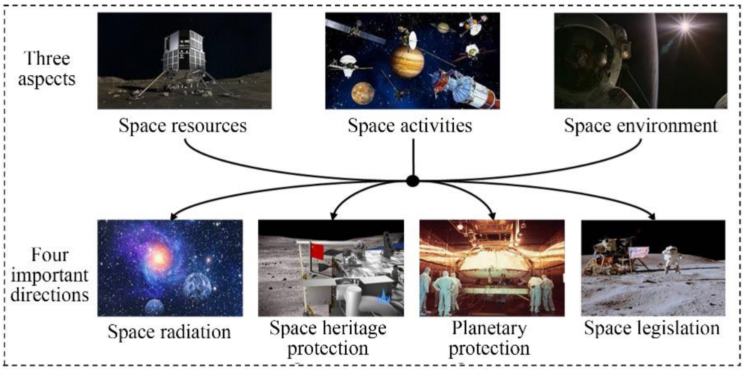

Fig. 1. Three basic aspects involved in deep-space security and four key directions of concern.

Although many deep-space exploration engineering tasks have been completed worldwide, and scientists are also intensively studying space radiation protection strategies, the current radiation protection technology system is far from perfect owing to the uniqueness and complexity of space radiation and radiation environments. The China National Space Administration, US National Aeronautics and Space Administration (NASA), European Space Agency (ESA), and space medical research institutions in various countries are all dedicating extensive efforts to this [8–10]. For example, in NASA's revised *Strategic Space Technology Investment Plan* (2015), technologies such as space radiation protection and mitigation are listed as core technologies and important issues that must be addressed before the implementation of detection missions [9].

3.2 Planetary protection

Planetary protection refers to the behavior [11] of adopting corresponding protection measures in deep-space exploration activities to protect the ecological environment of the Earth and extraterrestrial planetary objects from external interference. In the early days of space exploration, the notion of planet protection emerged to avoid contamination by other celestial organisms and Earth organisms [12]. Planetary protection is an important factor in realizing sustainable deep-space exploration activities, and its development is mainly divided into five stages [13].

The first stage is qualitative analysis. In 1958, the Committee for Space Research (COSPAR) was established [14], dividing planetary protection into corresponding protection categories and grades [15]. The United Nations Committee on the Peaceful Uses of Outer Space (COPUOS) was subsequently established. This has led to early research on planetary conservation.

The second stage is the "space treaty" phase. In 1964, the COSPAR set the first quantitative planetary protection target [16], and the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies* (1967), was subsequently proposed [17]. Some countries and organizations have formulated their planetary protection guidelines and policies, and planetary protection became an international consensus for deep-space exploration missions. COSPAR conducted research on ethical issues and issued corresponding policies and regulations, but it was not effectively implemented due to the complex international relations at that time.

The third and fourth stages are the stages of "outer space soft law", which refers to the legal norms formed by the international community in the exploration of outer space that is not legally binding but can produce an actual enforcement effect. The third stage refers to the initial period of the "outer soft method" in the 1980s and 1990s. After the promotion of planetary protection practices, countries realized that it was unrealistic to achieve the goal of planetary protection by treaty constraints alone, with many countries tending to take the more concrete and relatively weak binding force of the UN General Assembly resolution and COSPAR policy as the first choice. The fourth stage refers to the development period of the "outer space soft method", which has lasted for about 20 years since 1995. Since its infancy, the international community has issued documents on unanimous support from all parties. For example, the *Declaration on International Cooperation in the Exploration and Use of Outer Space for the Benefit and in the Interest of All States, Taking into Particular Account the Needs of Developing Countries*

(1996) [18] provides a clearer statement of the basic principles of the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*. However, in the context of conflicts among relevant interest groups, the final version remains flexible; The *Resolution on Domestic Legislative Recommendations Related to the Peaceful Development and Utilization of Outer Space* (2013) recommends that countries develop a domestic space law and calls on countries to fulfill their planetary protection obligations when exploring deep space.

The fifth stage refers to the domestic legislative stage initiated by the main space powers in recent years, with no clear time division. By the end of 2021, approximately 25 countries had completed their domestic space legislation. However, international space legislation remains in its early stages and requires further development and improvement.

At all stages of planetary protection development, space agencies in various countries have gradually improved planetary protection policies and space management agencies. NASA has the highest degree of specification in planetary conservation work and has a complete planetary conservation management architecture [19–21]. ESA has also developed a clear planetary protection system [22]. Although the Russian Federal Space Agency has yet to establish a special planetary protection management agency, it implements planetary protection while conducting deep-space exploration safety tests. The Japan Aerospace Research and Development Agency established a planetary protection mechanism. China is deepening planetary protection measures in the Tiangong-1 project, and has implemented microbial protection, protecting the moon and Mars; however, no special policies and regulations for planetary protection and special regulatory functions have been proposed.

3.3 Space heritage protection

According to United Nations Educational Scientific And Cultural Organization’s definition of the *Convention Concerning the Protection of the World Cultural and Natural Heritage*, space heritage is divided into human cultural heritage and natural heritage, among which cultural heritage includes legacy related to the process of conducting scientific research, near-Earth manned spaceflight, deep-related heritage, such as aerial exploration activities, and cultural heritage located outside the Earth (mainly referring to natural extraterrestrial phenomena with artistic and research value).

In 1957, “Sputnik 1” and later “Pioneer 1” were launched into orbit, opening the prelude to the human space age. Although the former only remained in space for a few months, it was the first man-made object to float in space, and extended the frontier of human archaeology to deep space; the latter is the longest man-made object in orbit and is expected to remain in deep space for the next 600 years [23]. Since then, space heritage has continued to progress, and now includes the Hubble Space Telescope, Kepler Space Telescope satellite, James Webb Space Telescope, and Voyager 1 and Voyager 2 in deep-space probes. These space heritages not only have served or serve human deep-space exploration, but also have milestone significance in some fields. As human deep-space exploration activities continue to advance, space heritage continues to develop; for example, the footprints of humans landing on the moon left by Apollo 11 in 1969, and the national flag deployed on the moon by Chang’e 5 in 2020. The natural environment, which is very different from Earth, also has an exceptionally high scientific value. For example, lunar soil samples brought back by the Apollo lunar exploration mission and the Chang’e-5 mission have provided important information about the Earth–moon system and the early evolutionary stages of the solar system.

Protecting the cultural and natural heritages created and discovered by humans in deep-space exploration will be an important consideration for future human deep-space exploration activities. It should also be noted that due to political, cultural, and legal differences between countries, there are still considerable disputes over the evaluation and protection of space heritage, and many treaties on space heritage have not yet reached an international consensus. Taken together, the development of human space activities has an unpredictable impact on the protection of space heritage.

3.4 Deep-space legislation

Deep-space exploration activities have promoted the development of related technologies and provided a potential way for humans to develop and utilize extraterrestrial resources and expand their living space. In the 1960s, the United Nations proposed the “outer space laws” related to deep-space exploration activities, including the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space such as the Moon and Other Celestial Bodies*; *Agreement on the Rescue of Astronauts, the Repatriation of Astronauts and the*

DOI 10.15302/J-SSCAE-2022.04.023

Return of Objects Launched into Outer Space; *Convention on International Liability for Damage Caused by Space Objects*; *Convention on Registration of Objects Launched into Outer Space*; and *Agreement on the Activities of States on the Moon and Other Celestial Bodies*, to guide the international community to use space peacefully and carry out various deep-space exploration activities in a standardized and orderly manner. Similarly, the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies* (1967) [23] and *Agreement on the Activities of States on the Moon and Other Celestial Bodies* (1979) [24] are also closely related to deep-space exploration.

The main idea of the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies* is that all countries can freely explore outer space in compliance with international agreements; no country may appropriate outer space and celestial bodies as their own in any way, and any organization should assume corresponding international responsibilities for its activities in outer space [25]. The treaty has been recognized by the United States, China, Russia, France, Germany, Italy, and Japan, among other countries. The *Agreement on the Activities of States on the Moon and Other Celestial Bodies* is based on the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*. It is an extension of lunar exploration activities and proposes that no country should take the moon as its own and that natural resources on the moon should not become the property of any country, government, non-governmental international organization, national organization, non-governmental entity, or any individual person’s property. However, the spatial laws of various countries are far from perfect, and there are many unreasonable and unclear clauses that cannot provide clear guidance for related activities. For example, in the COPUOS discussion meeting on the *2015 Space Resources Exploration and Utilization Act* proposed by the United States, the representatives of various countries failed to reach a unified conclusion [26].

At present, the international community’s laws and regulations in the field of deep-space exploration are mainly based on the *Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies* and *Agreement on the Activities of States on the Moon and Other Celestial Bodies*, and make appropriate amendments to the relevant international treaty provisions to guide the deep-space legislative activities of countries [25]. In China, although no specific laws and regulations have been formulated in the field of deep-space exploration, some researchers have explored the legislation of international deep-space exploration [26–29] and put forward opinions and suggestions on relevant legal issues in light of national conditions [30]. As an emerging hotspot in international space development, deep-space exploration is not only related to national interests, but also to international relations and politics. Actively formulating laws and regulations related to deep-space exploration will help maintain national security, regulate deep-space exploration activities, including commercial aerospace, promote the fulfillment of international obligations, and demonstrate the responsibility of a major country [31].

4 Challenges faced in deep-space security

4.1 Space radiation

Factors such as geomagnetic field and stellar activity have resulted in a complex and diverse space radiation environment. Space radiation sources, such as galactic cosmic rays and solar proton events, pose varying degrees of threat to the space activities of astronauts and the safe operation of space equipment in deep-space exploration missions, including manned moon landings [32–36]. Space environmental radiation is characterized by many types of threats and a high radiation intensity. Thus, effective protection is a realistic challenge in the implementation of tasks in deep-space exploration.

Galactic cosmic rays originate primarily from high-energy particles outside the solar system. The majority of the rays are protons (hydrogen nuclei) and alpha particles (helium nuclei), and contain a very small amount of heavy atomic nuclei; the ray energy is as high as the teraelectron volt level [33]. Spacecraft bulkheads cannot completely block these high-energy particles, and the organs of astronauts may be damaged upon exposure. In addition, secondary radiation particles may be generated by the interaction between the bulkhead metal and high-energy particles, increasing the radiation intensity [37].

Solar proton events are also called solar cosmic rays and high-energy solar particles, most of which are protons, a small number of alpha particles, and a very small number of heavy ions. Progressive solar proton events are characterized by long periods of slow travel and are caused by coronal mass ejections; pulsed solar proton events are short-lived and are produced by solar flares.

4.2 Planetary protection

Planetary protection faces both legislative and technical challenges. At the legislative level, there are three major challenges: (1) The formulation of planetary protection laws and policies should consider the scientific nature and current technical feasibility, although there is a lack of interdisciplinary talent involved in technology and policies; (2) Planetary detection technology is developing rapidly, and the targets, tasks, and scope of detection are constantly changing; while the current planetary protection policies are updated slowly, a rapid response mechanism should be established to deal with increasingly complex detection tasks. The focus of the planetary protection policy is to ensure that it is able to respond quickly and remain autonomous for extended periods of time after being released from ground support; (3) Planetary protection policies are mostly dominated by the United States, which is not conducive to the active participation of other countries to better protect the common interests of human society; and more countries and institutions should be encouraged to participate to ensure that human deep-space exploration activities as a whole comply with the principles and requirements of planetary protection.

At the technical level, the challenges faced in terms of planetary protection can be mainly divided into positive pollution protection (to protect the Earth from foreign organisms) and reverse pollution protection (to protect other planets from the Earth's biological pollution). For example, NASA developed a planetary protection essential document to guide various celestial exploration missions [38]. The corresponding technical challenges involved four aspects: (1) Biological contamination. Microbial contamination is relatively common, comprised mainly of spore-forming bacteria, and its quantity has been used as the standard for the microbial load of aircraft, further improving the understanding of the viability of microorganisms in extreme environments [39]. The appropriate biological contamination protection measures can eliminate the risk of contamination by microorganisms, and at the same time prevent the relevant life detection equipment from drawing erroneous analysis conclusions; (2) Organic pollution. Some compounds, emission products, and other organic substances carried by spacecraft may have an impact on the current detection mission and may further interfere with future deep-space exploration activities in the form of remnants, resulting in potential damage to planetary life detection [40], as well as contaminating the atmosphere of the planet, with unpredictable and severe consequences; (3) Deep-space spacecraft impact. The impact of deep-space spacecraft with planetary surfaces can have serious implications for planetary protection. For example, the solid water on the planet's surface may melt owing to the high temperature generated by the impact, thereby forming an area on the planet's surface that can affect future life detection. This may cause the surface of the planet to be contaminated by the surface and interior of the spacecraft. The asteroid deviates from its proper flight path; debris from the impact on the planet's atmosphere can be hazardous to future planetary exploration missions. (4) Secondary pollution. The disinfection and sterilization of deep-space spacecraft is an important step in preventing microbial contamination in planetary protection. However, the associated secondary pollution is also a serious challenge for planetary protection. New pollutants formed by the physical and chemical reactions of primary pollutants and their repollution should be avoided. Sterilized landers must be strictly protected with a biological shield to prevent the penetration of microorganisms. To prevent secondary pollution caused by other parts of low-disinfect-level detectors, additional protective components will need to be added to extraterrestrial celestial body detectors, such as landers and rovers.

4.3 Space heritage protection

The erosive forces that exist on Earth (e.g. wind, water, and organic processes) do not exist on the surface of deep-space and many stars, such as the moon (except for the effects of day-night temperature differences and micrometeorite impacts), and the space heritage status is almost unaffected [41]. At present, the protection of space heritage is significantly affected by human activities, and countries have not yet reached a consensus on protection. Therefore, there is a need to conduct research on strategies for the protection of space heritage.

The first objective involves the formulation of international laws and regulations. To date, the management of space heritage remains a contentious area of law, with most treaties and agreements in force only within countries. For example, the United States released *One Small Step to Protect Human Space* (2020), which aims to protect the historical relics and man-made objects left on the moon during the "Apollo" moon landing era. However, to effectively protect space heritage, solutions must be explored in a complex and intertwined context of national and international laws, regulations, treaties, and policies.

The second objective is the study of the identification standards for space heritage. As human space activities become more frequent, the protection of space heritage requires significant resources. Some studies have suggested that all early lunar exploration sites should be listed as important protected areas to protect them from

DOI 10.15302/J-SSCAE-2022.04.023

human influence [42]; based on the principle of protecting extreme environmental sites (e.g. Antarctica), arguments have been made for the establishment of a lunar park [43]. Although these suggestions have some value, they are difficult to implement in practice. Thus, in this context, accurately defining space heritage and establishing a scientific classification system have become urgent and realistic problems.

The third objective is to clarify the impact of detectors and human activities on deep-space exploration activities. The deepening of human deep-space exploration activities will inevitably cause incremental interference in the protection of space heritage. The trajectories of deep-space spacecraft as they land on extraterrestrial objects or travel at low altitudes can also cause damage to nearby space heritage sites. In the process of extraterrestrial object detection, the absence of governance rules may make it difficult to prevent the destruction of space heritage by human activities.

4.4 Deep-space legislation

The development and utilization of deep-space resources has become a new hotspot in deep-space exploration activities. To use deep-space resources scientifically, rationally, and sustainably, in addition to improving deep-space exploration technology, laws and regulations need to be formulated to restrain illegal development and technology abuse. At present, the laws and regulations related to deep-space exploration that are generally followed by the international community include the *Treaty on Principles for the Exploration and Utilization of Outer Space Activities by Countries, including the Moon and Other Celestial Bodies* issued by the United Nations, as well as agreement, policy, and regulatory documents issued by the United States, Luxembourg, and other countries [26,30]. Despite the rapid development of the field of deep-space exploration, challenges remain in legislation owing to complex international relations.

On an international scale, it is difficult to balance the requirements of different countries. While the deep-space exploration missions of most countries are limited to the solar system, some aerospace powers have begun to explore stars outside the solar system. On the other end of the spectrum, many countries have not yet been able to carry out any deep-space exploration missions. As such, the coverage of deep-space exploration missions in different countries is not the same, and their objectives also differ. The development of international deep-space legislation should consider the development status of deep-space exploration in various countries and reasonably balance the practical needs of each country.

Second, deep-space resources are a common wealth of all mankind, and the laws related to deep-space exploration cannot be separated from each other. In view of the complex and volatile international situation, the establishment of relevant laws is inevitably hindered by political factors, which poses a challenge to the stable development and peaceful application of deep-space exploration technology.

Third, aerospace legislative talent is lacking. Deep-space laws and regulations are unique beyond conventional legislation and require a large number of personnel with specific aerospace knowledge and a legal background. However, the international community does not pay enough attention to the field of aerospace legislation, and universities have yet to conduct systematic research on this type of legislation, resulting in a shortage of professionals in the field of deep-space legislation, which is not conducive to ensuring the legislative needs of the field of deep-space security are met.

5 Analysis of response strategies for key directions in deep-space security

5.1 Space radiation

Space radiation protection is divided into physical, biomedical, and chemical protection methods. At present, the physical protection methods are relatively mature, while research on biomedical and chemical protection is scarce. In practical applications, the complexity of real cosmic space radiation and the physical characteristics of space components are fully considered, and the scheme is optimized accordingly.

Physical protection can be subdivided into passive and active radiation protection methods. Passive radiation protection is the current mainstream radiation protection method that protects radiation by adding shielding or selecting antiradiation components. Thickening the bulkhead and designing a shielding material with a specific structure can make the charged particles deposited due to energy loss in the process of passing through the bulkhead, preventing most of the high-energy particles from penetrating the bulkhead [44]. Adopting special designs and process technologies can greatly improve the anti-radiation capability of components to ensure the safety of the detector system; however, their cost is much higher than that of ordinary components [45].

Active radiation protection deflects the path of radiation particles by artificially creating a protective field, mainly including a magnetic field, electrostatic field, plasma, and other methods [46]: (1) The magnetic field method deflects charged particles through the Lorentz force generated by a strong magnetic field, preventing the particles from hitting the deep-space spacecraft head-on, which can eliminate most of the secondary radiation. The mechanical strength of traditional conductive coils limits the magnetic field strength, and the development of superconducting technology has good application prospects after maturity; (2) Electrostatic field methods artificially generate electrostatic fields in the surrounding area of deep-space spacecraft equipment using the high potential of the electric field to slow down or deflect charged particles; (3) The plasma method is a combination of electrostatic and magnetic field methods, in which an electrostatic field is used to deflect positively charged particles.

Biomedical protection is an important means of protecting space from radiation. By the administration of drugs and supplementing nutrition, astronauts can develop radiation resistance and tolerance to a certain degree of space radiation, inducing radiation-resistant genes and proteins. This can regulate the expression of biological inflammatory, anti-inflammatory, and antioxidant protection, thereby achieving radioprotection [33].

The application of chemical radiation protection is limited because chemical radiation protection methods that are suitable for long-term use by astronauts remain poorly developed. Scavenging radiation-induced free radicals and neutralizing the oxygen effect on important biological macromolecules, such as deoxyribonucleic acid, thereby promoting the efficient processing of radiation by cells, is the most fundamental mechanism of chemical radiation protection methods [31].

5.2 Planetary protection

From a macro perspective, the rational analysis of tasks and the determination of requirements are key to formulating planetary protection strategies [11]. According to the specific deep-space exploration mission scheme based on the international policy of planetary protection, planning, designing, and reasonably allocating the corresponding requirements is an effective strategy to ensure compliance with the target pollution probability. Reasonable zoning management and the in-depth study of the deep-space environment will help enhance the protection effect. Automatic and remote-controlled unmanned tools can prevent direct contact or mutual pollution in the forward and reverse directions.

From a microscopic perspective, deep-space microbial detection and disinfection are the technical bases for planetary protection. These include identifying key microorganisms (e.g. extremophiles) during deep-space exploration [46], studying environmental- and material-friendly physical disinfection and sterilization technologies [46], developing aerospace materials that inhibit bacteria and do not affect the function of system components [45], and the development of microbial monitoring and disinfection systems that adapt to complex environments and various demands. In addition, organic content and waste discharge during deep-space exploration should be strictly controlled.

From a societal perspective, formulating planetary protection policy to consider both engineering feasibility and scientific research is the goal of future development [11]. Taking NASA as an example, the planetary protection office is also responsible for policy formulation, implementation, and supervision. It handles the relationship between “executor” and “supervisor” in planetary protection, and plays a role in effectively protecting future scientific achievements. Commercial companies are accelerating deep-space exploration activities, and there is an urgent need to formulate planetary protection specifications for commercial space activities.

From the perspective of humanistic care, considering the friendliness of both astronauts and the outer space environment is the only way to develop planetary protection policies. Both forward and reverse pollution protection cannot be separated from the interaction between astronauts and the outer space environment. The achievements of deep-space science and deep-space applications are also closely related to the working status of astronauts and the degree of deep-space pollution. The research and development of space life support systems with controllable pollution and superior performance, the exploration of deep-space environmental ecosystems, and the establishment of earth ecological transit stations are all necessary components of planetary protection.

5.3 Space heritage protection

In terms of international cooperation, there is a need to establish an international space heritage protection committee to accept nominations for space heritage protection, conducting a review of necessity, and supervising the management of protected sites and objects. According to the principle of “the exploration and utilization of outer space should be carried out for the benefit of all people, regardless of the degree of economic or scientific development" [47], the international space heritage protection committee should be composed of members representing as many different types of stakeholders as possible, including scientists, cultural heritage experts, and government representatives from aerospace and non-aerospace countries.

In terms of the assessment and classification of space heritage, considering the current shortcomings of relevant principles and laws, China should participate in UNESCO-related affairs and determine the basic principles and specific details of space heritage classification. China could also respond to UNESCO's call to identify potential astronomical and scientific sites and nominate them to the World Heritage List (WHL). The country could provide support for WHL nomination by summarizing the existing literature on space heritage, emphasizing the potential of the nomination to contribute to WHL and its relevance to a "balanced, representative, and credible World Heritage List".

In terms of spacecraft effects and the impact of human or artificial objects, there is a need to determine the descent and landing boundaries to avoid damage to space heritage by spacecraft or astronauts. Considering the possibility of astronauts destroying space heritage, the boundaries of human activities should be determined to prevent artificial objects from entering the safe range of space heritage. The specific descent, landing, and artificial activity boundaries should be reasonably planned according to factors such as the spacecraft scale.

5.4 Deep-space legislation

Attention needs to be paid to international exchanges and cooperation, and an international deep-space legislative committee should be established. Adhering to the principles of respecting sovereignty, equality, and mutual benefit, China will need to coordinate with countries to discuss and improve laws and regulations, promote international consensus, and promote the long-term sustainable development of deep-space exploration activities.

The corresponding research institutions in China should be established to provide a theoretical basis and practical arguments for participating in international deep-space legislation. The relevant institutions will carry out research on the composition and evolutionary history of various celestial bodies in deep space and conduct cooperative exploration with mineral resource management institutions, as well as track and study international space activities and provide a basis for participating in the formulation of international deep-space laws and regulations. At the national level, China should reasonably strengthen space-related legal research and investment, as well as recruit and train aerospace legal personnel.

In China, there is a need to improve relevant domestic laws and regulations and promote sound development of deep-space exploration activities. In terms of national security, there is a need to adhere to the peaceful use of deep space, oppose the weaponization of outer space, safeguard national rights and interests, and ensure that deep-space exploration activities are not illegally interfered with. In terms of planning and management, the division of responsibilities of relevant management departments should be clarified, any overlapping of functions should be eliminated, and a management system in the field of deep-space exploration should be established [3]. In terms of commercialization, social capital and commercial aerospace enterprises should be supported to participate in deep-space exploration and resource development activities [31], and the rights and obligations of entities participating in deep-space resource development should be established. In terms of international obligations, there is a need to formulate corresponding domestic regulations based on relevant international conventions and encourage active international cooperation and mutual assistance in deep-space exploration activities.

6 Conclusion

This study comprehensively analyzes the research status of space radiation, planetary protection, space heritage protection, deep-space legislation, and other deep-space security issues both in China and within the international community. At present, physical protection is currently the primary method of dealing with space radiation. In this context, the development of chemical and biological protection technologies has long-term application value. In terms of planetary protection, microbial disinfection is currently the primary strategy. Developing deep-space microbial detection technologies and establishing appropriate response policies are important for complex follow-up exploration tasks. The evaluation and protection of space heritage remains highly controversial. In this context, the strengthening of international cooperation and a reduction of the impact of deep-space spacecraft on humans are the key strategies to adopt in this area in the future. At present, deep-space legislation faces the challenge of reaching a consensus within the international community. Therefore, it is of great significance to establish international legislative committees and domestic research institutions to improve domestic legal systems.

Deep-space security involves a combination of the internal environment, technical factors, and international politics. This paper begins with the basic implications of deep space security, summarizes the key directions of deep-space security, presents the challenges faced by each direction, and proposes corresponding strategies that can provide a basic reference for follow-up research related to deep-space security in China.

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