Analysis the Principle and the State-of-Art Scenarios for Asteroid Detection

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Abstract: As a matter of fact, small celestial bodies are home to the elements that first made up the solar system and may hold crucial secrets about the beginnings of life and water on Earth especially based on the observations in recent years. In reality, they are living fossils that may be used to learn about the solar system's formation as well as evolution. For the main spaceflight nations, asteroid detection has emerged as one of the main development objectives in the realm of deep space exploration in recent years. With this in mind, this study briefly summarizes the international asteroid detection process and demonstrate the principle as well as the state-of-art detection facilities. At the same time, this research summarizes the research and development trends of asteroid detection and focuses on the main key technologies facing future asteroid detection missions. According to the analysis, this study puts forward relevant suggestions for China's subsequent asteroid detection activities.

1 INTRODUCTION

Small solar system objects refer to celestial bodies that orbit the sun but do not qualify as planets or dwarf planets, including asteroids, comets, meteors and other interstellar materials. Among them , asteroids contain valuable information regarding the beginnings, development, and evolution of the early solar system. They may additionally hold crucial hints regarding the beginnings of water and life on Earth. They serve as "living fossils" for research on the solar system's formation. Since the 1990s, exploration activities targeting asteroids have increased, becoming a hot topic in the field of deep space exploration and achieving relatively fruitful results (Ye et al., 2018; Sun & Meng, 2015). The lunar exploration project implemented in 2004 kicked off Chinese deep space exploration. In January 2019, Chinese "Chang'e 4" probe achieved the world's first soft landing detection on the back of the moon and achieved five achievements (Wu et al., 2017; Ye et al., 2017).

On the basis of the phased results achieved by the lunar exploration project, in January 2016, the first Mars exploration mission was approved (Geng et al. 2018), and deep space exploration was included in the "Outline of the Thirteenth Five-Year Plan for National Economic and Social Development of the People's Republic of China." Science and Technology Innovation 2030—Major Project". The white paper "China's Space in 2016" published on December 27 of the same year clearly stated that carry out in-depth demonstration and key technology research on plans for Mars sample return, asteroid detection, Jupiter galaxy and planetary transit detection, etc., and conduct timely research on key technologies. Start the implementation of the project to study major scientific issues such as the origin and evolution of the solar system and the search for information about extraterrestrial life. For the main spaceflight nations, asteroid detection has emerged as one of the main development objectives in the realm of deep space exploration in recent years. In August 2013, the International Space Exploration Coordination was jointly established by 14 space agencies including the China Space Administration, the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA). The group (referred to as ISECG) released the "Global Exploration Roadmap" (European Space Agency, 2019), which determined that the main tasks of small celestial body detection are: verifying innovative outer space exploration technologies and capabilities; deepenning the understanding of the evolution and life of natural celestial bodies in the solar system

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Evolution as well as testing methods for resisting risks from near-Earth asteroids. Based on a brief review of the history of human exploration of small celestial bodies, this article discusses the future planning of asteroid detection and the main key technologies it faces, and gives corresponding enlightenment and suggestions.

2 DEVELOPMENT HISTORY OF SMALL CELESTIAL BODY DETECTION

Humans initially used ground-based telescopes to observe and study asteroids, and could only obtain basic orbital parameters and some physical characteristics. The measurement of material composition, internal structure, gravitational field and other parameters was almost blank. With the development of aerospace technology, humans used spacecraft to conduct close observations of small celestial bodies in the 1970s. The last three decades have seen the completion of several distinct historic missions by the US, Europe, and Japan as part of an international effort to explore minor celestial bodies. 14 minor celestial body discoveries have been made so far by nations all around the world. Among them, the asteroid sampling return missions of Japan and America have reached the detection target, and sampling and other on-orbit operations are ongoing as shown in Figure 1 (Geng et al. 2018).

The exploration of asteroids has progressed from close flybys (e.g., the Deep Space 1, Stardust, and Rosetta missions) to asteroid orbiting detection (like the Near Earth Asteroid RendezvoHs (NEAR) detector and the Dawn detection mission). Following this, attached and in-place detection (like the Rosetta mission) has led to the current asteroid surface sample return programs (like the Hayabusa 1, Hayabusa 2, and OSIRIS-REx missions).

Judging from scientific results, through different detection missions, the precise orbit, movement speed, volume, material composition, and internal structure of the target small celestial body have been determined (Binzel, 2015; Bottke et al., 2006; Daly et al., 2017; Delbo et al., 2014; Hiroi et al., 2006; Hergenrother, 2013; Lauretta et al., 2015; Lauretta, 2017; Scheeres et al., 2016). For example, during its flight by comet 19P/Borrelly, the dimensions, shape, surface characteristics, brightness, mass, density, and rotational state of the cometary nucleus of both comets and asteroids were seen by the U.S. "Deep Space 1" mission. Additionally, the plasma properties of the coma were explored. The interaction between the comet's core and the solar wind, along with the brightness and characteristics of the dust and gas flows erupting from it, are crucial factors to take into account. the samples returned by the Japanese "Hayabusa 1" mission were analyzed in the ground laboratory for amino acids, polycyclic aromatic hydrocarbons Analytical tests of organic compounds have shown that Itokawa's organic compounds are of abiotic origin. These missions are mostly focused on scientific questions, such as how the solar system formed, how life first emerged, how to better understand the principles governing planet formation and evolution, and how life first emerged.

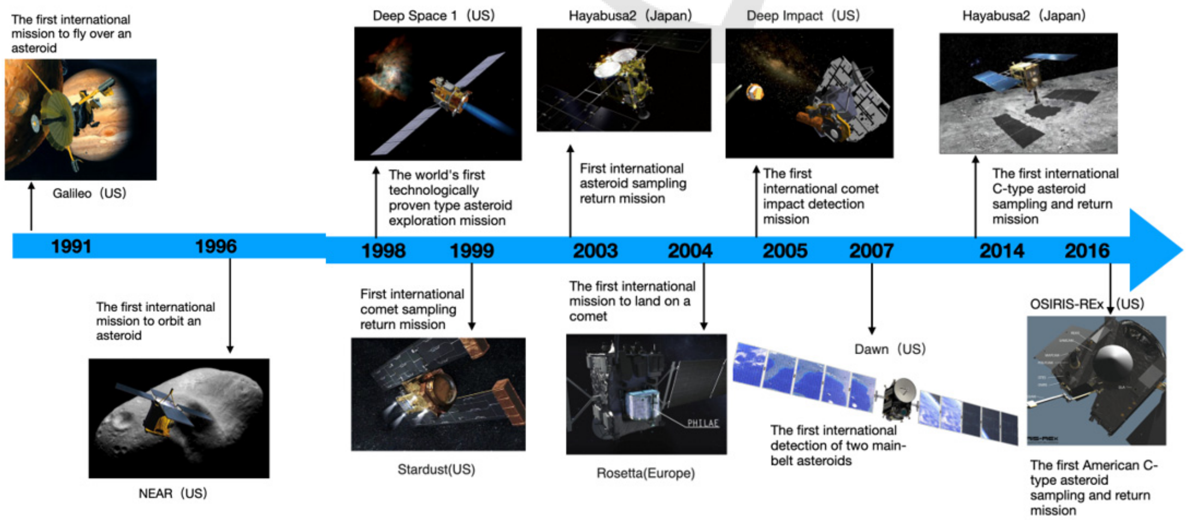

Figure 1: The mission's history of tiny body exploration (Geng et al. 2018).

3 CHARACTERISTICS AND DEVELOPMENT TRENDS OF SMALL CELESTIAL BODY DETECTION MISSIONS

In recent years, space agencies and countries such as the United States, ESA, and Japan have also planned multiple asteroid detection missions (Landis, 2019; Zou, 2017), as shown in Table 1.

Table 1: Planed asteroid exploration missions.

Mission	Country	Time	Main Task
Lucy	United State	2021	Fly to the Trojan asteroid
DART	United State	2021	Hitting a near-Earth double body asteroid
Psyche	United State	2022	Detecting the main belt M-type of Psyche
Destiny	Japan&Germany	2022	Asteroid dust detection
Gastonia	Europe	2028	Main belt comet 133P orbiting detection
GAUSS	Europe	2029	Ceres sampling return

3.1 Situation of United States

The U.S. that has initiated the detection of tiny celestial bodies earliest and carried out the most tiny celestial body detection missions to date is the United States. It has launched a total of 4 detectors with the main mission of asteroid detection. From comets to Kuiper belt asteroids, the detected objects range from near-Earth asteroids and main belt asteroids. Among them, the "Dawn" probe has completed the orbiting detection of the main belt "Ceres" (Ceres) and "Vesta" (Vesta); the "New Horizons" (New Horizons) flew over the The Kuiper belt small object 2014 MU69 (Ultima Thule) is a large solar object with a distance of 43 AU, and its shape directly confirms the pebble accretion model of planet formation. So far, human detectors have visited eight major planets, asteroids, comets, and Kuiper Belt objects. On September 9, 2016, the United States launched the asteroid sampling return probe "Osiris" to the ancient asteroid Bennu (Chesley et al., 2014; Lauretta, 2012), and arrived near the carbonaceous asteroid on December 3, 2018, a detailed investigation is currently being carried out, the sampling point has been determined, and the samples will be returned to Earth in September 2023. This mission is another NASA deep space sampling return mission after the "Apollo" lunar landing project collected lunar rock samples and the "Stardust" probe brought comet samples back to Earth. Through the implementation of this mission, the United States will continue to expand the technological gap with other countries and maintain its dominant status in the aerospace industry. NASA unveiled the "Lucy" and "Psyche" missions, two newly chosen low-cost, discovery-level detection missions, in January 2017. Among them, A mission named "Lucy" is scheduled to launch in 2021, enter the asteroid belt in 2025, and search for the Trojan group of asteroids between 2027 and 2033. The mission consists of five Trojan asteroids orbiting Jupiter and one target in the asteroid belt. Launched in October 2023, the "Psyche" mission is scheduled to reach the 16th asteroid, Psyche, in 2030. A huge metal body made of iron, nickel, and rare metals (including gold, platinum and copper) is the target. With a diameter of More than 200 km, the detector will launch a 20-month detection study. In addition, NASA will soon implement a Dual Asteroid Impact Mission (DART) to conduct early on-orbit verification of the "Kinetic Impact" defense technology. The DART impactor is expected to be launched in 2021 and will hit the target asteroid in October of the following year. The probe will detect the surface morphology and geology of the primary and secondary stars before impact. The impact will be carried out when ground observation capabilities allow. The entire process will be observed from the ground and the implementation effect of the dynamic impact will be evaluated.

3.2 The State of Japan

Japan started late in the field of asteroid detection, but with unique ideas and planning, it launched a mission with the goal of achieving a one-step return of asteroid samples and achieved major breakthroughs. In June 2010, Japan's Hayabusa successfully completed the world's first sample return mission and returned to Earth, causing a huge sensation in the industry. JAXA took advantage of the situation and launched the "Hyabusa 2" project. The "Hyabusa 2" was successfully launched on December 3, 2014, Beijing time. The probe arrived at the target asteroid in 2018 and has now completed two touch sampling operations in orbit, will return to Earth with samples in 2020. n 2022, Japan and Germany collaborated to launch the "Destiny+" probe. Around 2026, it will approach the near-Earth asteroid Phaethon, where it will measure the dust's velocity and direction and examine its composition. Fig. 2 shows Japan's small celestial body exploration plan. According to Japanese specialists, "Hyabusa 1" and "Hyabusa 2" are just the beginning of its program for deep space exploration. Japan will adhere to the concept of independent development and continue to conduct systematic and step-by-step research on the solar system and the origin and evolution of life. detection.This demonstrates Japan's aspiration to join the world's elite in the field of deep space exploration by leveraging the world-class research outcomes in asteroid detection (Chesley et al., 2014; Lauretta, 2012).

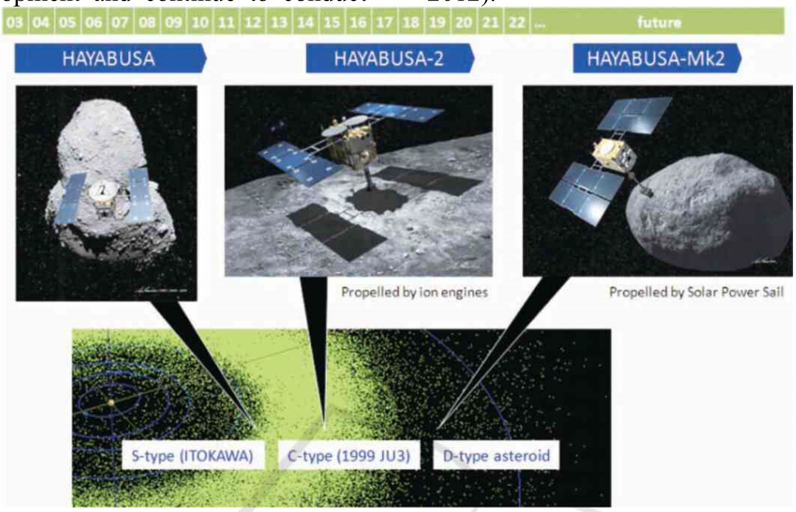

Figure 2: Roadmap of Japan asteroid exploration (Chesley et al., 2014).

3.3 The Status of European

Europe actively promotes asteroid sampling return missions through international cooperation. While it lacks experience in asteroid detection, Europe leads the world in comet detection. The implementation of asteroid detecting missions is aggressively promoted through international cooperation. On March 2, 2004,the "Rosetta-Philae" detector by ESA was launched successfully, and the target rendezvoused with the comet Churyumov-Gerasimenko (67P/Churyumov-Gerasimenko) and detect its position. The probe flew for ten years, relying three times on the gravitational acceleration of Earth and Mars. Philae touched down on the target comet's surface on November 12, 2014, and conducted in-situ detection.

While comet detection has made major achievements, Europe is also actively promoting asteroid detection missions. In 2015, the MarcoPolo-2D project was jointly proposed and applied for by the Beijing Institute of Technology, the Paris Observatory in France, the Open University in the UK, the China Academy of Space Technology, and other international and domestic research institutions to finish the 2011 SG286 asteroid. The samples were sent back, but for a variety of reasons they were not chosen. A Ceres sample return mission and a main-belt comet 133P detection mission have both been proposed recently by European scientists.

3.4 The status of China

In the early 1990s China launched relevant basic research on asteroid detection. With ongoing observations of solar system asteroids by astronomers, the Observatory System of the Chinese Academy of Sciences has a solid basis in asteroid observation, asteroid orbital mechanics, and ephemeris prediction. Theoretical research has been conducted on asteroid detection orbit design, faint celestial body identification and tracking, and other technologies. On December 13, 2012, at 16:30, the "Chang'e 2" spacecraft of China successfully detected Toutatis (Toutatis/4179), an asteroid located around 7 million kilometers from Earth, through a near flyby. The successful acquisition of the first-ever high-resolution optical photograph of an asteroid established the foundation for engineering practice that China will need to conduct comprehensive asteroid exploration (Huang, 2013). Tutatis has an uneven form, as determined by the study of the asteroid's interior structure, physical properties, and potential origin using high-resolution photos of asteroid No. 4179 taken by "Chang'e 2". A flat surface, shaped like a piece of ginger, consisting of a smaller end "Head" and a larger end "Body". Through research, some new features of Toutatis' surface were discovered that had not been discovered in earlier ground radar observations: at the end of the "body" is a massive basin with a diameter of approximately 800 meters, and more than 50 clearly visible spots may be located on the surface. Craters of various sizes, including two that partially obscured one another after being created close to the same spot; the "neck" connects the "head" and "body" at a nearly vertical angle; there are There are more than 30 areas with boulder features; evenfeatures such as smaller linear structures can be distinguished via Fig. 3 (Huang et al., 2013). Tutatis is most likely a Close Approach binary asteroid with a rubble pile structure based on its structural features. It could be the result of the YORP effect or the slow approach of two separate little objects. Alternatively, there may be a widespread impact to blame. In addition, since 2010, relevant domestic research institutions and universities, with the support of civil aerospace advance research, natural funds, etc., have carried out research and advanced technical research on asteroid detection, including research on asteroid monitoring and defense technology and small celestial body detection strategies (Relevant research results have been achieved in aspects such as target selection), asteroid resource development and utilization technology, and surface detection of weak gravity small celestial bodies.

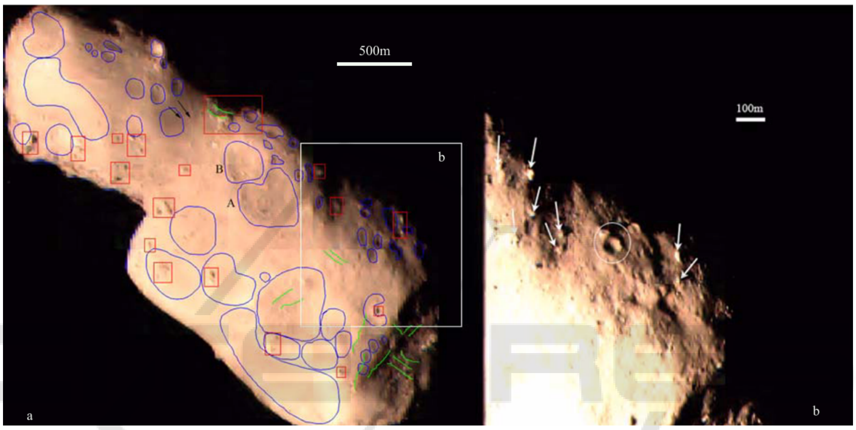

Figure 3: Physiognomy Features of Tutattis (Huang et al., 2013).

3.5 Main Implications

Summarizing the development history of asteroid exploration over the past many years, it can be seen from the implemented tasks and plans of various countries that asteroid exploration, lunar exploration, and Mars exploration are both important research directions for deep space exploration in the 21st century. The following trends are shown:

Asteroid detection has progressed from flyby and companion flight detection to surface soft landing and sample return detection. In the early days of asteroid detection, only flyby or companion flights could be completed due to technical limitations, making it impossible to accomplish asteroid surface landing and return detection. Asteroid detection was mostly completed as an expansion stage of a certain detection mission. However, with the continuous advancement of orbit design and navigation control technology, advanced propulsion technology and surface operation technology, the form of asteroid detection has gradually developed into in-place detection and sample return detection, thus enabling greater scientific detection results. At present, Japan has achieved the return of samples from the surface of the asteroid, and the European "Rosetta-Philae" probe is also conducting more detailed scientific research on the surface of the comet. The United States, Europe, and Japan are all actively promoting follow-up plans. Implementation of the asteroid sampling return mission.

The asteroid exploration mission has many bright spots in scientific objectives and new technologies are highly motivating. Small solar system objects, including asteroids and comets, are thought to represent leftovers of the solar system's early development and can offer crucial hints for fundamental scientific studies on the genesis of planets, the solar system's history, and the beginning of life. Scientists have brought up cutting-edge scientific questions about small celestial bodies, including "the origin of organic matter, the distribution and source of water, dynamic formation and evolution, and the threat of collisions with near-Earth asteroids." Scientists' interest in exploring these scientific questions has grown significantly. The implementation of small celestial body detection missions also involves a series of key technologies such as space propulsion technology, space energy technology, small celestial body surface attachment technology, and sampling technology under microgravity conditions. The long detection mission cycle, long target distance, and moderate target size make the detection of small celestial bodies has become a unique testing ground for these new technologies. The U.S. Deep Space 1 probe and Japan's Hayabusa probe have both achieved important results in the demonstration and verification of new technologies. The verified technologies have also provided important technical support for countries in subsequent deep space exploration missions.

A potential basis for global collaboration in the high-tech aerospace sector is asteroid detection. There are a large number of small celestial bodies, complex and changeable orbits, and different shapes, making detection very difficult. International cooperation is now necessary because no one nation or institution can carry out in-depth research on several asteroids on its own. For example, the scientific payload of the "Dawn" probe came from multiple aerospace departments or research institutes such as Germany and Italy, and the "Rosetta-Philae" probe brought together the efforts of America, Italy, Germany, France, and other countries to complete the current mission. Complete scientific payload configuration and international cooperation will achieve "normalization" in subsequent asteroid exploration.

4 MAIN KEY TECHNOLOGY

An environment of "microgravity and uncertainty" is what asteroids are like. "Microgravity" means that the surface of the asteroid is in a microgravity environment (about 10-4g) and the escape velocity is very low; "uncertain" means that there is very little prior knowledge about the asteroid, and before the detector arrives, it can generally only be determined with the help of Astronomical observations and theoretical assumptions predict its rotation period, topography, surface physical properties, etc., and there is little prior knowledge. Therefore, the implementation process of asteroid sampling return technology is fundamentally different from that of large planets such as the moon and Mars. Further advancements in many of key technologies are required to support programs aimed at exploring Mars and the Moon. Among these are critical technologies that urgently require advancements: light and compact high-speed re-entry and return; long-life electric propulsion; precise point attachment control; and mild gravity attachment sampling.

Because of the asteroid's great distance from Earth, only a limited set of physical attributes and fundamental orbital parameters can be obtained by ground observations. The asteroid's weak gravitational field prevents the establishment of an orbit, so the resolution of the asteroid's material composition and shape is very limited, and the size and structure of the asteroid are very limited, topography, motion characteristics (rotation axis direction, precise rotation period), gravitational field, magnetic field and other physical information are almost blank. Traditionally, the laws of detection targets and their environment are the conditions for spacecraft landing and navigation, but asteroid attachment detection is a scientific activity carried out to obtain these laws. Traditional navigation methods cannot support the safe and accurate attachment of a probe to the surface of an asteroid with a size of only a few hundred meters. In addition, there is a certain deviation in the ephemeris of asteroids. As the detector's distance from the earth increases, the accuracy of ground-based orbit determination also decreases significantly. It is difficult to rely solely on ground-based orbit determination results to meet the mission requirements of the detector to rendezvous and attach to the asteroid.

In summary, whether in terms of model establishment, control schemes or sensor capabilities, higher margins and greater robustness are required to adapt to the impact of uncertainty in asteroid target characteristics (Cui & Cui, 2002; Li et al., 2012). For the detector to be safe and to fulfil its mission objectives, it must be equipped with high-precision, high-robust autonomous navigation and fixed-point attachment control capabilities (Ye et al., 2015).

The asteroid's surface is where the detector is fixed. Sampling the asteroid is an important way to obtain asteroid information. It is necessary to achieve the rendezvous, attachment and sampling of asteroids in a weak gravity environment. Long-term attachment will be crucial for future missions due to the need for the growth and utilization of asteroid resources, and multi-point sampling detection on the surface will increase the mission's detection range and enhance its return on investment. The asteroid attachment sampling process can be divided into attachment surface, sample collection, sample transfer and other links. Each link faces new problems and technical challenges.

During the process of attachment to the surface, the gravitational field of the asteroid is weak and the surface escape velocity is small. The most likely possibility is that it will rebound during attachment. Uncontrolled rebound is the most dangerous part of the asteroid attachment. The detector may lose control of its attitude, roll over, or even be damaged by collision. How to maintain posture and avoid losing control during contact with an asteroid is one of the challenges. During the sample collection process, unlike the moon and Mars, all materials during the asteroid sample collection process are basically in a state of free movement, and the open shovelling and digging methods that can be used in a gravity environment are ineffective. Special sample collection methods adapted to microgravity environments need to be developed, and challenges such as how to constrain the movement direction of the samples need to be solved.

The sample transfer process is similar to sample collection. It is necessary to find a solution to the constraint problem regarding the direction of sample movement and to maximize the sample transfer method's flexibility. In addition, in order to ensure successful sampling and meet mission requirements, it is also necessary to confirm the final state of the sample transfer to the returner and measure the sample collection volume. The asteroid attachment sampling process is complex and has many interface constraints. The technical challenges in each link mentioned above have brought great difficulties to the system design, test verification, etc. of the sampling mechanism, sample container, etc. It is necessary to carry out integrated and refined design of the attached sampling system and build an integrated verification environment based on the top-level requirements of the task, carry out sufficient ground testing and verification work.

The probe flies from the earth to the target asteroid far away from the main belt for orbiting detection. The whole process requires a speed increment of about 8 km/s. On the one hand, as the detector travels further from the sun and the main belt, the solar wing's power production capacity reduces correspondingly. A wide range of multi-working point adjustments must be possible for the power of the ion electric propulsion system in order to match the output power of the solar sail panel under different distances of solar conditions. On the other hand, the electric propulsion system must be able to operate continuously for an extended period of time. For example, the ion electric thruster of the "Dawn" detector has been ignited in orbit for more than 30,000 hours; at the same time, considering the harsh environmental conditions during the mission, the electric propulsion is in hot Design, dust-proof design and other aspects also need to be considered. Therefore, the ion electric propulsion for asteroid detection needs to be able to adjust at multiple operating points within a wide power range and can work autonomously and continuously for a long time. Technical research and experimental verification need to be carried out based on the specific needs and constraints of the mission.

In the asteroid sampling return mission, the re-entry speed of the returner will exceed the second cosmic speed, reaching about 13 km/s; the re-entry process will withstand a heat flow of up to about 12 MW/m^2. According to the on-orbit data study of the American Stardust and Origin returners, the turbulent heat flow after return is several times higher than the laminar heat flow (Ye et al., 2015). If the traditional laminar flow thermal environment prediction method is directly used to predict the re-entry thermal environment of the returner, the heat protection structure on the leeward side may be too weak, and the structure may burn through under turbulent heat conditions during re-entry. However, according to the turbulent heat design. This will cause the structure to be overweight. In view of the mission requirements and constraints of high-speed re-entry and return of asteroids, research and analysis on transition criteria for ultra-high Reynolds number and ultra-high sonic turbulence are required; research and development of functionally graded anti-insulation materials and high-strength materials that are resistant to high enthalpy and high heat flux density Supersonic parachute; carry out lightweight and refined system design of returners.

5 CONCLUSIONS

Asteroid exploration "sees the big from the small", the mission reflects the diversity and uniqueness, focuses on exploring the origin and evolution of the universe, material structure and other major basic and cutting-edge scientific issues, and reflects the basic engineering issues of public interest (resource development and impact warning) , has become a hot spot for deep space exploration. It is of significant significance for opening new territories, revealing the origin of life, promoting technological progress, developing natural resources, and protecting the security of the earth. It is one of the major practical activities to promote the transformation from a space power to a space power and implement the national strategy of innovation-driven development. Asteroid detection will face more new technological challenges and more cutting-edge and fundamental issues. China used the "Chang'e 2" probe to seize the opportunity and successfully realized the flyby detection of the asteroid "Tutatis" and accumulated certain engineering experience; the successful implementation of the "Chang'e 5" flight tester" made a breakthrough and has mastered the key technology of high-speed re-entry and return; "Chang'e 5" will break through in unmanned automatic lunar sampling technology. These engineering achievements prove that China has initially mastered multi-target detection mission design, detector orbit measurement, and high-reliability autonomous control and management target acquisition and other theories and technologies have laid a good foundation for carrying out multi-target and multi-mission detection of asteroids. Activities related to asteroid exploration can serve as a solid foundation for both regional and global space collaboration, and they are a potent first step for China when it comes to pursuing international space exploration cooperation. The realization of scientific results and engineering practices can greatly enhance China's participation in international space coordination and activities. The implementation of asteroid exploration will drive the coordinated development of China's space science and detection technology, and play a role in connecting the past and the future in the planetary exploration development plan. Choosing the right time to implement asteroid detection missions and obtaining scientific results with originality and world influence will further promote innovation and breakthroughs in aerospace technology, space science and other fields.

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