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Response to Risk of Near-Earth Asteroid Impact

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Abstract: Near-Earth asteroid (NEA) impacts on Earth have caused at least 10 biological extinction events of different degrees, posing a long-term threat to all human beings. The prevention of NEA impacts concerns global security and the survival of human civilization, and urgently requires extensive research. This paper discusses the hazards and risks of NEA impact on Earth and the significance of active response. The current international research situation and trends regarding NEA impact risk response were analyzed, including response procedures, monitoring and early warning, impact hazard assessment, and active defense. Further, the progress and shortcomings of NEA impact risk response in China were summarized. Based on the above analysis, development goals and a system structure for NEA impact risk response in China are proposed, and the key tasks were summarized and discussed, including monitoring and early warning, active defense, disaster rescue, basic research, and international cooperation. Furthermore, we suggest that China should strengthen the top-level design and long-term planning of its impact risk response, establish an integrated impact risk response system, develop impact risk response and innovation capabilities, and build a community with a shared future for mankind, creating a planetary defense system that adapts to China’s national conditions and achieves accurate monitoring, reliable warning, effective disposal, and efficient rescue.

Keywords: near-Earth asteroid; impact hazards; impact risk response; monitoring and early warning; NEA active defense; international cooperation

1 Introduction

Asteroids within a perihelion distance of 1.3 AU (1 AU = 1.496 × 10^8 km) are called near-Earth asteroids (NEAs). As of March 7, 2022, 28, 464 NEAs had been identified [1]. Specifically, 10 024 NEAs were over 140 m in diameter and 887 were over 1 km in diameter. There were 2263 asteroids identified with potential hazards. NEAs are hard to discover because of their weak brightness and wide distribution. Moreover, their orbits are easily changed owing to the traction of major planets and probably intersect Earth’s orbit. As a result, NEA impact on Earth is certain to be abrupt and have occurred frequently in history [2–6]. Earth has experienced 22 extinction events of varying degrees, at least 10 of which were caused by NEA impact [7]. On February 15, 2013, an NEA with a diameter of approximately 18 m and mass of approximately 7000 t exploded at a height of approximately 30 km above the Chelyabinsk region of Russia at a speed of 18.6 km/s, which caused personal injury and property damage. In 2021, there were approximately 1600 NEA fly-by events around the world, and 29 NEAs were observed entering the Earth’s atmosphere. In addition, a bolide occurred in Zhumadian City, Henan Province, China.

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NEAs flying to Earth explode in the atmosphere. NEA impacts on Earth cause earthquakes, tsunamis, and volcanic eruptions, and also catastrophic changes in the global climatic environment, or even global biological extinction and the disappearance of civilization. As a major long-term potential threat facing humanity, NEA impacts on Earth need to be handled jointly by all countries worldwide. This brings major scientific and technological challenges to the international aerospace and astronomical communities. The NEA impact risk response is also known as planetary defense. Driven by the comet–Jupiter impact in 1994 and the NEA impact in Chelyabinsk, Russia in 2013, the international community has paid careful attention to relevant issues. For example, planetary defense organizations for active response were established by the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS) at governmental and non-governmental levels. In 1995, the United Nations held the first international seminar on "preventing near-Earth objects (NEOs) from impacting the Earth." In 2014, the International Asteroid Warning Network (IAWN) and Space Mission Planning Advisory Group (SMPAG) were established under the UNCOPUOS framework. In 2016, the United Nations General Assembly designated June 30 as International Asteroid Day to educate the public about the potential threats of NEAs to Earth. Since 2009, the International Academy of Astronautics and the United Nations Office for Outer Space Affairs have held regular international Planetary Defense Conferences (PDCs). At the governmental level, the United States established the Planetary Defense Coordination Office (PDCO) in 2016. It issued the *National Near-Earth Object Preparedness Strategy and Action Plan* (2018) [8], aiming to improve NEA detection, tracking, and characterization, and develop NEA deflection and destruction technologies. Moreover, it published a *Report on Near-Earth Object Impact Threat Emergency Protocols* (2021) [9]. Germany, the United States, Russia, and Japan successively established centers for the monitoring, early warning, and defense of NEOs.

Research on NEA impact risk response in China started late. Most of the research is spontaneous and sporadic, and lacks comprehensive deployment planning and special support channels. This results in a weak foundation, low international contribution, and limited voice in the international discourse. Increasing gaps between China and other countries that have advantages in this aspect not only threaten national security but also weaken independent decision-making and leadership in the face of major events concerning global security. This is incongruent with China's image as a competent global power and its international status as a science, technology and aerospace power. In 2021, the China National Space Administration, together with relevant ministries, demonstrated China's medium- and long-term development plan for NEA impact risk response, aiming to systematically enhance the ability to respond to NEA impact risks. Accordingly, this paper discusses the demand for response, describes current situations and trends, and summarizes relevant gaps. Moreover, this paper proposes development objectives, system composition, and key tasks. It aims to provide a basic reference for national planning and overall research related to NEA impact risk response.

2 Significance of active response to NEA impact risk

2.1 Overview of NEA impact hazards

Damage caused by NEA impact on Earth is directly related to the impact energy [10]. The corresponding process can be divided into three stages: entering the atmosphere at a high speed, impacting the Earth, and causing long-term environmental effects (Fig. 1). When an NEA enters Earth's atmosphere at an extremely high speed (approximately 20 km/s), it forms a high-temperature, high-pressure shock wave in the atmosphere. Subsequently, the shock wave propagates to the Earth's surface, causing overpressure damage to the surface. Under the coupled action of aerodynamic heat and force, the NEA burns violently and disintegrates or even explodes to form a fireball in the air. This, together with the ionization of atmospheric molecules, forms thermal radiation, which is transmitted to the Earth's surface, causing thermal radiation damage and inducing forest fires. Fragments with small diameters and high structural looseness burn to ash in the atmosphere, while those with large diameters and low structural looseness pass through the atmosphere to hit the Earth, rapidly releasing huge kinetic energy. Generally, only stony meteorites (Type S) with a diameter of over 60 m or iron meteorites (Type M) with a diameter of over 20 m can pass through the Earth's atmosphere and hit the Earth's surface [11].

After a NEA impacts the Earth, materials in impact areas will instantly undergo extreme states as the temperature rises from 300 K to 10^5 K, pressure increases from 0.1 MPa to 10 TPa, and a strain rate as high as 10^8/s is produced. As a result, these materials break, melt, gasify, and even change into plasma, producing impact craters [12]. NEA impact causes chemical reactions (producing various gases) on the surface rock. The gases produced may propel part of the surface substances and dust into the air (producing ricochet debris clouds), and the corresponding shock waves can induce strong earthquakes. These gases, dust, and ash permeate the atmosphere, blocking out sunlight.

This can lower the annual average temperature of Earth by 2–5 °C, and may leave an effect lasting millions of years [13,14]. A direct NEA impact on the ocean will stir up huge waves of hundreds of meters in height, triggering strong tsunamis, earthquakes, and evaporation/sputtering of a large amount of seawater. Moreover, seafloor sediments and rock dust are ejected into the stratosphere and trapped there, causing death to many organisms in the ocean.

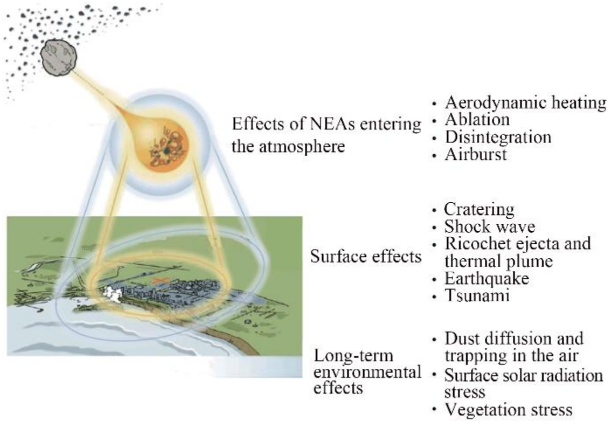

Fig. 1. Schematic of the process and hazards of NEA impact on Earth.

NEA impact on Earth is a highly coupled physical–mechanical–chemical process. Only by conducting experiments of super-speed entry and impact in combination with numerical simulation and theoretical analysis can accurate models be established for the processes and effects of NEAs entering the atmosphere and impacting the Earth. This is a major frontier and a difficult problem worldwide. Compared with other parameters, NEA diameters can be easily obtained, and the mass of NEAs can be estimated using equivalent diameters. Thus, equivalent diameters are typically used internationally to characterize impact hazards. Corresponding hazard levels are mainly divided into five categories according to the NEA's diameter [8,15]: (1) For NEAs spanning at least 1 km, disasters on a global scale can be induced, for example, the K-T event 65 million years ago. Such events may occur once every 1×10^8 years. (2) For NEAs spanning 140 m, intercontinental disasters can be induced, such as the 2019 OK asteroid event. Such events may occur once every 1000 years. (3) For NEAs spanning 50 m, disasters at a large city level can be induced, for example, the Tunguska event in Russia in 1908. Such events may occur once every 100 years. (4) For NEAs spanning 10 m, disasters at a small-town level can be induced, for example, the Chelyabinsk event in Russia in 2013. Such events may occur once every 30–50 years. (5) For NEAs spanning 1 m, airbursts and bolides are mostly produced, for example, bolides in Zhumadian City, Henan Province, China in 2021. Such events frequently occur. Statistics of impact events show that the impact points of NEAs are uniformly distributed on the Earth's surface [16].

2.2 NEA impact risks

Impact risks refer to the product of the probability of impact on Earth and impact-induced hazards. NEA impact risk assessment usually involves the Torino [17] and Palermo scales [18]. The former uses 11 integers (0–10) to divide risk grades into five categories, corresponding to different impact probabilities and hazards, whereas the latter is calculated using the impact probability, time to the occurrence of impact, and impact energy. To further clarify the physical significance of relevant indices, some researchers [19] established a quantitative assessment index of the impact-induced death toll by introducing casualty estimation into the assessment of NEA impact risks. This index is based on impact probability, impact event type, and early warning time. According to the data analysis [1], the most threatening NEA within 100 years is asteroid No. 99942, with a diameter of approximately 370 m. It is predicted to fly over 3.1×10^4 km above the Earth's surface (lower than GEO orbit) on April 14, 2029, and approach the Earth again in 2068 (with an impact probability of approximately seven parts per million). The most threatening NEA within 10 years is asteroid No. 2016NL39, with a diameter of approximately 18 m. It is predicted to fly over at a distance of 1.2×10^5 km from the Earth (approximately 1/3 of the Earth–Moon distance) on June 30, 2030.

It should be noted that more than 98% of NEAs have not been discovered and cataloged, which may seriously threaten Earth [8]. Approximately 70% of NEAs with diameters greater than 140 m, approximately 97% of those with diameters of 50–140 m, and approximately 99% of those with diameters of 10–50 m have not been identified [20]. The orbits of these undiscovered NEAs orbits change because of the gravitational influence of other large celestial bodies. As a result, it is difficult to predict impact threats accurately, and the actual risks are much more serious than the known risks. Thus, there is an urgent need to improve NEA detection and develop more accurate theories and models for impact risk prediction. Historically, NEAs with diameters greater than 1 km have a low probability of impact, and effective in-orbit disposal can hardly be carried out in the short term. Although the impacts of NEAs with diameters less than 10 m occur frequently, the actual hazards are small. Thus, the international community should focus on NEAs with diameters of 10–1000 m, especially those with diameters of 30–50 m.

Internationally, impact risks and the corresponding early warning and response are divided into four levels according to the equivalent diameters of NEAs [8,15]: (1) Level I risks (red alerts) refer to extremely serious intercontinental to global hazards, mainly caused by NEAs with diameters greater than 140 m. (2) Level II risks (orange alerts) refer to serious hazards affecting large cities up to intercontinental levels, mainly caused by NEAs with diameters of 50–140 m. (3) Level III risks (yellow alerts) refer to less serious hazards affecting small-medium to large cities, mainly caused by NEAs with diameters of 20–50 m. (4) Level IV risks (blue alerts) refer to ordinary hazards affecting towns to small-medium cities, mainly caused by NEAs with diameters less than 20 m.

2.3 Significance of NEA impact risk response

Unlike natural disasters such as earthquakes and floods, NEA impacts on Earth have the following characteristics: First, they cause instantaneous global disasters. No country or people can survive the impact of an NEA with a diameter greater than 50 m, especially greater than 140 m. Second, impact threats are predictable. We can predict the impact time, impact points, and hazard degree of NEAs relatively accurately, as long as we continuously improve our monitoring and early warning abilities and strengthen international cooperation. Third, the impact hazards are preventable. Impact-induced loss can be avoided completely or significantly reduced by forming an active defense capacity through the active development of multi-means in-orbit disposal technology. Enhancing the NEA impact risk response is of practical and far-reaching historical significance.

First, implementing the principles of national security is indispensable. Although there is a low probability of NEA impact on Earth, it causes tremendous hazards. This is closely related to the security of almost all areas in the national security system. NEA impacts on Earth directly threaten residents’ lives and properties, thus affecting economic and social development, security, and stability. A reliable response to NEA impact risks is not only crucial for coordinating various undertakings, but is also an important starting point for building a solid foundation of national security and promoting in-depth integrated development.

Second, the NEA impact risk response is an important impetus for innovative developments in science and technology. It requires us to solve basic scientific and key technical problems in astronomy, mathematics, physics, mechanics, geoscience, information science, control science, aerospace science, and the science of law, showing remarkable interdisciplinarity. Improving scientific and technological levels in related fields to form systematic capabilities is an important way to plan the exploitation and utilization of outer space resources in advance, leading to the development of new space technology. This also drives the development of associated industries and accelerates the construction of a science, technology, and aerospace power.

Third, it is important to promote the construction of a community with a shared future for mankind in outer space. Once NEAs impact Earth, all human beings will suffer. The effectiveness of response concerns the survival of human civilization. Therefore, it is the common responsibility of all human beings to deal with impact risks and protect the Earth. China’s active response to NEA impact risks and cooperation with the international community to protect human security will demonstrate the good image of China as a responsible aerospace power, embody China’s consistent purpose of peacefully using space, improve human well-being, and support the construction of a new model of international relations and a community with a shared future for mankind.

3 International research on NEA impact risk response

3.1 Impact risk response process

By referring to international research on NEA impact risks, we can summarize the response process as follows (Fig. 2): (1) Monitoring and early warning, which includes search and discovery, tracking of determined orbits and data updating, measurement of physical properties, and impact risk forecasting, thus providing inputs for impact risk assessment. (2) Impact risk assessment, which includes calculating impact probability, estimating impact risk corridors, predicting impact points, and analyzing impact effects according to the orbital and physicochemical parameters of NEAs, thus providing inputs for in-orbit disposal. (3) In-orbit disposal. Considering the early warnings of dangerous NEAs, we can change the orbits of these NEAs to avoid their impact on Earth or fragment them to avoid or reduce their hazards to Earth. This includes disposal task planning, scheme design, task implementation, and effect assessment, providing inputs for disaster rescue. (4) Disaster rescue. In the case of early warning failure or unsuccessful disposal of impact, we will establish an emergency response mechanism against impact disasters and carry out disaster rescue to reduce loss and restore the environment.

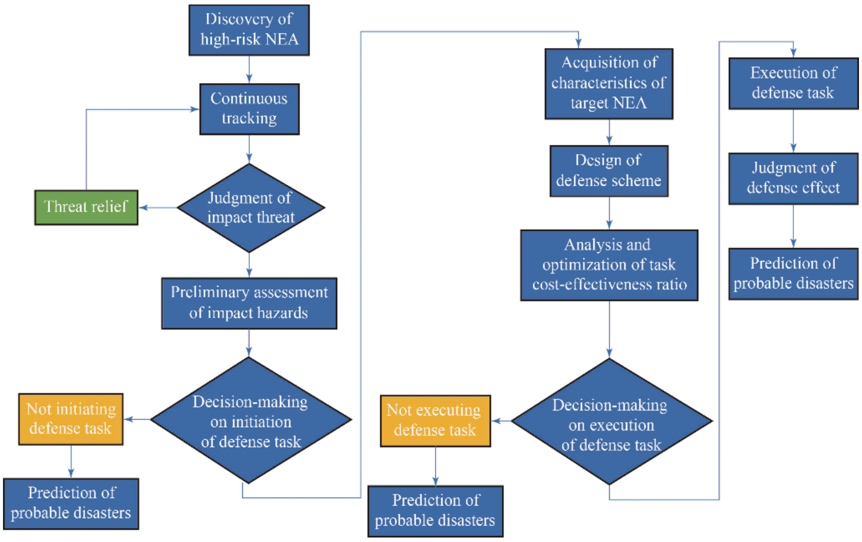

Fig. 2 General process of the NEA impact risk response.

3.2 Research progress in monitoring and early warning

Monitoring and early warning of NEAs can be performed in several ways. Observation positions can be classified into ground-based and space-based monitoring. The technical principles can be divided into optical observations, infrared spectrum observations, and radar detection. There are three main scenarios for monitoring and early warning: (1) Routine cataloging. The celestial sphere is scanned routinely using special-purpose space-based and ground-based equipment to find new NEAs and track them with precision telescopes to obtain sufficient data for orbit determination and cataloging. (2) Early warning of threats. NEAs with an impact probability of over 1% within 20 years identified in routine cataloging are tracked precisely by special-purpose/multi-purpose ground-based and space-based equipment to obtain precise orbits and evaluate the detailed impact risk and hazards. (3) Short-impending prediction. NEAs with an impact probability of more than 10% within a range of 7.5×10^6 km from Earth are intensively tracked and measured to obtain physicochemical characteristics and continuously predict impact regions (points).

The NEA monitoring and early warning program in the United States (Spaceguard Survey) began in 1992. Currently, the United States has established a relatively complete monitoring network dominated by ground-based observations and supplemented by space-based observations. They are the pioneer and main contributor of NEO monitoring worldwide. Their monitoring and discovery system is characterized by a multi-aperture configuration, optics–radar cooperation, Southern/Northern Hemisphere arrangement, and special- /multi-purpose equipment integration. The United States has provided over 98% of data in international NEA catalogues. In terms of routine cataloging, they have 11 special-purpose optical telescopes (with apertures of 0.5–1.8 m) and multi-purpose telescopes with a maximum aperture of 4.2 m [1]. On average, approximately 1500 new NEAs are discovered every year, and a database has been constructed and published. A space-based infrared telescope (with an aperture of 0.5 m) and ground-based wide-field survey telescope (with an aperture of 8.4 m) are under construction. With such telescopes, we can monitor NEAs with a diameter of 30 m within 1 AU from Earth. The European Space Agency (ESA) established the Planetary Defense Office in 2013 to conduct NEA monitoring, data processing, and in-orbit disposal. They have 14 multi-purpose telescopes (with apertures of 0.4–4.2 m), which have a contribution rate of 0.88% to international cataloging. A “fly eye” system with an aperture of 1 m is being built to significantly improve search efficiency. Meanwhile, Russia established the Planetary Defense Center in 2002. It currently has nine special-purpose telescopes (with apertures of 0.2–0.7 m); however, these provide little monitoring data for international sharing (with a contribution rate of 0.08% to international cataloging). Multi-purpose telescopes in service have a maximum aperture of 2.6 m, and are mainly used for measuring the characteristics of NEAs. The large telescope

AZT-33VM (with an aperture of 1.6 m), operational in 2016, can detect remote NEOs. Based on monitoring and cataloging, the United States precisely determines the orbits of threatening NEAs and measures their characteristics using ground-based optical equipment, namely, the Arecibo radio telescope and Goldstone Solar System Radar to evaluate impact risks in detail. Sentry, the established impact monitoring system, can analyze and determine the precise orbits of newly discovered NEAs and calculate the probability of NEA impact on Earth. It searches for NEAs that may approach the Earth in the next 100 years and updates and publishes analysis results in a timely manner to provide decision-making support for the PDCO. In the meantime, it has a good capacity for short-impending prediction of many NEAs that cannot be cataloged in the short term and may suddenly approach Earth (for example, the impacts of NEAs 2008 TC3, 2014 AA, 2018 LA, and 2019 MO on Earth).

Construction of ground-based monitoring and early warning systems began early, and construction technologies are relatively mature. Although the system is the backbone equipment at present, it has insurmountable inherent defects in terms of accuracy, efficiency, and capacity, failing to realize full-space all-time monitoring and early warning. The limitations are mainly because that such a system is restricted by atmospheric conditions and station positions, and thus there is a “blind corner” in the sunlight irradiation zone, which makes the system only able to monitor approximately 30% of the sky. Moreover, the system works in a mode of “waiting for targets,” which takes a long time to reach the detection peak and thus fails to complete detection within a given time limit. Space-based monitoring and early warning systems have a wide monitoring range, various tracking means, and accurate orbit prediction, which can compensate for the inherent defects of ground-based systems. Therefore, it has become the focus of construction in various countries. However, such a system is also restricted by high cost, difficult in-orbit maintenance, and a single payload configuration. Therefore, equipment and technology for monitoring and early warning must be developed in the following directions: the transformation of ground-based systems to ground-/space-based cooperative systems; further increase in aperture and broadening of the field of view; extension of visible light to infrared light and shift from single band to multi-band integration; demonstration and verification of cutting-edge technologies and upgrading of software and hardware. Moreover, a capacity for ground–space integrated monitoring and early warning will be formed to catalog at least 90% of NEAs with diameters of over 140 m and carry out monitoring, early warning, and cataloging of NEAs with a diameter of 50 m.

3.3 Progress in impact hazard assessment

The United States National Aeronautics and Space Administration (NASA) extended aerodynamic technology developed for hypervelocity vehicles to research NEAs entering the atmosphere. It has established coupling algorithms for high-temperature flow, shock-layer radiation, and ablation of NEAs entering the atmosphere at hypervelocity; ground test methods of NEA ablation and radiation effect during entry; and a quantitative method to simulate shockwave effects during entry. Thus, the aerodynamic thermal environment, ablation, and shockwave propagation of NEAs have been studied in detail. The Lawrence Livermore National Laboratory developed impact dynamics methods to simulate the entry and impact effects of NEAs. In addition, it studied the breakup and airburst of NEAs during entry, as well as impact cratering and impact-induced tsunamis. In 2017, NASA established a system for probabilistic asteroid impact risk (PAIR) analysis and assessment. The system can quantitatively analyze the process and effect of preset NEA impacts on Earth and assess hazards to ground populations and facilities. Thus, it has become the main supporting tool for joint emergency tabletop exercises and drills against NEA impacts. Imperial College London, the von Karman Institute for Fluid Dynamics in Belgium, the University of Stuttgart in Germany, and the Academy of Sciences of the Czech Republic studied the break-up, airburst, and thermal radiation during NEA entry at hypervelocity and impact cratering, developing corresponding simulation methods for impact dynamics. Scientific research institutions in the United States have established models for NEA entry and impact effects, developed software for NEA impact hazard assessment, and provided open services.

At present, hotspots and problems in NEA impact hazard research include the precise description of NEA impact on Earth, the revelation of hazard-causing and hazard-evolution mechanisms, and the establishment of models for a whole-process response and hazard evolution. (1) In terms of studying the effect and mechanism of NEAs entering the atmosphere at hypervelocity, no high-temperature gas model or ground test technology is available yet for speeds higher than 12 km/s on Earth. The difficulty is further increased owing to the porosity, cracks, anisotropy, and complex geometry of NEAs. As a result, research has progressed slowly in recent decades. (2) The effect and modeling of NEA impact on the Earth at hypervelocity cannot be tested yet, as the impact becomes a strong physical–mechanical–chemical-coupled process due to the extremely high relative speed (20 km/s on average) and impact-induced solid–liquid–gas–plasma multiphase mixture. Moreover, materials in impact regions are in a solid–liquid–

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gas mixed state, and the theoretical modeling to describe such a wide-range and multiphase state is still rudimentary. (3) In terms of the hazard-causing mechanisms and long-term environmental effects of NEA impact on Earth, existing work have focused on individual types of disasters such as shock waves, earthquakes, fire, ejecta, impact cratering, tsunamis, and volcanic eruptions. However, the coupling effect of various impact-induced hazards has not been studied, and there is a gap in the study of long-term hazard evolution after impact.

3.4 Research progress on in-orbit disposal

Research on in-orbit disposal (also known as active defense) began in the 1980s and has formed a relatively complete technical system [15]. It has focused on developing two methods: instantaneous action based on kinetic impact, which has been demonstrated and verified in orbit, and long-term action such as laser ablation, tugging, and gravitational traction, which are still under conceptual exploration.

The United States successfully carried out the Deep Impact mission in 2005 [21]. During the mission, a copper impactor with a mass of 370 kg hit the nucleus of Comet Temple-1 at a relative speed of 10 km/s after a flight distance of 4.3×10^8 km. This mission verified the technical feasibility of asteroid defense through kinetic impact. NASA and ESA jointly carried out the Asteroid Impact & Deflection Assessment (AIDA) mission [22] to further verify kinetic impact-based defense technology in orbit. The Double Asteroid Redirection Test mission of the AIDA project was carried out by NASA, and its spacecraft was launched successfully on November 24, 2021. As planned, in September 2022, an impactor with a mass of 550 kg was used to hit secondary member B (with a diameter of 160 m) of the binary asteroid 65 803 1.1×10^7 km away from Earth at a relative speed of 6.6 km/s. After the impact, the speed of B was expected to change by approximately 0.4 mm/s, and the orbiting period to shorten by approximately 32 min. Ground optical equipment and a small accompanying satellite (separated from the impactor 10 days before the impact) will be used for joint observation in the follow-up mission to demonstrate and verify key technologies, such as those for approaching detection, kinetic impact, and effectiveness assessment. The ESA is responsible for conducting the measurements and accurate assessment of impact effects in the mission. The corresponding accompanying satellite will be launched in 2024 and orbit the impacted asteroid in 2026 to assess the effect of kinetic impact more accurately and to modify the deflection model of kinetic impact.

Future directions of studies on in-orbit disposal are as follows: to further verify the effectiveness of kinetic impact-based deflection in orbit and improve disposal-assessment integrated technology; to develop new technologies such as laser ablation-based deflection and tugging to progress from conceptual research to technological development; to comprehensively analyze and assess the applicability, effectiveness, and costs of individual disposal technologies for various targets and design efficient disposal schemes of multi-means cooperation; and to integrate in-orbit and ground demonstration and verification to accelerate the practical application of asteroid defense.

4 Current situation of NEA impact risk response in China

4.1 Overall progress

Relatively speaking, asteroid defense research in China started late. Since 2000, as a result of the special scientific research project on space debris conducted by the State Administration of Science, Technology, and Industry for National Defense of China, common technologies and equipment have been successfully developed for the monitoring, early warning, and removal of space debris, providing a key foundation for NEA impact risk response. In 2018, the 634th Xiangshan Science Conference was held with the theme of “Frontier Science and Key Technologies of Asteroid Monitoring and Early Warning, Security Defense, and Resource Utilization,” focusing on asteroid defense. The Planetary Defense Seminar was held once a year from 2018 to 2020. At the 21st Annual Meeting of the China Association for Science and Technology in 2019, the “Survey, Defense, and Exploitation of Small NEOs” was selected as one of the 20 major frontier scientific issues and engineering-technical problems that play a guiding role in scientific development and a key promoting role in technological and industrial innovation. In October 2021, the first China Planetary Defense Conference was held with more than 300 attendees.

In 2020, an expert panel was established by the China National Space Administration (CNSA) to demonstrate schemes for NEA impact risk response. In April 2021, the CNSA announced that they would demonstrate and implement the fourth phase of the Lunar Exploration Project, Planetary Exploration Project, International Lunar Research Station, and NEA defense system. Since then, a new chapter has opened in China’s space exploration in the new era. In 2021, China’s medium- and long-term development plan for NEA impact risk response was formulated and announced by a panel led by the CNSA. The year 2021 can be considered as the beginning year for

China's comprehensive construction of the operational architecture, mechanism process, and system capacity for planetary defense.

4.2 Technological research and international cooperation

In terms of ground-based observations, the 1 m-aperture telescope in the Purple Mountain Observatory, Chinese Academy of Sciences, is the only special-purpose equipment for NEA monitoring in China (located in Xuyi County, Huai'an City, Jiangsu Province, with D29 as its international station number). It has joined the international joint survey network to support daily cataloging and monitoring of NEAs with diameters greater than 300 m [16]. As of 2021, it had discovered 33 NEAs with a contribution rate of 0.13% to international cataloging. There are 32 other telescopes in China (with apertures of more than 1 m) that can also be used for NEA monitoring.

In terms of space-based observations, China has no space-based monitoring and early warning equipment for in-orbit services yet. China proposed the construction of a space-based NEA survey and positioning system using heterogeneous constellations [16]. As planned in the scheme, several small satellites will be deployed in an orbit similar to that of Venus at a distance of 0.6–0.8 AU from the Sun (including one main maneuvering satellite with a narrow-field-of-view optical-infrared telescope and several micro-satellites with wide-field-of-view optical telescopes). A heterogeneous design is adopted in multiple aspects, including satellite constellations, fields of view, resolution, sensitivity, celestial sphere scanning mode, and on-board computing, thus forming a space-based task mode with a combination of general and detailed surveys. Moreover, Chinese scholars have proposed the concept of space-based monitoring and early warning telescope missions in Earth's piloting orbit. Specifically, by deploying space-based telescopes at approximately 1×10^7 km in front of or behind the Earth, we can provide a feasible scheme to compensate for blind areas of ground-based monitoring and issue early warnings of NEAs coming from the daytime sky [23]. To date, China has not yet established an asteroid database.

In terms of impact hazard assessment, China has initiated studies on the physicochemical characteristics and statistical distribution of NEAs with observational data and explored some key technologies and ground scaling test methods in advance. In addition, the aerodynamic thermal environment, ablation, shock waves, ground cratering, and reverse ejection clouds that may occur when NEAs enter the Earth's atmosphere have been investigated, and quantitative simulation methods for NEA impact on land and sea have been developed. Models were also preliminarily established to analyze and evaluate the effects of NEAs entering the atmosphere and impacting Earth [12]. Studies have been conducted on the modeling and simulation of the momentum transfer of kinetic impact-based asteroid deflection and the technical feasibility of laser-ablation-driven deflection based on ground testing and semi-physical simulation of active space-debris removal by laser ablation [24]. Thus, the basic capacity for evaluating the effectiveness of kinetic impact have been obtained. Enhanced kinetic-impact defense schemes, such as deflecting asteroids by capturing another asteroid [25] and combining a spacecraft with the upper stage of the launch vehicle [26] were proposed, providing new options for defending large, potentially threatening NEAs, in addition to nuclear explosions. The mechanisms of NEA defense using nuclear explosions were studied by quantitative simulation, and NEA deflection behavior under different nuclear explosion conditions were obtained. Moreover, the safety of typical nuclear facilities under NEA impacts was assessed and analyzed.

China attaches great importance to international cooperation in NEA defense, and its participation in this field has steadily increased in recent years. In 2018, the Council of Asia-Pacific Space Cooperation Organization approved the Asia-Pacific Space Science Observatory project, planning to deploy one small-aperture telescope in each of the eight official member states (including China) for studying NEA monitoring and early warning. In 2019, the Xuyi, Changchun, Xinjiang, and Weihai stations of the Chinese Academy of Sciences and universities participated in the international joint observation of asteroid 1999 KW4. In addition, research on laws and regulations concerning planetary defense in China is still in its infancy because of the broadness of the legitimacy, responsibilities, obligations, and decision-making mechanisms related to defense.

4.3 Urgent problems in development

However, China has to resolve several issues in developing its NEA risk response. First, China has no top-level plan and system design yet, and the corresponding organizational systems, process mechanisms, and responsibilities of various actors are yet to be defined.

Second, China lacks special-purpose monitoring equipment and information platforms. Only one special-purpose telescope is currently available, which can only monitor NEAs more than 300 m in diameter (with brightness equivalent to an absolute magnitude of 20). However, it lacks the capacity for NEA orbit cataloging. In addition,

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China has not yet independently established an NEA information platform; thus, it is unable to gather data for early warnings. It relies on open international platforms to access monitoring and early warning data.

Third, the scientific research and technical reserves of the NEA impact risk response in China are insufficient. Systematic analysis, system arrangement, and in-depth research on these issues are necessary. Current research tends to pay more attention to technology and less to science. In-orbit disposal technology is under conceptual research, and both the research depth and breadth of impact hazard assessment and in-orbit disposal are insufficient. Whole-process simulation platforms for impact hazard assessment and in-orbit disposal have not been established; thus, whole-process exercises/drills cannot be supported.

Fourth, China has low international contribution and influence in the field of planetary defense. Restricted by NEA monitoring equipment and technology, institutions in China can provide limited observational data to the international community. Thus, China has not yet achieved an influence in this field befitting its international status, especially in the research and formulation of relevant international rules.

5 NEA impact risk response system in China and its key tasks

5.1 Development objectives of the response system

Based on national conditions and similarities, the response system of NEA impact risk in China should be developed according to the principles of consolidating the foundation, making up for the deficiency, exploiting the potential, strengthening the system, and raising the level. Equal attention should be paid to international cutting-edge research and the guarantee of high operational capacity, and the response system should be set up with both as the core targets. China should implement major projects such as space–ground integrated asteroid monitoring networks, demonstration and verification systems for in-orbit disposal, and major disaster rescue systems to form a planetary defense capacity with “precise monitoring, reliable early-warning, effective disposal, and powerful rescue.”

In the near term (before 2025), China should focus on constructing an NEA monitoring and early warning network with the capacity to independently discover and continuously catalog NEAs 140 m in diameter to improve its contribution to international cataloging. Research on key technologies for in-orbit disposal, such as kinetic impact deflection, should be completed, and such technologies should be demonstrated and verified at an appropriate time. A special disaster rescue system should be preliminarily established to improve the supply capacity of advanced disaster rescue equipment. In addition, China should establish domestic response and international cooperation mechanisms.

In the medium term (before 2030), China should focus on improving its capacity for in-orbit disposal and establishing a space–ground coordinated monitoring and early warning network. China should have the capacity for independent discovery and continuous cataloging of NEAs with a diameter of 50 m, and build an NEA database with independently obtained data to further improve its contribution to international cataloging. Disposal technologies, such as kinetic impact deflection and the assessment of disposal effects, should be demonstrated and verified in in-orbit scenarios to acquire the capacity for in-orbit disposal of NEAs with a diameter of 50 m. Joint exercises and drills should be carried out regularly. The comprehensive capacity for special disaster rescue should be enhanced.

In the long term (before 2035), the response capacity should be enhanced comprehensively, establishing an all-around reliable monitoring and early warning network. China should be able to independently discover and continuously catalog NEAs 30 m in diameter to increase its cataloging contribution rate to an internationally advanced level. In-orbit demonstration and verification of disposal technologies should be improved to acquire the capacity for multi-means in-orbit disposal of NEAs with a diameter of 50 m. China should significantly enhance the comprehensive strength of emergency rescue during compound catastrophes. China should strive to build a community with a shared future for mankind in the field of planetary defense.

5.2 Composition of the response system

The NEA impact response system is mainly divided into a decision-making and command layer, an organization and coordination layer, and an execution layer (Fig. 3). An expert committee is established to support the technical work at all levels, which formulates working mechanisms and regulates processes to form a hierarchical scientific work procedure. The decision-making and command layer is responsible for making decisions on major issues related to NEA impact prevention. The organization and coordination layer is responsible for resource coordination and task planning and carries out routine work. The execution layer is responsible for the implementation of prevention decisions, which mainly involves monitoring and early warning, in-orbit disposal, disaster rescue, and international cooperation: (1) Carrying out regular monitoring after the discovery of NEA impact threats, conducting emergency monitoring, identifying risks, and reporting early warning information to provide early warning data and inputs for in-orbit disposal. (2) Assessing NEA impact hazards, formulating disposal plans, conducting in-orbit disposal tasks, and evaluating disposal effects. (3) Ensuring good emergency preparedness, initiating emergency rescue after receiving early warnings and hazard assessment, and carrying out emergency recovery after impact events. (4) Participating in international joint monitoring/defense/rescue, data exchanging or sharing, and formulation of relevant international policies, regulations, and standards, thereby proposing international research plans for NEA impact risk responses that could expand China's influence.

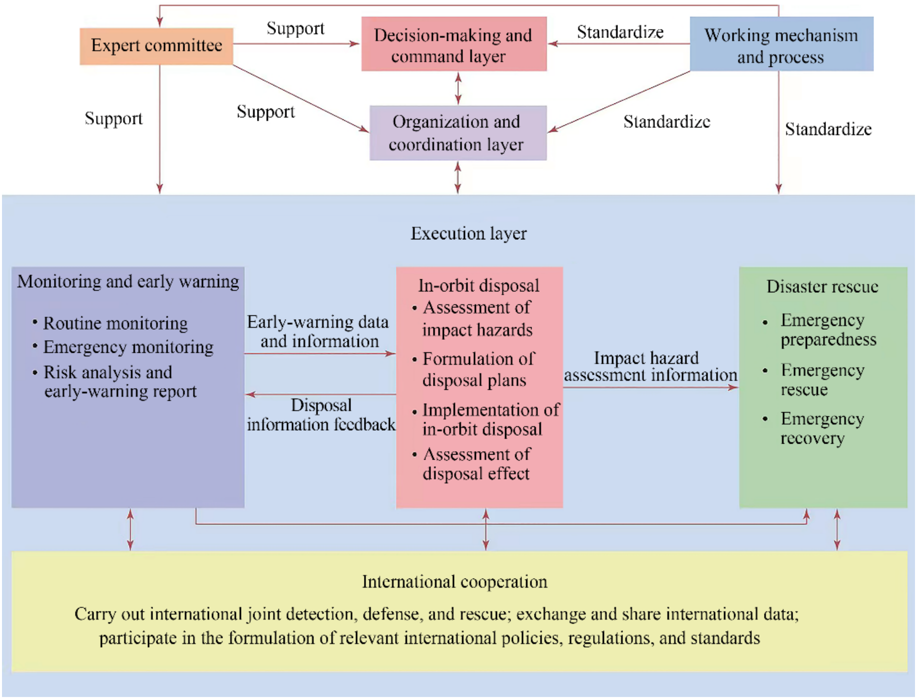

Fig. 3 Composition of the NEA impact risk response system in China.

5.3 Key construction tasks of the response system

5.3.1 Monitoring and early warning

Construction should focus on a space–ground integrated monitoring system and comprehensive service platform. A space–ground integrated collaborative monitoring and early warning system with accurate early warning and routine operation should be constructed according to the basic idea of space–ground coordination, capacity complementation, scenario driving, and service operation.

Based on the basic conditions of existing ground-based equipment, the capacity for daily cataloging of NEAs with a diameter of 140 m should be built to form a ground-based monitoring network with a multi-aperture configuration, multi-function integration, and efficient coordination. A world-leading ground-based monitoring network should be built according to the technical route of "optimizing domestic arrangement, promoting overseas station construction, and comprehensively developing general/precise monitoring." A space-based monitoring network should be constructed with capabilities for "space region-oriented complementation, time-sharing collaborative cataloging, short/imminent detection and warning, and wide-area celestial sphere scanning," working efficiently with the ground-based monitoring network. Comprehensive breakthroughs should be achieved in key technologies, such as the overall establishment of space-based monitoring systems and advanced monitoring loads in accordance with the technical evolution route of "test demonstration, monitoring-system deployment, and capacity improvement." The focus is placed on space-based monitoring equipment (Fig. 4) that can be deployed at the near-Earth orbit, Earth–Moon Lagrangian points, Moon, Sun–Earth Lagrangian points, Earth's orbit around the Sun, and orbit of a Venus-like body to enrich space-based monitoring. This aims to help China catch up with and surpass pioneer countries and attain an advanced international level as soon as possible.

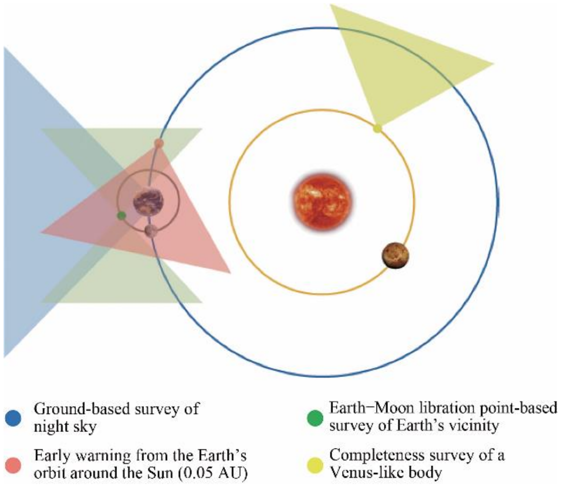

Fig. 4 Layout of space-based monitoring and early-warning system and equipment.

The comprehensive service platform should be equipped with various functions such as task planning, data integration, catalog updating, risk analysis, information release, decision-making and command, resource scheduling, and rescue support. According to the development route of "preliminary platform construction, demonstration application, extended and upgraded application, service operation, strengthened cohesive and outreach operation, and effective decision-making support," advanced software should be developed and necessary hardware should be completely equipped to provide a comprehensive service guarantee for the coordinated operation of the space–ground integrated monitoring network and implementation of early warning services.

5.3.2 In-orbit disposal

Construction should focus on a technology system of in-orbit disposal centered on kinetic impact deflection to carry out demonstrations and verification with Chinese characteristics and international highlights. To accomplish in-orbit tasks, such as the combination of disposal and assessment and multi-objective/multi-means coordination, China should study key technologies, focusing on the instantaneous action of kinetic impact deflection, supplemented by long-term action such as towing and laser-ablation-driven deflection, and consider new concept-based disposal technologies. A disposal technology system covering instantaneous action, medium- and long-term action, and cutting-edge exploration should be developed and improved. Its effectiveness (in terms of applicability, efficiency, maturity, and cost) should be assessed comprehensively, and its adaptability should be clarified. Systems for in-orbit disposal decision-making support and assessment, full-process task design and simulation, and ground test verification should be established to support tabletop exercises and in-orbit verification. According to the strategy of "hitting, deflection, and defense," in-orbit demonstration and verification with high international awareness and influence are carried out step by step to form the capacity for multi-means coordinated in-orbit disposal of NEAs with a diameter of 50 m. Considering the physicochemical characteristics of NEA targets, various hazards of NEA impact on Earth should be studied to establish a theoretical model of hazard effects. Based on the Lunar Exploration Project, the scheme of studying, testing, and constructing an observation–disposal integrated system that takes into account both space-based monitoring, early warning, and in-orbit disposal is a breakthrough for China's planetary defense to catch up with and surpass the advanced international level.

5.3.3 Disaster rescue

Based on the existing national emergency rescue system, the focus should be placed on capacity development for compound-catastrophe emergency rescue according to the disaster characteristics of NEA impact on Earth. Following the development path of "completing the system and mechanism, enhancing comprehensive capacity, improving ability significantly," China should construct a step-by-step system and synchronously improve emergency command organizations at all levels. A monitoring, early warning, and assessment system covering multiple disaster types and chains should be established. Disaster evolution and rapid assessment models under complex scenarios should be optimized to realize regular rescue exercises/drills for NEA impact-induced disasters through simulation platforms. Special disaster rescue forces required by the NEA impact risk response should be strengthened specifically, improving guarantee capacities in major scenarios.

5.3.4 Related cutting-edge basic research

According to the basic principle of "leading discipline development, and guiding and supporting future significant tasks," relevant basic research and concept/principle research should be carried out considering the development trends of planetary defense in the next five to ten years to enhance capacity for basic research and innovation in the field, and cultivate a team of high-level professionals. With a focus on orbital motion laws, physicochemical characteristics, impact effect and disaster-causing mechanisms, and disposal response mechanisms of NEAs, the following frontier basic research should be pursued: origin and evolution of asteroids, orbital dynamic evolution mechanisms of asteroids, material composition and structural/radiation characteristics of NEAs, orbital uncertainty of NEAs under the perturbation of large celestial bodies, coupling of thermal-mechanical and ablation/explosion fragmentation mechanisms of NEAs entering the atmosphere, instantaneous effects of NEA impact on the Earth and the mechanisms of consequent secondary disasters, influence on the long-term evolution of the Earth's environment of NEA impact, dynamic response and energy transfer of NEAs under kinetic impact, action mechanisms and effect of short-range nuclear explosion on NEAs, and deflection mechanisms and orbit displacement of NEAs under non-contact action such as laser ablation.

5.3.5 International cooperation

The characteristics of NEA impact hazards indicate that international cooperation is indispensable for effective defense. With the basic idea of "enhancing integration into the international system, developing regional cooperation, and contributing more Chinese strength," China should strongly participate in international organizations (such as IAWN, SMPAG, and PDC) and actively carry out international bilateral and multilateral cooperation according to its actual conditions. International bilateral cooperation, joint observation, disposal, and rescue should be conducted with full use of China's bilateral space cooperation mechanisms to improve data sharing and promote joint consultation for response and construction of equipment to stimulate vitality in space cooperation. In terms of international multilateral cooperation, China should be deeply involved in formulating and improving relevant regulations of international cooperation, and put forward international research plans, negotiation rules, and cooperation mechanisms of China-led NEA impact risk response under the concept of building a community with a shared future for mankind in outer space.

6 Countermeasures and suggestions

6.1 Strengthening top-level design and long-term planning of impact risk response

China should fully exploit the advantages of a new nationwide system in building its space industry to strengthen the construction of organizational systems and response process mechanisms, and clearly define responsible actors in various links. China should also strengthen its top-level design to speed up the formulation and timely release of medium- and long-term development plans and roadmaps for the NEA impact risk response. Work must focus on building a monitoring and early warning system by 2025, improving the disposal capacity by 2030, and comprehensively enhancing the response capacity of the system by 2035. This aims to equip China with the capacity to detect and prevent impact threats as soon as possible and to form a national NEA response system in accordance to the international status of China.

6.2 Efficiently establishing an impact risk response operation system with internal cohesive and external connection

An expert committee on NEA impact risk response should be established to provide intellectual support for the impact risk response. Relying on superior technical units, China can establish a national research center for asteroid monitoring and early warning. An asteroid information platform should be established, and a high-level, professional, and open national R&D force should be built to regularly carry out daily cataloging, threat early-warning, short-impending prediction, and information sharing. The security of planetary defense data should be enhanced, and China's international discourse should be elevated to ensure NEA risk defense under coordination mechanisms at the national level. Social forces should be mobilized actively and commercial development modes partially adopted.

6.3 Rapidly forming the capacity for impact risk response and innovation

China should establish a joint fund for planetary defense between the National Natural Science Foundation of China and the CNSA to support research on basic scientific issues involved in NEA impact risk response through major special projects to provide a solid scientific foundation for planetary defense engineering. China should establish major national scientific and technological projects on NEA impact risk response by coordinating the space debris project and civil aerospace project, further taking into account the demonstration and implementation of planetary exploration projects conducted by CNSA. This aims to support research on key planetary defense technologies and building a system capacity for NEA impact risk response as soon as possible. China should also urgently establish a deep-space exploration national laboratory to gather advantageous forces in relevant fields, build innovative R&D systems and mechanisms integrating science, technology, and engineering, and support the construction of a national platform of science and technology for collaborative innovation in planetary defense.

6.4 Focusing on building a community with a shared future for mankind in planetary defense

China should remain mindful of the potential risks. Guided by the ideal of building a community with a shared future for mankind, it should participate in international planetary defense affairs with an open, inclusive, cooperative, and leading attitude and jointly carry out NEA impact risk response. It should strongly participate in relevant United Nations organizations and take the initiative in relevant work. Moreover, China should discuss joint defense mechanisms, share joint test data, and co-build joint rescue forces with the international community, actively contributing Chinese wisdom, plans, and strength to the international planetary defense.

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