Near-Earth Object Early Warning and Defense: A Review (Postprint)

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Abstract

Near-Earth objects are numerous, and their impact hazards are substantial; conducting warning and defense against them constitutes a fundamental means to effectively address their impact threats, with specific warning and defense technologies having become an international research focus. China has now joined international organizations specifically responsible for near-Earth object warning and defense, though its specific research remains largely in the initial stages. This paper elaborates on the necessity of developing near-Earth object warning and defense technologies and the basic response procedures, expounds on the progress of international research across various aspects including search and monitoring, international organizations and their technical research, and deep space exploration projects, briefly analyzes the basic strategy of orbit deflection defense and the principles, advantages, and disadvantages of five primary defense methods—nuclear explosion, kinetic impact, gravity tractor, altering solar radiation pressure, and laser ablation, summarizes four key future directions for work in the near-Earth object warning and defense field, and finally offers several suggestions and reflections regarding China' s current research status.

Full Text

Preamble

Near-Earth Object Warning and Defense: A Review

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Abstract: Near-Earth Objects (NEOs) pose a significant impact threat due to their large numbers and high relative velocities. Early warning and defense constitute fundamental means for effectively addressing this threat, with specific warning and defense technologies having become a major focus of international research. China has joined the specialized international organizations responsible for NEO warning and defense, though specific research efforts remain largely in their initial stages. This paper elaborates on the necessity of developing NEO warning and defense technologies and the basic response procedures, reviews international research progress in search and monitoring, international organizations and their technical research, and deep space exploration projects, briefly analyzes the basic strategies for orbital deflection defense and the principles, advantages, and disadvantages of five main defense methods including nuclear explosion, kinetic impact, gravitational traction, solar radiation pressure modification, and laser ablation, and summarizes four key future directions for the NEO warning and defense field. Finally, several recommendations and considerations are proposed based on China' s current research status.

Keywords: Near-Earth Object defense; orbital deflection; kinetic impact; Space Missions Planning Advisory Group (SMPAG)

1.1 Threat

Near-Earth Objects pose an impact threat to Earth for three primary reasons. First, their orbital paths closely approach Earth' s orbit, creating genuine collision possibilities. Second, their relative velocities with respect to Earth reach several tens of kilometers per second, generating enormous impact energies that can cause major disasters upon collision. Third, NEOs are extremely numerous and the vast majority remain undiscovered, resulting in high potential impact risks.

The risk of impact is real. The 1994 Shoemaker-Levy 9 comet impact with Jupiter, along with newly observed craters on the Moon and Mars, demonstrate that small body impacts in the solar system are not isolated incidents. The mass extinction event 65 million years ago was likely caused by a NEO impact, and the Chelyabinsk event on February 15, 2013, confirmed as a small asteroid impact, injured approximately 1,500 people and damaged thousands of buildings. Furthermore, according to information released by the International Asteroid Warning Network (IAWN), more than 100 close approach events within lunar distance have occurred between NEOs and Earth since June 2016.

Impact events cause severe damage. Estimates indicate that a 1-kilometer-diameter asteroid impact could generate 80,000 megatons of impact energy and trigger global catastrophe, potentially destroying human civilization. A 100-meter-scale asteroid could produce 80 megatons of energy, exceeding the power of the strongest hydrogen bombs and causing regional devastation. Even a 30-meter asteroid could generate 2 megatons of energy (note: 1 MT = 10 tons of TNT equivalent), while the 1945 Hiroshima nuclear explosion was only approximately 0.02 MT. Simultaneously, smaller NEOs are more numerous and have higher impact probabilities.

Undiscovered targets present high potential risks. According to NASA reports, less than 20% of the theoretically predicted number of 100-meter-scale NEOs have been discovered, yet they are capable of causing significant damage, thus constituting a high potential impact risk. As shown in [Figure 1: see original paper], the green curve (left axis) represents discovered numbers, the red curve (left axis) shows theoretically predicted numbers, and the blue curve (right axis) indicates the corresponding search completion percentage for NEOs of different sizes.

1.2 Response Methods

To effectively respond to NEO impact threats and minimize or mitigate the resulting damage, several steps are necessary. First, NEOs must be searched for and tracked to obtain orbital and characteristic measurement data. Second, based on processed monitoring data, NEOs must be cataloged and managed. Then, using cataloged orbital and characteristic data, impact risks must be assessed and warnings issued for hazardous events. Finally, when dangerous events occur, capabilities for active defense or passive response must be available. The response flow diagram is shown in [Figure 2: see original paper].

Current NEO monitoring and early warning efforts are primarily jointly managed by the Minor Planet Center (MPC) and the Jet Propulsion Laboratory (JPL). The MPC receives data and conducts preliminary processing and risk identification, while JPL performs precise orbit determination and risk analysis for potentially hazardous targets and releases threat assessments. Throughout this process, observation systems continuously track and monitor targets while uploading data. A successful early warning was achieved in October 2008 for a hazardous NEO (provisionally designated 2008 TC). Discovered on October 6 by the Catalina Sky Survey, calculations predicted it would impact Earth within 24 hours. Researchers successfully captured images of the asteroid entering Earth' s atmosphere in the predicted region in the early hours of October 7. Fortunately, the object was small and disintegrated during atmospheric ablation, producing only minor meteorites without causing damage.

Existing detection capabilities are insufficient, with low cataloging percentages. A 100-meter-scale NEO can cause major damage, yet the discovery and cataloging rate remains low, primarily due to inadequate detection capabilities. Ground-based optical telescopes are the main detection tools, facing several challenges: (1) Most NEOs remain far from Earth for extended periods, and smaller objects constitute a higher proportion, making them extremely faint and difficult to detect; (2) Ground-based telescopes can only observe at night due to sky background limitations, making it impossible to detect objects approaching from the dayside, particularly those inside Earth' s orbit that remain in the dayside hemisphere; (3) The unique motion characteristics of NEOs present additional technical challenges for ground observation, such as angular velocities similar to high-orbit space debris during close approaches, making discrimination difficult.

Newly discovered objects have limited monitoring data, resulting in large warning uncertainties. When NEOs are newly discovered (within days), monitoring data covers only a tiny fraction of their orbital period (on the order of years), and telescopes can only measure direction, not distance. Even though angular measurement precision can be very high, orbit determination accuracy remains limited without distance constraints. Furthermore, because physical characteristic information is more difficult to obtain than orbital information, many cataloged NEOs still lack accurate feature data. Consequently, risk analysis results for many (especially newly discovered) NEOs have significant uncertainties.

Defense technologies remain immature. Several NEO defense strategies have been proposed and studied, including nuclear explosion, kinetic impact, solar radiation pressure modification, laser ablation, and gravitational traction. Among these, only kinetic impact technology is relatively mature; other methods remain largely in theoretical research stages, while nuclear explosion technology faces significant legal constraints. Even kinetic impact technology is constrained by imprecise knowledge of NEO size, structure, and other characteristics, making accurate assessment of defense effectiveness difficult.

2 International Research Status

Due to the large number of NEOs and the heavy, difficult task of search and tracking, global joint observations are needed to improve efficiency and effectiveness (especially for "sneaker" events like Chelyabinsk). Similarly, because impact threats are severe and impact times and locations are difficult to predict accurately, joint response measures from all nations are required. Therefore, international cooperation is essential for humanity to address NEO impact threats. Specialized international organizations now coordinate NEO warning and defense work, including the former Action Team on Near-Earth Objects (AT-14), the International Asteroid Warning Network (IAWN), and the Space Missions Planning Advisory Group (SMPAG). Additionally, some defense-related projects involve multinational joint research and development, such as the US-European Asteroid Impact and Deflection Assessment (AIDA) mission.

2.1 International Organizations

Action Team on Near-Earth Objects (AT-14). Following the 1994 Shoemaker-Levy 9 impact, the United Nations Office for Outer Space Affairs (UNOOSA) organized the first international conference on NEOs at UN Headquarters in New York in 1995. The conference explicitly recognized the potential threat of NEOs to Earth and recommended strengthening existing monitoring capabilities to search for and track NEOs, as well as assessing the probability of medium and large NEO impacts. In 1999, the NEO impact threat received further attention at the Third United Nations Conference on the Exploration and Peaceful Uses of Outer Space. The resulting "Vienna Declaration on Space and Human Development" contained 33 specific recommendations, including one to enhance international cooperation and coordination concerning NEO activities. To implement these recommendations, the Committee on the Peaceful Uses of Outer Space (COPUOS) established AT-14 in 2001 to coordinate international mitigation actions for NEO impact threats. AT-14 was officially dissolved in 2015 after successfully completing its coordination mission.

International Asteroid Warning Network and Space Missions Planning Advisory Group. Following the Chelyabinsk event in February 2013, the UN General Assembly officially established IAWN and SMPAG at its 68th session in December 2013 (China formally joined both organizations in January 2018). IAWN is responsible for NEO discovery, tracking, cataloging, and characterization, and periodically organizes international joint observation campaigns to improve cataloging and warning accuracy for selected NEOs while enhancing international coordination capabilities. For example, the October 2017 international campaign on asteroid 2012 TC successfully obtained extensive observational data and calculated a precise orbit, ruling out any Earth impact possibility within 100 years. SMPAG is responsible for NEO defense response, with specific duties including: (1) monitoring relevant activities of space agencies and organizations; (2) identifying technical and scientific activities related to planetary defense space missions requiring attention; (3) developing/updating international strategies for future missions and supporting planetary defense mission research and development; (4) analyzing and reporting on the effectiveness of international cooperation and funding planetary mitigation activities.

2.2.1 SMPAG Mission Plans

To effectively conduct and promote NEO defense technology research, SMPAG has organized its work into 11 task plans, assigning lead organizations for each to advance relevant research and requiring progress reports at SMPAG meetings (approximately twice yearly). These 11 task plans cover nearly all aspects of the defense process, including standards or thresholds for initiating response actions (Task 1), mitigation mission types and technologies (Tasks 2-4), action plans and coordination methods when threats exist (Tasks 5-6), roadmapping for future work based on current capabilities (Task 7), preliminary studies of mitigation mission consequences (Task 8), standards for NEO orbital deflection (Task 9), feasibility studies of nuclear options (Task 10), and preliminary studies of payload characteristics for active defense (Task 11). Task 1 has produced an initial report with NASA-proposed response thresholds: (1) IAWN should issue alerts for all NEOs with impact probability >1% and size >10 meters (approximately absolute magnitude 28 or brighter); (2) Defense planning and ground-based preparations should begin for NEOs with >10% impact probability within 20 years and size >20 meters (approximately magnitude 27 or brighter); (3) SMPAG should initiate defense missions for NEOs with >1% impact probability within 50 years and size >50 meters (approximately magnitude 26 or brighter).

Task plan of SMPAG

2.2.2 Defense Strategy Research

NEO defense difficulty is closely related to factors including size, mass, orbital status, and warning time. For short-warning scenarios like the sudden Chelyabinsk event, only near-space defense using ground-based assets is currently feasible. For longer warning times (years to decades), NEO defense implementation involves two phases: interplanetary trajectory transfer (launching spacecraft from Earth to the NEO) and actual defense technology implementation. Defense technologies fall into two categories: orbital deflection (changing the hazardous object' s orbit to miss Earth) and fragmentation (breaking the object into pieces to reduce or eliminate impact hazard). Interplanetary transfer technology is relatively mature, with the US, Europe, Japan, and Russia having successfully conducted deep space missions, and China' s Chang' e-2 having performed a flyby of Toutatis asteroid. Celestial autonomous navigation will be a key technology during mission execution. Defense technologies include nuclear explosion, kinetic impact, gravitational traction, solar radiation pressure modification, and laser ablation, with only kinetic impact having relatively high maturity.

Orbital Deflection Strategy. The minimum orbit intersection distance between a NEO and Earth is typically represented by MOID. Orbital deflection aims to change the NEO's orbit by taking measures before the MOID time. Specific measures include instantaneous impulse methods (kinetic impact, nuclear explosion) and continuous thrust methods (gravitational traction, solar pressure modification, laser ablation). Let $\delta\sigma = [\delta a, \delta e, \delta i, \delta\Omega, \delta\omega, \delta M]^T$ represent the orbital element changes and $\delta\mathbf{r} = [\delta r, \delta h, \delta s]^T$ represent the relative position vector changes at MOID time under deflection strategies, with the relationship given by:

$$\begin{bmatrix}\delta r\\ \delta h\\ \delta s\end{bmatrix} = \begin{bmatrix}\frac{r}{a}\delta a - a\cos f\delta e + \frac{ae\sin f}{\eta}\delta M\\ r\delta i\\ \frac{r\sin(\omega+f)}{\sin i}\delta\Omega + \frac{a(1-e^2)}{r}\delta\omega + \frac{ae\sin f}{\eta}\delta M\end{bmatrix}$$

where f is the true anomaly at MOID time, $\eta = \sqrt{1-e^2}$, and subscripts r, h, s represent radial, orbit-normal, and orbit-transverse directions, respectively, forming a right-handed coordinate system. The deflection strategy objective is to maximize the evaluation function:

$$J = \delta r^2 + \delta h^2 + \delta s^2$$

The orbital element changes $\delta\sigma$ depend on different deflection technologies. For impulse methods, the NEO experiences instantaneous velocity change from external forces, altering its orbit immediately. For continuous thrust methods, the NEO experiences a perturbing force over an extended period (duration depends on implementation), causing gradual orbital changes. When developing deflection strategies, initial designs are based on a two-body model of the NEO and Sun, then optimized considering complete perturbation forces to obtain precise strategies, potentially employing newer optimization algorithms such as genetic algorithms, particle swarm optimization, or machine learning algorithms.

1) Nuclear Explosion. This approach either fragments the hazardous object directly or uses the explosion' s thrust to alter its orbit. Nuclear explosions can be non-contact or contact, with the choice depending primarily on the object' s size and composition. Non-contact explosions detonate the device above the surface without contact; the released energy vaporizes surface material, which jets outward, and by momentum conservation, pushes the object in the opposite direction. Contact explosions detonate on or within the surface, potentially fragmenting the object. While contact explosions utilize energy more efficiently, they face higher challenges: demanding detonation conditions requiring prior impact or drilling, and difficult-to-control fragmentation effects where resulting debris could still threaten Earth.

2) Kinetic Impact. This method uses one or more spacecraft impacting the hazardous object at high relative velocity to change its trajectory. Based on momentum conservation, the velocity change depends on spacecraft mass, impact velocity, and momentum transfer coefficient. Spacecraft mass depends on launch mass and consumption during transfer, impact velocity relates to trajectory design, and the momentum coefficient (dependent on target composition, shape, and structure) determines efficiency. These characteristics are typically unknown precisely, especially for short-warning objects. Kinetic impact offers relatively high feasibility with advantages including: (1) high technology readiness, preliminarily validated by NASA' s Deep Impact mission; (2) flexibility for implementation in deep space or near-Earth space, applicable to various warning times, including emergency scenarios.

3) Gravitational Tractor. This method stations a spacecraft near the target, using gravitational attraction to slowly alter its orbit. The advantage is that only target mass needs to be known, without requiring knowledge of composition, structure, or rotation. The main challenge is long-term reliable station-keeping. Gravitational force depends on spacecraft and target masses; increasing spacecraft mass rapidly raises launch costs. An "enhanced gravitational tractor" concept involves collecting material from the target to increase the spacecraft' s gravitational field, but this requires new technologies for successful material collection without spacecraft damage and imposes higher station-keeping requirements.

4) Solar Radiation Pressure Modification. Solar radiation pressure is a major perturbation affecting NEO orbits. As the radiation source is the central body (Sun), the pressure acts as a central repulsive force proportional to the object' s albedo, illuminated area, and solar radiation intensity. Modifying this force can change orbital trajectories through: (1) applying specific coatings to alter albedo; (2) placing solar sails on the surface to increase illuminated area; (3) deploying space-based reflectors to enhance solar radiation. Since solar pressure is typically very small, long times are required for orbital changes, making this suitable only for long-warning scenarios.

5) Laser Ablation. This technique uses a high-power laser system to irradiate the NEO surface, with the recoil force from ablated plasma jets altering the object' s orbit. Laser-equipped spacecraft could be deployed on the Moon or in Earth orbit, or small laser systems could be sent to the NEO vicinity to provide additional force during gravitational traction. The effectiveness depends on laser power, but the technology readiness for high-power systems required for NEO defense remains very low.

2.2.3 Deep Space Exploration Projects

Deep space exploration is crucial for improving NEO defense capabilities by: (1) enhancing measurement and understanding of NEO physical characteristics to improve risk estimation and defense effectiveness assessment; (2) testing spacecraft trajectory transfer, asteroid rendezvous, and landing technologies, and validating actual defense method effectiveness.

NASA' s 2005 Deep Impact mission successfully validated kinetic impact technology, with an impactor striking comet Tempel 1 at 10.2 km/s, creating a 28-meter crater (left image in [Figure 3: see original paper] shows the comet 67 seconds post-impact). The 2016 OSIRIS-REx mission aims to land on asteroid Bennu and return 60 grams to several kilograms of samples, providing PHA characteristic data and validating near-asteroid operations. The spacecraft arrived at Bennu in December 2018 and began surface exploration.

JAXA' s Hayabusa-2 mission (with German and French participation) plans to land on near-Earth asteroid Ryugu, collect samples, and return, providing data directly relevant to deflection studies. Hayabusa-2 successfully rendezvoused with Ryugu in June 2018 and deployed a rover on September 21 to begin surface exploration.

The US-European AIDA mission is under development to study and validate kinetic impact effects, testing whether spacecraft impact can successfully deflect asteroid orbits to eliminate Earth impact threats. The mission comprises two components: NASA' s DART spacecraft to impact Didymos' s moonlet Didymoon, and ESA' s AIM spacecraft to monitor the impact. DART is planned for 2021 launch with a 2022 impact. AIM was canceled in 2016 due to funding, but ESA proposed the Hera spacecraft in 2018, planned for 2023 launch to rendezvous with Didymos in 2026 for orbital investigation.

[Figure 3: see original paper] Image of Tempel 1 comet 67 seconds after impact (left) and diagram of DART mission (right)

2.2.4 Legal Issues

As planetary defense science and technology advance, legal issues in NEO defense have become increasingly important, requiring legal development or refinement considering current scientific, technological, socioeconomic conditions, and existing treaties. Key legal issues include: (1) Applicability of nuclear weapons —whether nuclear options should be included is a prominent issue, facing significant international political pressure from treaties like the Partial Test Ban Treaty and Comprehensive Nuclear-Test-Ban Treaty; (2) Legal issues following active defense implementation—how to allocate and define legal responsibilities or obligations in cases of partial or complete mission failure. Active defense involves complex projects across multiple nations, disciplines, and technologies, with potential failure causes including inadequate planning, execution errors, insufficient deflection, or suboptimal impact points. Additionally, incomplete success could cause direct impact damage and secondary disasters (earthquakes, tsunamis). How should legal responsibilities be divided among participating parties?

SMPAG agreed at its 6th meeting in February 2016 to establish a dedicated legal working group composed of space law experts and scientists/engineers to discuss and recommend legal approaches for NEO deflection missions for test purposes and emergency planetary defense. Objectives include: (1) developing and refining legal issues requiring clarification in SMPAG work; (2) considering legal issues within existing agreement contexts; (3) developing action plans to address outstanding issues.

3 Future Work Priorities

Comprehensive analysis indicates four main future priorities in NEO warning and defense:

(1) Enhance Search and Cataloging Capabilities. Searching for and cataloging NEOs forms the foundation for warning and defense. Since 100-meter-scale NEOs can cause serious damage but less than 20% have been discovered, monitoring capabilities must be improved. NASA proposed the goal in 2007 to "discover and catalog 90% of NEOs 140 meters and larger by 2020" (GEB), leading to the Large Synoptic Survey Telescope (LSST) project. The latest schedule indicates LSST will be completed in 2021 for testing and operational by 2023, with simulations showing 12 years of observation will achieve the GEB goal. Additionally, the space-based infrared telescope project NEOCam plans to operate at Sun-Earth L1 point, aiming to discover two-thirds of PHAs within four years.

(2) Enhance Physical Characteristic Detection. Understanding NEO physical characteristics is crucial for reliably estimating ground impact effects and designing effective deflection missions. During short-warning emergencies, rapidly obtaining threat object parameters (shape, rotation rate, albedo, composition) is critical. Physical characteristic data collection relies on major telescopes (optical and infrared) and radar facilities. To maximize efficiency, observatory cooperation and coordinated observation strategies should be promoted. Deep space missions providing close-range observations significantly enhance understanding of NEO physical diversity relevant to mitigation, as demonstrated by ongoing Hayabusa-2 and OSIRIS-REx missions.

(3) Promote Defense Technology Research. Research has focused on kinetic impactors and gravitational tractors as currently feasible or near-feasible methods. However, new deflection methods should be encouraged, including alternatives based on ion beam propulsion and laser ablation that may become practical through future development. Research should emphasize the smaller end of the size distribution (50-200 meters), where most new discoveries with relatively high Earth impact probabilities occur. Regarding post-deflection orbital evolution: both test missions and emergency responses produce uncertain outcomes, requiring modeling analysis of uncertainties and result ranges from complete failure to greater-than-expected deflection to understand subsequent effects. Emergency deflection requires understanding how tests affect long-term impact risk, ensuring test missions do not significantly increase future impact risk regardless of outcome.

(4) Conduct Deflection Test Missions. While theoretical and technical research forms the foundation, practical test missions are equally important to validate NEO deflection technologies on real targets. Actual test missions can verify and refine space technologies such as actual deflection effectiveness and autonomous navigation/control systems required for approaching or landing on weakly gravitating, irregularly shaped asteroids—challenges difficult to fully address in ground laboratories. The AIDA project mentioned above represents such a test mission. Additionally, the European NEOShield-2 project proposed the relatively low-cost NEOT IST kinetic impact test mission, planning to impact asteroid Itokawa at a location far from its rotation axis to change its spin rate and study relationships between kinetic impact efficiency and NEO structural characteristics. These results help reduce scientific and technical preparation required for emergency deflection missions.

4 Summary and Recommendations

Humanity has made significant progress in NEO monitoring, warning, and defense over the past decade, but much work remains before Earth can be fully protected from catastrophic asteroid impacts. NEOs of 100 meters and below are numerous with low discovery rates, requiring enhanced monitoring for comprehensive cataloging. Physical characteristic information is critical for accurate risk analysis and defense effectiveness assessment, necessitating improved data collection and analysis. Most NEO defense technical methods have low maturity, requiring continued theoretical and technical research, including modeling of overall post-defense risks. Theoretical defense strategies still require validation and refinement through actual test missions.

Although China joined IAWN and SMPAG in January 2018, its NEO threat response capabilities currently concentrate in search and monitoring, using the NEO telescope in Xuyi and optical telescopes at Lijiang and Xinglong stations, though capabilities remain insufficient compared to international levels. Defense technology capabilities are relatively weak and essentially in initial stages.

This paper recommends strengthening China' s capabilities and research in NEO search, monitoring, warning, and defense through:

(1) Rapidly improving autonomous faint target monitoring capabilities to enhance independent NEO cataloging, enabling earlier discovery of smaller or more distant objects and avoiding surprise attacks. This includes building new large-aperture optical telescopes and utilizing existing large radio telescopes (such as FAST) for joint radar observations to improve detection of faint NEOs.

(2) Promoting basic science and technology research in NEO defense to enhance technical and personnel reserves. NEO impact threats represent a long-term challenge for human civilization, and current defense methods suffer from low technology readiness or high outcome uncertainty. New technical methods require years of development from concept to practical application, necessitating enhanced reserves and long-term research commitment.

(3) Actively participating in international organization cooperation to learn advanced foreign technologies and management experience, improving China' s independent NEO threat response capabilities and enhancing discourse power in international exchanges. Participate in or join legal working groups to protect national interests in international rule-making.

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Note: Figure translations are in progress. See original paper for figures.