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Advancements in Understanding and Mitigating Near-Earth Asteroid Threats: Technology, Classification, and Global Cooperation

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Abstract. The study of near-Earth asteroids (NEAs) is vital for understanding the solar system and enhancing planetary defense. By researching these asteroids, scientists gain valuable insights into planetary evolution and impact history, aiding in the prediction and prevention of potential future threats. This article introduces how advancements in technology have enabled more precise classification and analysis of NEAs, such as categorizing them into groups like Amor, Apollo, and Aten. It points out that accurate orbital analysis enhances the ability to assess collision probabilities and develop preventive measures against catastrophic impacts. Additionally, the article examines global efforts in addressing NEA threats, which involve collaboration among international organizations, government agencies, and private enterprises. Organizations like the United Nations play crucial roles in coordinating observation missions and sharing information to improve awareness and response to asteroid risks. Tools like the Torino and Palermo Scales help translate complex data into information that policymakers and the public can understand. The article also highlights those future challenges, such as the potential impact of an asteroid like Apophis, underscore the necessity for continuous observation and technological development, including methods to alter an asteroid's path. Furthermore, the study emphasizes the importance of strengthening international cooperation through sample return missions and advanced monitoring networks to enhance global defense capabilities. In conclusion, the article underscores the critical role of global collaboration and scientific innovation in addressing NEA challenges, ensuring the long-term safety and prosperity of the planet and civilization.

Keywords: Near-Earth Asteroid, Torino Scale Classification, Apophis.

1. Introduction

In astronomy, asteroids with a perihelion distance of less than 1.3 Astronomical Units (1AU=149.6km) are classified as Near-Earth Asteroids (NEA). Near-Earth asteroids that intersect or graze Earth's orbit pose potential risks. When these asteroids collide with Earth, they can release energy equivalent to tens of megatons (for those with diameters of 50 meters) to millions of megatons (for diameters of several kilometers), threatening human life and property safety. As of August 4, 2024, a total of 35,296 near-Earth asteroids have been discovered. Among them, 10,938 are located 140 meters or further from Earth, while 864 are situated one kilometer or further away [1]. Therefore, assessing the risk of impacts by near-Earth asteroids is crucial for the future of humanity.

The assessment of the risk posed by asteroid impacts intersects physics and astrophysics, focusing on comprehending and quantifying the physical processes of these cosmic events and their potential impacts on Earth's environment. Throughout history, in 1908, The Tunguska event involves an asteroid or comet fragment estimated to be only tens of meters in diameter, exploded in the skies above Siberia, releasing energy equivalent to 10 to 15 megatons of TNT, flattening over 2,000 square kilometers of forest [2]. These impacts entail massive energy conversions and trigger a cascade of complex geophysical responses, ranging from earthquakes and tsunamis to long-term climatic changes.

Humans actively monitor and defend against potential threats from near-Earth asteroids through a multi-tiered and multi-faceted approach. This includes implementing several observation projects such as Pan-STARRS, LINEAR, and NEOWISE, in conjunction with the Jet Propulsion Laboratory (JPL) Small-Body Database and automated warning systems to calculate the orbits of NEAs. Additionally, they conduct DART impact tests, follow-up studies like HERA, and advance missions such as OSIRIS-Rex [3]. Through international cooperation frameworks like the International Asteroid Warning Network (IAWN) and the United Nations, along with public education programs, they effectively address these potential threats. In contemporary research, the challenge lies in accurately calculating the orbital parameters of asteroids, simulating the extreme physical conditions at the moment of impact, and evaluating their direct effects on Earth's surface and crust. Furthermore, studies on near-miss asteroids have revealed the diverse range of impact scenarios, including Hypervelocity Impacts, Cratering Impacts, Airbursts, and Fragmented Impacts.

These findings underscore the need for precise calculations of entry angles and velocities, as well as accurate predictions of secondary hazards such as seismic waves and tsunamis following an impact.

2. Classification of Near-Earth Asteroids

Near-Earth asteroids (NEAs) refer to asteroids whose orbits intersect or come close to Earth's orbit. Their orbits typically have a higher eccentricity compared to asteroids in the main asteroid belt and are thus closer to Earth. These celestial bodies play a significant role in scientific research and are closely monitored due to their potential threat of impacting Earth. NEAs are primarily classified based on their orbital characteristics and physical or chemical properties, mainly into three types: Amor, Apollo, and Aten. These classifications are crucial for understanding their origins, evolution, and potential risk of impacting Earth.

2.1. Aten Asteroids

Aten asteroids have a semi-major axis of less than 1 astronomical unit (AU) and overlap with Earth's orbit near their aphelion. This category includes all asteroids with a semi-major axis less than 1.0 AU and an aphelion distance greater than or equal to 0.983 AU, which is the current perihelion distance of Earth. From 1976 to 1979, three Aten asteroids were discovered in succession, all of which are deep quadruple intersection objects, meaning their orbits almost continuously overlap with Earth's orbit [4].

2.2. Apollo Asteroids

Apollo asteroids have a semi-major axis (a) greater than 1.0 AU and a perihelion distance (q) less than or equal to 1.017 AU, which is Earth's current aphelion distance. The first Apollo asteroid was discovered by K. Reinmuth in 1932. The orbits of Apollo asteroids overlap with Earth's orbit at their perihelion. Of the 22 Apollo asteroids with relatively well-determined orbits, 21 cross Earth's orbit [4].

2.3. Amor Asteroids

Amor asteroids are defined by their perihelion distance, specifically ranging from 1.017 AU to 1.3 AU. Although these asteroids come relatively close to Earth, they currently do not overlap with Earth's orbit. This group is named after the asteroid "Amor," which was discovered by E. Delporte in 1932. It is noteworthy that due to long-term perturbation effects, some Apollo asteroids can evolve into Amor asteroids and vice versa, making the distinction between Amor and Apollo types somewhat arbitrary [4].

3. The Origin and Evolution of Near-Earth Asteroids

Understanding the origin and evolution of near-Earth asteroids (NEAs) is crucial for grasping the history of the formation and evolution of the solar system. Through modern observational techniques and in-depth research, the research can better describe the motion patterns of these asteroids and provide scientific evidence for Earth's defense strategies. Continued attention and research on these asteroids not only help in avoiding potential threats but also advance the fields of astronomy and planetary science.

The origin of NEAs involves disturbances in the asteroid belt, planetary gravitational perturbations, cometary degradation, and the early formation of the solar system. Most NEAs are thought to originate from the asteroid belt between Mars and Jupiter. In this region, asteroids are influenced by gravitational disturbances (especially from Jupiter's gravity) and collisions among asteroids, causing their orbits to change and enter near-Earth orbits [5]. Additionally, the gravitational slingshot effect and resonances involving Jupiter and Mars can alter the orbits of asteroids. For example, the Voyager 1 and 2 probes utilized the gravitational slingshot effect of Jupiter and Saturn to accelerate and venture out of the solar system [6]. On the other hand, some NEAs are remnants of degenerated comets. As comets approach the sun, their volatile materials vaporize due to high temperatures, leaving behind a solid rocky core, which eventually loses its comet-like characteristics and becomes an asteroid [5].

Once an asteroid enters a near-Earth orbit, its evolution is influenced by several factors, including gravitational effects, non-gravitational effects, and collisions. The orbits of asteroids are affected by various gravitational and non-gravitational effects and may undergo collisions and fragmentation.

Earth's and other planets' gravity can significantly alter an asteroid's orbital path, especially during close encounters. Additionally, some asteroids may enter stable orbital resonance zones, such as 1:1 (Trojan asteroids) or 3:2 resonance, leading to long-term stability with subtle changes [7]. Non-gravitational effects like the Yarkovsky effect, caused by an asteroid's rotation and asymmetric thermal radiation, and solar radiation pressure, particularly influence smaller celestial bodies [8]. High-speed collisions can result in the fragmentation of asteroids, altering their orbits and producing secondary small bodies that may enter different orbits and continue evolving [5]. The initial orbital changes of collision products are dramatic but gradually stabilize, potentially forming new asteroid families.

4. Current Efforts to Address Near-Earth Asteroid Impact Threats

To mitigate the risk of near-Earth asteroid impacts, organizations and nations across the globe have been actively involved in discovering, exploring, predicting, and assessing potentially hazardous asteroids. The United Nations and related entities, in collaboration with national governments and non-governmental organizations, have set up dedicated agencies to address these potential threats.

In 1995, the UN held its first international conference on "Preventing Near-Earth Object Impacts." In 2014, under UN coordination, the International Asteroid Warning Network and the Space Mission Planning Advisory Group were established. In 2016, the UN General Assembly designated June 30 as International Asteroid Day to raise public awareness of these risks. Since 2009, the International Academy of Astronautics and the UN have regularly hosted the International Planetary Defense Conference. At a national level, the United States established a Planetary Defense Office in 2016 and released a preparedness strategy and action plan in 2018 to improve the detection, tracking, and characterization of asteroids and to develop technologies for dealing with them. In 2021, the U.S. released emergency protocols for asteroid threats. Starting in 2021, China, in cooperation with relevant departments, began formulating a mid-to-long-term development plan to respond to asteroid impact threats. These efforts represent a global initiative to enhance capabilities in dealing with the potential impacts of asteroids [9].

5. The Torino Scale: Classification and Practical Application

In response to the risk of near-Earth asteroid (NEA) impacts, scientists have developed various models and systems to predict and assess potential impact threats. These models combine astronomical observations and simulations to provide data for decision-making. One such system is the Torino Scale, proposed by American astronomer Richard P. Binzel in 1999 during the

International Astronomical Union conference held in Torino, Italy. The Torino Scale is a tool used to assess the impact risk of NEAs and comets on Earth, taking into account both the probability of impact and the potential consequences.

5.1. Torino Scale Classification

The Torino Scale ranges from 0 to 10, with increasing numbers indicating higher levels of risk. Here's a breakdown of the scale: At Level 0, objects pose no threat of collision with Earth and require no attention. Level 1 indicates an extremely low collision probability, less than those posed by random objects of similar size, necessitating only routine monitoring. Levels 2 to 4 indicate a small but present risk of impact. Levels 5 to 7 are considered threatening. Finally, Levels 8 to 10 involve certain or nearly certain collisions, leading to serious disasters ranging from localized devastation at Level 8, regional devastation at Level 9, to global catastrophe at Level 10, which could endanger human civilization [10].

5.2. Practical Application and Case Study

The use of the Torino Scale translates complex scientific predictions into simple numerical values, making it easier for decision-makers and the public to understand and respond to the potential impact risks posed by NEAs. It also provides governments and international bodies with scientific guidance for developing emergency plans and resource allocation [10].

5.3. Case Study: 2004 MN4 (Apophis)

A notable example is the asteroid Apophis (99942 Apophis), initially designated 2004 MN4, discovered by Roy A. Tucker, David J. Tholen, and Fabrizio Bernardi on June 19, 2004. Early observations in December 2004 indicated a 2.7% probability of a collision with Earth on April 13, 2029, causing significant concern. Subsequent observations refined the predictions, ruling out a collision in 2029.

However, concerns remained about Apophis passing through a "gravitational keyhole" in 2029, which could set it on a collision course for April 13, 2036. This narrow corridor, less than about 965 kilometers (600 miles) wide, sustained Apophis at Level 1 on the Torino Scale until 2006, when further observations greatly reduced the keyhole passage probability. By 2008, the keyhole's width was narrowed to less than 1 kilometer. During this period, Apophis reached a record-high Level 4 on the Torino Scale. Observations in January 2013 by the Goldstone Radar effectively ruled out the 2036 impact, and by May 6, 2013, the probability of an impact in 2036 had been eliminated. As of October 8, 2014, the JPL Sentry risk table calculated a 1/149,000 probability of an impact on April 12, 2068, based on observations up to February 26, 2014.

Apophis' discovery and early predictions highlighted the importance of continuous monitoring and precise trajectory calculations for NEAs [11]. Initially, alarming predictions gave way to more accurate risk assessments with improved observational data, enhancing public understanding of NEA risks. This underscores the critical role of international scientific cooperation in mitigating potential asteroid impacts.

5.4. Limitations and Complementary Tools

While the Torino Scale is a valuable tool, it has limitations. Predicting impact energy accurately is challenging under current observational conditions, and the scale's integer-based classification may oversimplify risk assessments. To address these limitations, scientists have developed other assessment tools, such as the Palermo Technical Impact Hazard Scale, which offers more granular risk evaluations. In conclusion, the Torino Scale facilitates public education and communication, provides a scientific basis for governmental and institutional decision-making, and helps prioritize monitoring resources. The Apophis case exemplifies its application in real-world scenarios, highlighting the importance of ongoing observation and international collaboration to manage and mitigate potential NEA impact risks [12].

6. Conclusion

The study of near-Earth asteroids is crucial for scientific exploration and planetary defense, helping shape people's response to space environment challenges. By researching these asteroids, scientists gain insights into solar system formation, planetary evolution, and impact history, which can aid in predicting and preventing future threats. Technological advancements have refined NEA classification into categories like Amor, Apollo, and Aten, allowing for accurate orbital analysis and collision probability assessments. This ongoing scientific exploration pushes the boundaries of planetary science and supports measures to prevent catastrophic impact events. Globally, efforts to address NEAs are collaborative, involving international organizations, government agencies, scientific alliances, and private enterprises. Entities like the United Nations, NASA, and ESA enhance asteroid risk awareness and response through coordinated missions, information sharing, and joint exercises. Models such as the Torino Scale and the Palermo Scale help the public and policymakers understand complex data, translating it into actionable information.

Future events involving NEAs, such as Apophis, underscore the importance of continuous observation and data updates. This improves risk assessments and supports the development of technologies to deflect or destroy potentially threatening asteroids. For example, advancing planetary defense methods like kinetic impactors or gravity tractors can alter an asteroid's orbit, reducing collision risks with Earth. To ensure future safety, global cooperation in planetary defense and space exploration must be strengthened. Projects like sample return missions, defense simulations, and advanced monitoring networks enhance the capability to handle asteroid threats. This involves technological advancements and developments in policy, law, and societal awareness, fostering a comprehensive planetary defense system.

In summary, global collaboration and innovation in science and technology empower us to tackle future challenges from NEAs. These efforts not only protect the planet but also ensure human civilization's continued prosperity, creating a safer and more sustainable future for generations to come.

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