IAC-14-B3.1.8

AN OVERVIEW OF NASA'S ASTEROID EXPLORATION EFFORTS: PAST AND PRESENT

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The National Aeronautics and Space Administration (NASA) is actively pursuing an ambitious goal of robotically capturing a near-Earth asteroid (NEA) and then redirecting it to a stable lunar orbit. From this stable orbit, humans will then have the opportunity to visit and explore the asteroid. This plan, called the Asteroid Redirect Mission (ARM), is part of NASA's larger Asteroid Initiative, which also encompasses the agency's Asteroid Grand Challenge (AGC) – a global effort that seeks to find all asteroid threats to human populations and know what to do about them. NASA's Asteroid Initiative is a bold strategy that will steadily advance human space exploration capabilities into deep-space, while at the same time expand and intensify efforts to defend the Earth from potentially catastrophic impacts.

NASA's Asteroid Redirect Mission is the culmination of many years of study and builds on a significant foundation of research and conceptual design work. While most of the effort has been focused on the work performed under the Obama Administration, human exploration of an asteroid has piqued the interest of scientists, engineers, and space enthusiasts for decades.

Beginning with an investigation of the historical interest in human exploration of an asteroid, this paper will synthesize the more recent efforts of NASA to achieve this goal. A primary objective of this examination will be to illustrate the evolution of NASA's conceptual strategy to enable humans to explore an asteroid and focus will be placed on notable efforts leading to the announcement of the agency's Asteroid Redirect Mission in 2013. In addition to an overview of the evolving policies and plans, attention will be given to how the technical concepts have progressed with a brief synopsis of the agency's current efforts.

I. INTRODUCTION

Second only to self-destruction through war or environmental decimation, a large asteroid strike – or perhaps more accurately a collision – poses the only known threat to humanity and other life on Earth, as some postulate caused the extinction of the dinosaurs 65 million years ago.[1]

Our awareness and fascination with objects in the sky dates back to the earliest periods of human history, with the first recorded knowledge of a NEO occurring early in the 19th century. Science fiction is also rich with concepts of human-robotic exploration, exploitation, and mitigation of these mineral- and volatile-rich remnants of our early solar system.

II. HISTORICAL CONTEXT

Exploration

Starting in the mid 1960s, aspirations of asteroid exploration and prospecting began to surface in Presidential Commission reports[2], hailing the space objects as valuable resources, rich with raw propellant that could be used to extend human presence farther and farther into the solar system. In addition to the potential to increase in-space propulsion capabilities, asteroids could potentially unlock untold clues to the origins of our solar system and the beginnings of life in the universe. In 1986, the *The Report of the National Commission on Space*[3] included asteroid exploration in its step-by-step approach to inner solar system exploration, and since then has been a familiar and recurring component in nearly every Presidential Commission report regarding human spaceflight.

Science

NASA's efforts to explore an asteroid have followed the familiar "bots before boots" model, starting with Pioneer 10 in 1972, which became the first spacecraft to travel through the asteroid belt, relaying important interplanetary data back to Earth. In February 2000 NEAR Shoemaker became the first robotic mission to orbit and touch down on an asteroid, as shown in Figure 1.[4] JAXA also accomplished a significant technological feat by returning samples of Itokawa in its Hayabusa-1 mission, and plans are under way for JAXA's Hayabusa-2 and NASA's OSIRIS-Rex – the next two robotic asteroid sample return missions on the horizon.

Fig. 1: One of the final images from NEAR-Shoemaker before its successful descent to the surface of Eros in 2001 (Credit: NASA/JPL).

Planetary Defense

Global efforts to track potentially hazardous asteroids have gained traction in the past decade, beginning with the NASA Authorization Act of 2005. Within a section of this legislation, known as the George E. Brown, Jr. NEO Survey Program, Congress directed NASA to detect, track, catalogue, and characterize the physical characteristics of NEOs equal to or larger than 140 meters in diameter orbiting within 1.3 Astronomical Units (AU), to be completed by 2020.[5]

The United Nations has also played an active role and in 2007, it established a working group on NEOs under its Science and Technical Committee. The working group has enabled a more coordinated effort to detect, track, and characterize NEOs, and in 2013, they created the International Asteroid Warning Network (IAWN). The IAWN Steering Committee conducted its first meeting this year, with the objective of providing timely warnings to national authorities in the event an asteroid impact threat is detected. The IAWN represents collaboration among dozens of nations and academic institutions, fostering an unprecedented aggregation of NEO observation data from across the globe.[6]

Policy Context

In 2009, newly elected President Barack Obama commissioned the Review of U.S. Human Spaceflight Plans, dubbed the Augustine Review, led by Norman Augustine. The "Augustine Report"[7] asserted that NASA's Constellation Program was on an "unsustainable trajectory" due to insurmountable cost, schedule, and systems development challenges. The report endorsed a "flexible path" approach to human space exploration, which would include a series of new destinations, including Lagrange points, NEOs, an orbit around Mars, and special interest in visiting a Martian moon where astronauts might teleoperate robotic vehicles on the surface.

Shortly after the Augustine Report was published in 2010, the new administration cancelled NASA's Constellation program, which was five years into development of a deep-space crew capsule and a powerful new rocket to ferry crews and substantial infrastructure to the lunar surface. The Constellation program built on what was learned during Apollo, expanding the lunar surface expedition scope from weeks to months and even years. Here, astronauts would learn to live and work for long periods away from Earth, preparing for Mars missions in the 2030s. In parallel with the Constellation Program, NASA managed a Program to facilitate development of private U.S. industry cargo transportation systems to low-Earth orbit (LEO) to enable the US to become competitive in the global launch industry, stimulate new markets, and support human presence in LEO following the agency's planned shuttle retirement and renewed vision for lunar operations.

Instead of a return to the lunar surface, Obama declared in a speech at the Kennedy Space Center in April 2010,[8] NASA would send astronauts to an asteroid by 2025 and to Mars by the 2030s.[9] Congress and the Obama Administration reiterated their support for this new direction in the 2010 NASA Authorization Act, which asserts that NASA will continue to extend human presence beyond LEO, through exploration of multiple solar system destinations, including NEAs.[10]

III. NASA IMPLEMENTATION EFFORTS

Within the new U.S. space policy context, NASA's space architecture teams began to evaluate the systems and resources required to send humans to a near-Earth asteroid (NEA). NASA conducted this body of research in collaboration with external groups representing scientific, academic, and engineering communities, and in August 2010, NASA hosted a comprehensive Exploration of NEO Objectives Workshop (ExploreNOW) to solicit input from these communities on all facets of near-Earth asteroids.[11] Also in 2010, NASA established the NEA User Team (NUT) to serve as a comprehensive NEA planning, analysis, and concept of operations "office."[12] To support the hunt for an asteroid accessible in its native orbit, an analysis team from the Goddard Space Flight Center, supported by the Jet Propulsion Laboratory, developed a searchable and regularly updated NEA database (called Near-Earth Object Human Space Flight Accessible Targets Study, or NHATS) to enable searching and filtering of potential targets using community-developed filter criteria.[13]

The long journey to an asteroid in its native orbit, lasting many months to a year in the distant deep-space environment posed significant health risks to the astronaut crew and required new additional exploration systems beyond those developments authorized by Congress. Because these additional risks to crew and mission placed the proposed development beyond NASA's foreseeable budget, NASA sought to better understand and reduce risks associated with candidate NEA missions.

Using underwater environments, NASA conducted field tests simulating asteroid missions, mimicking the isolation, constrained habitat and crew quarters, harsh environment, and reduced gravity challenges that astronauts would experience exploring at an asteroid. NASA's Extreme Environment Mission Operations analog field tests, or NEEMO, helped astronauts, engineers, and scientists to refine operational techniques and develop innovative methods to address challenges related to communication delays, anchoring, sampling, and workload distribution among astronauts.[14]

Fig. 2: An "aquanaut" practices simulated asteroid operations during NASA's NEEMO 16 Field Test Mission in 2012.

The Asteroid Redirect Mission

Although a human mission to an asteroid seemed infeasible by 2025 within the budget environment, there was another concept that put the burden of distance and environmental factors onto a robotic system. Leveraging research conducted for the Keck Institute of Space Studies' 2012 *Asteroid Return Mission Study Report*[15], on which several NASA personnel collaborated, NASA announced plans for an Asteroid Redirect Mission (ARM) in April 2013. Through this mission, NASA plans to robotically redirect an asteroid from its native orbit to a more accessible location in the lunar vicinity where astronauts can visit it in a matter of days. This mission will serve as an early test of new deep-space systems, capabilities, and operational techniques needed to support future human missions to Mars – all while still in relatively close proximity to Earth.

There are currently two robotic capture concepts for ARM: one using an inflatable system to envelop an entire, free-flying asteroid, shown conceptually in Figure 3; and the other using robotic arms to retrieve a boulder mass from a larger asteroid, shown conceptually in Figure 4. Both concepts provide opportunities to demonstrate planetary defense techniques, and NASA has already identified three validated candidate asteroids for each concept. This December, agency mission planners will down-select to one robotic capture concept before entering mission concept review in February 2015.

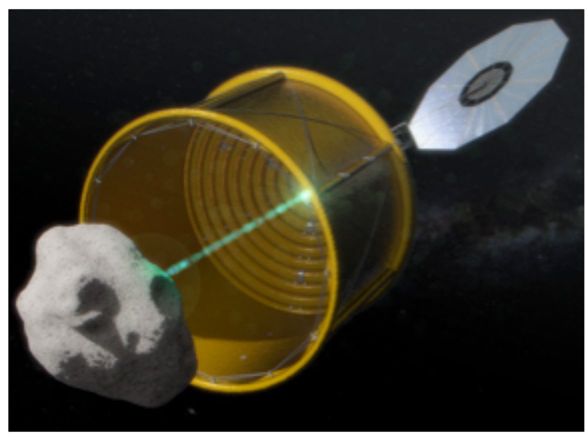

Fig. 3: Robotic mission Option A – small asteroid capture option (Credit: NASA/JPL).

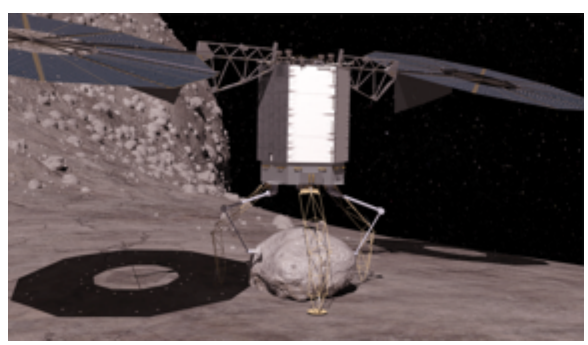

Fig. 4: Robotic mission Option B – robotic boulder

capture option (Credit: NASA/AMA, Inc.).

The ARM is a key component in what NASA calls the "proving ground," or the next phase of space exploration beyond LEO that will prove the capabilities necessary to send humans to Mars and return them safely to Earth. The proving ground encompasses the gamut of deep-space human operations – everything from transportation vehicles, to space suits, autonomous operations, and vehicle rendezvous and docking. Astronauts who visit the asteroid will learn how to interact with and sample the asteroid, building on concepts developed for robotic asteroid missions. Taking what has been learned on the International Space Station (ISS), and advancing the technologies for exploration missions that are less dependent on Earth, NASA will demonstrate deep-space crew operations that are crucial to validate prior to sending humans to greater distances, such as Mars.

Science

Although ARM is primarily an exploration mission, mission planners intend to bring the greatest scientific value to the operations as possible. Through continued engagement with the scientific community, NASA is developing ARM crew operations to ensure that visiting crews are able to make real-time decisions to adapt to unforeseen sampling challenges. Astronauts visiting the captured asteroid will bring an unprecedented mass of asteroidal material back to Earth for analysis, and will have the benefit of in-situ, hands-on analysis to make assessments regarding the proper tools and techniques to extract samples.

Planetary Defense

All have heard the recent mantra: If the dinosaurs had a space program, they might still be here today. While it is certainly reassuring to believe that, and box office films may instill a sense of confidence among the general public that there is a plan to mitigate impact threats, the fact is that years of advanced warning and a diversity of expertise is required to be able to deflect a hazardous asteroid.

NASA's Asteroid Initiative is a broad strategy that leverages the relevant portions of the agency's science, technology, and human exploration capabilities and aligns them toward achieving common goals. The robotic component of the ARM provides an opportunity to demonstrate long-lead deflection techniques, contributing to the planetary defense component of the Asteroid Initiative. Both options could potentially demonstrate ion beam deflection and gravity tractor techniques, with Option B having the additional capability of potentially demonstrating a gravity tractor enhanced by the boulder mass.

Observation Assets

NASA's Near Earth Objects Observation (NEOO) Program coordinates NASA-sponsored efforts to detect, track and characterize potentially hazardous asteroids and comets that could approach the Earth. With over 90% of NEOs larger than one kilometer already discovered, the NEOO Program is now focusing on finding 90% of the NEO population larger than 140 meters. In addition to managing the detection and cataloging of NEOs, the Program is responsible for facilitating communications between the astronomical community, U.S. government agencies, and the public, should any potentially hazardous objects be discovered.

In the normal course of searching for these potentially hazardous objects, the NEOO Program is able to detect, track, and characterize suitable candidates for ARM robotic concept B, as well as smaller NEAs that could be candidates for the robotic option A. Through the Asteroid Initiative, the NEOO Program budget has doubled from $20 million per year to $40 million.

In an effort to accelerate the work NASA is already doing for planetary defense, the agency issued the Asteroid Grand Challenge (AGC) in June 2013 to complement the ARM under the umbrella of the Asteroid Initiative. The AGC is the agency activity seeking the best ideas to find all asteroid threats to human populations and identify mitigation techniques. The AGC reaches outside the traditional government-funded NEO disciplines, engaging citizen innovators to become "asteroid hunters." Through the Grand Challenge, ordinary citizens are equipped with world-wide observation data and encouraged to help find new potentially hazardous asteroids and further characterize the existing body of known asteroids.[16]

Current Candidate Asteroids for ARM

Before an asteroid can make the valid candidate list, NASA's ARM target identification criteria must be met. Scientists must determine the rotation, shape, precise orbit, spectral class, and most importantly, size of the asteroid itself. With the asteroid millions of kilometers away from Earth, defining these factors requires a series of observations and analysis.

The three valid candidates already identified for Option A (small asteroid concept) are 2009 BD, 2011 MD and 2013 EC20. The size of 2009 BD is estimated to be roughly 4 meters in size, while 2011 MD is estimated to be approximately 6 meters. These sizes are inferred by analysis data provided by the Spitzer observatory. 2013 EC20 is only about 2 meters in size, as determined by radar imaging.

There are currently three validated asteroid candidates being considered for the boulder concept:

Itokawa, Bennu and 2008 EV5. Itokawa, shown in Figure 5, was well characterized by close and direct observation on the Japanese Hayabusa mission and is known to contain boulders at an ideal size of roughly 3 meters (10 feet). Both 2008 EV5 and Bennu have been imaged via radar, collecting data from which it can be inferred they have boulders of the appropriate size. In addition, NASA's OSIRIS-REx mission, planned for launch in 2016, will closely study Bennu, and conduct detailed mapping of the surface of the asteroid in addition to taking samples and returning them to Earth for further study.

Fig. 5: Itokawa, valid candidate for the ARM robotic Option B, , as imaged up close by JAXA's Hayabusa. (Credit: JAXA).

IV. PARTNERSHIP OPPORTUNITIES

As NASA moves forward toward a downselect decision on ARM robotic mission option concepts A and B, the agency is actively incorporating considerations from partner communities. Since announcing the Asteroid Initiative in April 2013, NASA has extended several efforts to solicit input and encourage participation from commercial space, international space, academic, science, and citizen innovator communities. The opportunities for engagement continue to evolve, and NASA has leveraged community interest to help refine ARM mission concepts.

International Partnerships

As one of 14 member agencies in the International Space Exploration Coordination Group (ISECG), NASA is a contributing author to the Global Exploration Roadmap (GER), a narrative that outlines common exploration objectives, identifying a complement of individual contributions from each agency that will foster a coordinated global effort to maximize human and robotic exploration into the solar system.[17]

With the publication of the second iteration of the GER in 2013, NASA and its partners demonstrated a continuing commitment to a common strategic exploration plan toward the horizon goal of Mars.

The GER outlines many opportunities and potential locations where humans may operate in the lunar vicinity in the mid-2020s. Whether on its surface, in its surrounding orbit, or at a Lagrange point nestled in the gravitational pulls of the Earth and moon systems, opportunities abound in this human foray to our "closest NEO". Like NASA, its GER co-authors envision lunar vicinity operations that ultimately will have the potential to inform future missions to Mars.

ARM Industry Engagement

To broaden participation from partners and the public, NASA issued a Request for Information (RFI) in June 2013 to seek new ideas on how to implement the ARM and the AGC. An enthusiastic response followed the release of the RFI: the agency received 402 responses, 40 percent of which were from individuals and members of the general public. All of the submissions were evaluated and rated, then 96 were chosen to explore in greater depth at the *Asteroid Initiative Ideas Synthesis Workshop*, held in two parts at the Lunar and Planetary Institute in Houston, Texas, in September and November 2013. NASA is already acting on the ideas submitted through the RFI process.[18]

On March 21, 2014, NASA issued an ARM Broad Agency Announcement (BAA) soliciting proposals for concept studies in areas including asteroid capture systems, rendezvous sensors, adapting commercial spacecraft for the ARM and feasibility studies of potential future partnership opportunities for secondary payloads and the crewed mission.[19,20] Following the BAA release, on March 26, 2014, NASA hosted the *Asteroid Initiative Opportunities Forum* at NASA Headquarters to provide status updates from ongoing ARM concept and extensibility refinement and communicate the opportunities in the BAA.[21] On June 18, NASA announced the selection of 18 proposals, of the 108 received, for six-month studies, totaling $4.9 million in awards. The study reports will be completed in January 2015, and it is expected that they will inform upcoming ARM milestones, including the Mission Concept Review.

Commercial and Economic Interests

Just as humans have forged the frontiers of land and sea for glory and for profit, economic expansion into space is imminent. Asteroids stand at the forefront of economic prosperity in space, representing the potential to extract resources. Several commercial entities are actively planning to blaze the trail in asteroid mining, developing plans for long-term commercial prospecting in space. Asteroids could be mined for precious metals including gold, platinum, and rhodium, as well as more common metals on Earth such as nickel and cobalt.

Beyond prospecting for resource return to Earth, C-type (carbonaceous chondrite) asteroids are abundant with water, a crucial compound in rocket fuel, and in sustaining life during long-duration human exploration missions. By harvesting these elements in space, outside Earth's gravity well, the applications for affordable exploration missions are compounded.

V. SUMMARY

This beginning foray into human asteroid exploration is nearly 60 years in the making. By leveraging investments across the agency and interest from industry and international partners, NASA's strategy builds on decades of research and mission-based knowledge to embark on the first human mission to an asteroid – the Asteroid Redirect Mission. The ARM capitalizes on NASA and its partners' collective spaceflight experience, and represents an endeavor that embodies advancements in exploration, science and planetary defense. The progression of policy development and mission planning to meet multiple goals has provided a rich context for NASA's asteroid exploration mission implementation efforts, leading to the development of the ARM.

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