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# Scientific exploration of near-Earth objects via the Orion Crew Exploration Vehicle

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**Abstract**–A study in late 2006 was sponsored by the Advanced Projects Office within NASA's Constellation Program to examine the feasibility of sending the Orion Crew Exploration Vehicle (CEV) to a near-Earth object (NEO). The ideal mission profile would involve two or three astronauts on a 90 to 180 day flight, which would include a 7 to 14 day stay for proximity operations at the target NEO. This mission would be the first human expedition to an interplanetary body beyond the Earth-Moon system and would prove useful for testing technologies required for human missions to Mars and other solar system destinations. Piloted missions to NEOs using the CEV would undoubtedly provide a great deal of technical and engineering data on spacecraft operations for future human space exploration while conducting in-depth scientific investigations of these primitive objects. The main scientific advantage of sending piloted missions to NEOs would be the flexibility of the crew to perform tasks and to adapt to situations in real time. A crewed vehicle would be able to test several different sample collection techniques and target specific areas of interest via extra-vehicular activities (EVAs) more efficiently than robotic spacecraft. Such capabilities greatly enhance the scientific return from these missions to NEOs, destinations vital to understanding the evolution and thermal histories of primitive bodies during the formation of the early solar system. Data collected from these missions would help constrain the suite of materials possibly delivered to the early Earth, and would identify potential source regions from which NEOs originate. In addition, the resulting scientific investigations would refine designs for future extraterrestrial resource extraction and utilization, and assist in the development of hazard mitigation techniques for planetary defense.

## INTRODUCTION

The concept of sending astronauts on missions to near-Earth objects (NEOs) is not new. Such ideas have been under consideration since the mid-1960s by engineers exploring the possibility of sending humans to other destinations beyond the Earth-Moon system. One of the first concept designs involved a mission to the asteroid 433 Eros using a modified Apollo capsule and a Saturn V rocket (Smith 1966). This proposed flyby mission would have involved a crew of six astronauts, traveling on a 527-day round trip voyage to 433 Eros during its 1975 opposition, when the asteroid passed within 0.15 AU of the Earth. The opportunity to visit a NEO with a human crew and collect scientific data was recognized during this early stage of space development as an important aspect for furthering planetary science, developing space exploration technologies, and utilizing extraterrestrial resources (Smith 1966).

Since 1966, the concept of traveling to NEOs has been examined by several other studies, one of which analyzed the potential of NEO exploration missions as part of NASA's Space Exploration Initiative (Davis et al. 1990). Four other papers have also investigated the prospects for human exploration missions to NEOs and recommended their inclusion into future space exploration strategies (Nash et al. 1989; Jones et al. 1994, 2002; Mazanek et al. 2005). A more recent study was sponsored by NASA's Constellation Program in late 2006. The study team, consisting of representatives from across NASA, examined the feasibility of sending a Crew Exploration Vehicle (CEV), also known as the Orion spacecraft, to a NEO using the Ares family of launch vehicles currently under development by the Constellation Program. The ideal mission profile would involve a crew of two or three astronauts on a 90 to 180 day flight, which would include a 7 to 14 day stay for proximity operations at the target NEO.

One of the significant advantages of this type of mission is that it strengthens and validates the foundational infrastructure for the United States Space Exploration Policy (USSEP) and the Exploration Systems Architecture Study (ESAS) (Stanley et al. 2005). The intent of the current USSEP architecture and the design of the Constellation systems is to be sufficiently flexible to accommodate exploration missions to multiple destinations beyond low Earth orbit (LEO) (Hanley, personal communication). Sending a human expedition to a NEO, within the context of the USSEP and ESAS, would demonstrate this broad utility and flexibility for human exploration. In addition, missions to NEOs would help develop exploration architectures and evaluate technologies required for future human expeditions to Mars and other deep space destinations that are being considered under the USSEP.

However, one of the more compelling aspects of sending humans to NEOs via NASA's Constellation systems is the potential for rich scientific return. These missions would provide detailed information on the physical characteristics of NEOs. Essential physical and geochemical properties of NEOs can best be determined from dedicated spacecraft missions. Although ground-based observations can provide general information about NEO physical properties (rotation rates, taxonomic class, size estimates, general composition, etc.), dedicated spacecraft missions to NEOs providing extended periods of proximity operations are needed to obtain detailed characterizations of surface morphology, internal structure, mineral composition, topography, collisional history, density, particle size, etc. The presence of a crew would greatly enhance the quality of the scientific data returned from these missions, which are vital to understanding the evolution and thermal histories of primitive bodies during the formation of the early solar system. Data collected from these missions would also constrain the suite of materials believed to have been delivered to the early Earth, and identify potential source regions (e.g., main belt asteroid and comet reservoirs) from which the NEO population originates (e.g., Bottke et al. 2002; Weissman et al. 2002).

## NEAR-EARTH OBJECTS

Near-Earth objects include asteroids and comets whose orbits approach or intersect the Earth's orbit around the Sun and have perihelion distances of 1.3 AU or less and aphelion distances of 0.983 AU or more (Rabinowitz et al. 1994). These objects can range in size from a few meters in diameter to more than 30 km across as in the case of asteroid 433 Eros (Stuart and Binzel 2004). In general, NEOs also appear to have a range of compositions and structures based on evidence obtained via ground-based observations, spacecraft missions, and laboratory studies of meteorites (Gaffey et al. 1993; Brearley and Jones 1998; Mittlefehldt et al. 1998; Veverka et al. 2000; Britt and Consolmagno 2003; Fujiwara et al. 2006). Some NEOs appear to have compositions similar to rock-like materials, some are rich in metal, and some may be rich in clays and organics (Binzel et al. 2002; Gaffey et al. 2002). Their internal structures also seem to vary widely from gravitationally bound rubble piles to monolithic rocky or metallic objects (Hudson et al. 2000; Ostro et al. 2006; Fujiwara et al. 2006; Busch et al. 2007). The primary source for these objects is the main belt asteroid region, but a small percentage (~5–10%) of NEOs appears to originate from cometary reservoirs such as the Kuiper belt and the Oort cloud (Bottke et al. 2002; Weissman et al. 2002; Abell et al. 2005; Fernández et al. 2005).

Due to their close proximity to Earth, many NEOs are more easily accessible than the Moon in terms of the required propulsive change in velocity ($\Delta v$) (Binzel et al. 2004). Some of these objects are in orbits similar to Earth's, and given their small size, do not have an appreciable gravity well compared to that of the Moon and Mars. Hence, only a relatively small $\Delta v$ is required to brake into the vicinity of, and to depart from, a typical NEO. As a comparison, the last mission sent to the Moon, Apollo 17, required a total $\Delta v$ of ~9.1 km s$^{-1}$, which included injection from low-Earth orbit, descent, lunar landing, ascent, and return to the Earth (Orloff 2001; Adamo, personal communication). Several of the NEOs examined in this study have total mission $\Delta v$ requirements on the order of only ~5.7 to ~7.0 km s$^{-1}$.

Given that the orbits of some NEOs actually intersect and cross Earth's orbit, they have the potential to impact the planet. The cratering record from both the Earth and the Moon indicates that NEOs have impacted the Earth-Moon system for billions of years (Shoemaker 1983). As such, they pose a distinct hazard to Earth's flora and fauna. It is now commonly recognized that the impact of a 10 km object into the Yucatán Peninsula ~65 million years ago was the cause of the massive K/T extinction event (Alvarez et al. 1980). In recognition of this potential impact threat, and in response to Congressional direction, NASA started the Spaceguard project with the goal of detecting and cataloging 90% of all NEOs with diameters of 1 km and larger by the end of 2008 (Morrison 1992). More recently, it has been recognized that even relatively small-sized objects can cause regional devastation (e.g., Boslough and Crawford 1997). Therefore, in 2005 Congress implemented the NASA Authorization Act, which directs NASA to detect, track, catalogue, and characterize 90% of all NEOs down to 140 m in size by 2020.

Current estimates suggest that over 100,000 NEOs equal to or greater than 140 m in diameter exist within our solar system; of this number, ~20,000 are thought to be potentially hazardous (Stokes et al. 2003). Since the end of the Constellation-sponsored feasibility study in February 5, 2007, more than 1500 new NEOs have been discovered by the existing search telescopes. As of September 29, 2009, only 6,482 NEOs have been catalogued with about 1,072 of these classified as potentially hazardous objects (Fig. 1). Two new telescope facilities, the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) and the Large Synoptic Survey Telescope (LSST), will be used in the near future to help locate the rest of this estimated NEO population (Ivezić et al. 2007; Jedicke et al. 2007). A Pan-STARRS prototype telescope is already being tested on Haleakala, Hawai'i, and a second one is expected to become operational in 2010. The LSST is still under design and development, but is expected to be fully operational sometime after 2015 atop Cerro Pachón, Chile. When both of these new facilities come on line, the detection rate of NEOs and potentially hazardous objects will increase by more than a factor of 50 (2007 NASA Report to Congress, http://www.hq.nasa.gov/office/pao/FOIA/NEO_Analysis_Doc.pdf). Therefore, toward the end of the next decade, there may be many more candidate NEO targets for piloted CEV missions.

## ROBOTIC MISSIONS TO NEOs

There have only been two spacecraft missions that have explored NEOs to any extent: NASA's NEAR Shoemaker spacecraft at asteroid 433 Eros in 2000 (Veverka et al. 2000) and the Japan Aerospace Exploration Agency's (JAXA) Hayabusa probe at asteroid 25143 Itokawa in 2005 (Fujiwara et al. 2006) (Fig. 2). Both of these robotic missions are considered to be extremely successful and have generated much scientific interest in NEOs. However, even though the scientific community has a better understanding of NEO physical properties and compositions based on the data from these missions, many questions remain unanswered. For example, in spite of having several months' worth of remote sensing data from both spacecraft, as well as data from one landing by NEAR Shoemaker (Veverka et al. 2001) and two touchdowns by Hayabusa (Yano et al. 2006), investigators have thus far been unable to identify the exact composition and internal structure of these asteroids. Therefore, even though both missions are considered to have achieved almost all of their scientific goals, they were limited by the capabilities of their spacecraft. For example, NEAR Shoemaker was not built for sample return, and Hayabusa's collection mechanism was designed to obtain only two small samples from Itokawa (Yano et al. 2006). It is not yet clear whether Hayabusa managed to obtain a sample of this asteroid.

The types of terrains discovered on both Eros and Itokawa present many intriguing surprises and new paradigms for asteroid scientists to consider. Eros' "ponds" and Psyche crater (Veverka et al. 2001), as well as Itokawa's smooth regions (e.g., Muses-Sea) and its rubble pile nature (Fujiwara et al. 2006), demonstrated that previously conceived notions of NEO physical properties were not as simple as some investigators had imagined. It is now apparent these NEOs have much more complex processes, geophysical conditions, and surface environments than had been previously thought. The data provided by the NEAR Shoemaker and Hayabusa missions revealed terrains and environments that required more detailed investigation in order to be completely understood, but such activities were beyond the designs of each spacecraft. Like many other scientific investigations, more questions were generated than answers.

Although scientific exploration of NEOs can be accomplished by robotic spacecraft, more detailed explorations of these bodies and their complex environments would be best enabled by a human presence. For example, both the Hayabusa spacecraft and its ground controllers encountered challenging situations during close proximity operations at Itokawa. A human crew, on the other hand, would be able to perform scientific tasks and react more quickly in a micro-gravity environment than any robotic spacecraft could, as demonstrated by the rapid yet delicate maneuvering performed consistently by Gemini, Apollo, Skylab, Space Shuttle, and International Space Station astronauts. The recent Hubble Space Telescope servicing mission (Atlantis STS-125) is also a prime example of how well a human crew is suited to performing complex tasks under such conditions. In addition, a human crew would be able to test several different sample collection techniques, and to target specific areas of interest via extra-vehicular activities (EVAs) much more capably than a robotic spacecraft. Such capabilities would greatly enhance the scientific return from future missions to NEOs.

Near-Earth object environments would provide new challenges for human EVA and proximity operations of spacecraft such as the CEV. For example, astronauts would need to match rotation rates with NEOs, maintain precise navigation and control during proximity operations, perform tasks and interface with natural materials under microgravity environments, react to complex dynamical interactions, and

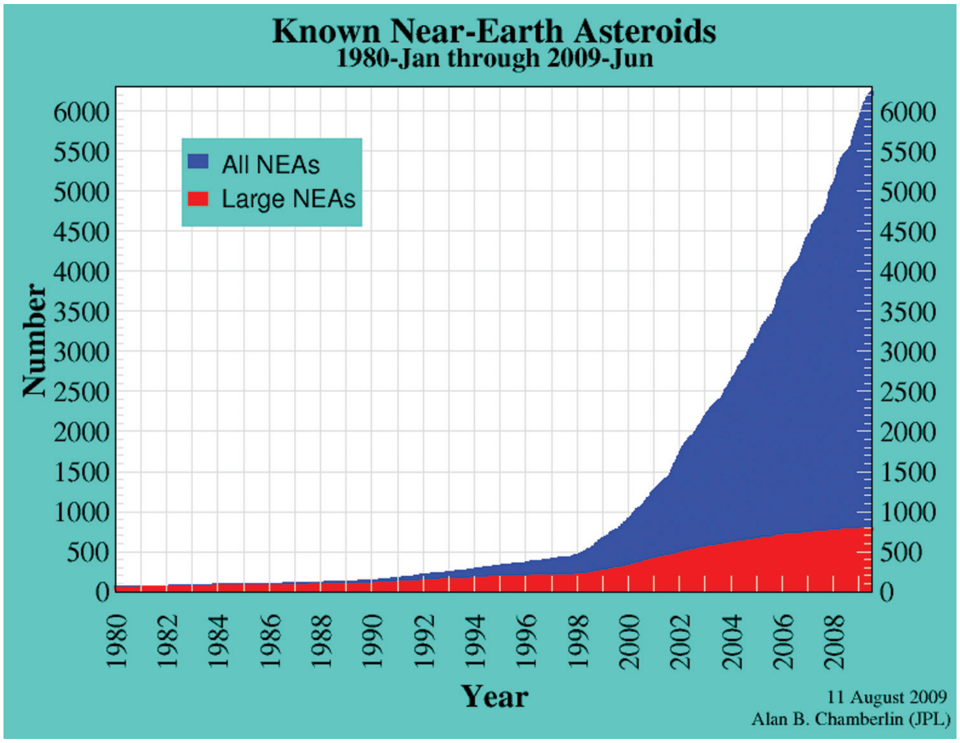


Fig. 1. A plot showing the relative increase in the number of known NEAs from January 1980 through June 2009 (Chamberlin 2009). Note that since the end of the Constellation NEO feasibility study in 2007, more than 1,500 new NEOs have been discovered. The current number of NEOs is now over 6,400 objects with the majority of these being sub-kilometer bodies. The entire NEO population 140 m and greater in size is thought to be over 100,000 objects (Stokes et al. 2003).

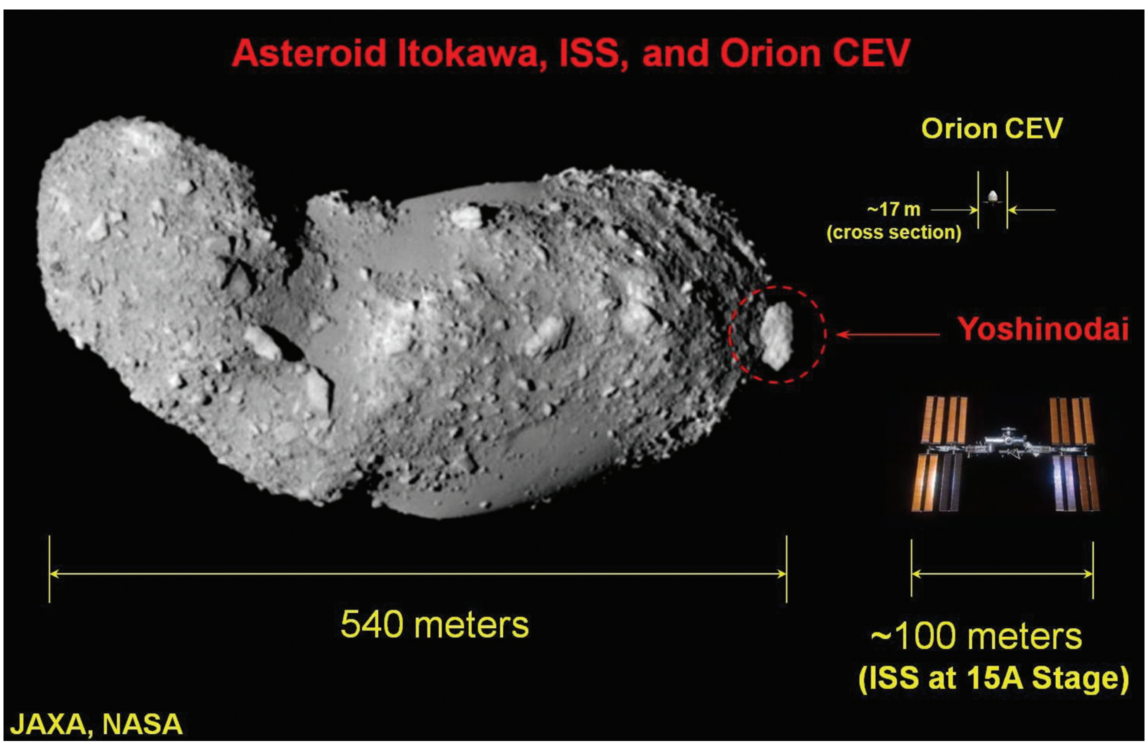


Fig. 2. A comparison of asteroid 25143 Itokawa, the International Space Station, and the Orion spacecraft, with its solar panels deployed, to scale (courtesy of JAXA and NASA). Note that the boulder Yoshinodai is approximately 50 m in length, which is roughly the same size as the estimated diameter of the Meteor Crater and Tunguska impactors.

work in varying lighting conditions. Undoubtedly these particular aspects will require more detailed study and additional examination before decisions are made to pursue exploration of NEOs in the context of NASA's human space flight program. However, past EVA experience at the International Space Station and the Hubble Space Telescope has shown the adaptability and ingenuity of astronauts to deal with such complex issues.

Ideally, a combination of robotic and crewed exploration of candidate NEOs would be planned since prior robotic reconnaissance would significantly reduce the operational risk to the crewed mission. These prior missions would be useful in identifying any potential hazards to the astronauts and to the CEV (and any of its deployable assets/instruments). NEOs may have their own small satellite(s) or have complex surface morphologies, which may not be detectable from prior ground-based reconnaissance. Such in-depth examinations by small robotic spacecraft would help identify the general characteristics of a potential NEO selected for study. A robotic precursor mission to a NEO would be akin to what the Ranger and Surveyor probes were for the Apollo program. Knowledge of the NEO's gravitational field, shape, surface topography, and general composition, etc. would aid in planning for later CEV proximity operations. This information would refine the scientific issues to be addressed by the subsequent human mission and define the instrument suites to be carried by the CEV and its astronauts. Missions to NEOs conducted in this manner would also provide an important synergy between the Science Mission Directorate (SMD), the Space Operations Mission Directorate (SOMD), and the Exploration Systems Mission Directorate (ESMD), which will be crucial for development of future NASA deep space exploration architectures.

## AN ORION CEV MISSION CONCEPT FOR NEO EXPLORATION

The NASA Constellation Program study focused on the feasibility of mounting piloted missions to NEOs utilizing the hardware developed for human return to the Moon as described within the existing planned launch vehicle infrastructure. This initial study was constrained to limited modifications to the Orion CEV (e.g., reduction of the crew to two or three astronauts, inclusion of a science instrument module (SIM) bay on the service module section of the Orion spacecraft, etc.). Four distinct launch options were assessed. These were respectively referred to as the lower bookend option, the mid-volume Ares IV single launch option, the mid-volume Ares V single launch option, and the upper bookend option. The lower bookend option consists of a dual-launch of an Evolved Expendable Launch Vehicle (EELV), such as the Atlas 5 or Delta 4 Heavy, carrying a Centaur upper stage, and an Ares I rocket carrying a CEV. The mid-volume Ares IV single launch is a modified Ares V with an Ares I upper stage carrying a CEV. Similarly, the mid-volume Ares V single launch is an Ares V with a CEV on top. The upper bookend option is a dual-launch scenario most like the proposed Constellation lunar architecture, with a spacecraft similar to the Altair lunar lander atop an Ares V vehicle, and an Ares I rocket carrying a CEV (Fig. 3).

The total $\Delta v$ capability of each of these configurations ranges from just over 4.5 km s$^{-1}$ for the lower bookend to 7.25 km s$^{-1}$ for the mid-volume Ares V single launch. The other two configurations have $\Delta v$ capabilities of 6.0 km s$^{-1}$ and 6.3 km s$^{-1}$, with the mid-volume Ares IV launch having the slightly higher value. Even though the proposed lunar mission configuration (involving Ares I and Ares V launches) has more capability (modified Altair lander, larger crew size, etc.) than the mid-volume scenarios, it has less $\Delta v$ due to the extra payload mass being carried out to the NEO. These four total $\Delta v$ values were compared to the energy requirements for missions to NEOs in the existing JPL Horizons database (Giorgini et al. 1996). The NEOs were filtered for spacecraft accessibility based on their heliocentric orbital parameters such as semi-major axis ($a$), eccentricity ($e$), and ecliptic inclination ($i$). More than 1,200 NEOs were examined as potential mission targets, with those objects in Earth-like orbits (e.g., low eccentricity, semi-major axis ~1 AU, and low inclination) considered as the best candidates. Out of the then-current JPL catalogue, nine candidate NEOs were found that presented good opportunities for piloted CEV missions within the 2020 to 2035 time frame. Three of the NEO targets were reachable with mission durations of 150 days and all nine were reachable with mission lengths of 180 days (Fig. 4) (Table 1). Several NEOs were attainable under 90 and 120 day mission scenarios, but not before 2035. However, with the expected increase of the known NEO population by more than a factor of 50 from the contributions of the Pan-STARRS and the LSST systems (NASA Report to Congress 2007), it is expected that the number of viable mission targets will also increase significantly.[1] This may also result in more frequent launch opportunities for human NEO missions within the desired 2020 to 2035 time frame. Hence these next-generation NEO search systems provide not only a more detailed understanding of the potential impact hazard, but also crucial situational awareness for identification of future human mission targets.

In general, the total mission $\Delta v$ can be reduced by a longer duration mission (i.e., 210 days), shorter stay times at the NEO (i.e., 3 to 5 days), and a possible lunar gravity assist if the NEO orbit is in an optimum location for the CEV trajectory. The typical NEO mission has two equal launch windows on either side of the NEO close approach to Earth. Such a mission could depart prior to the close approach and then return at/near the close approach of the NEO to Earth, or could depart at/near the close approach

[1]Note that since the end of this feasibility study in early 2007, an additional 31 NEOs have been identified as potential human mission targets as of December 2009.

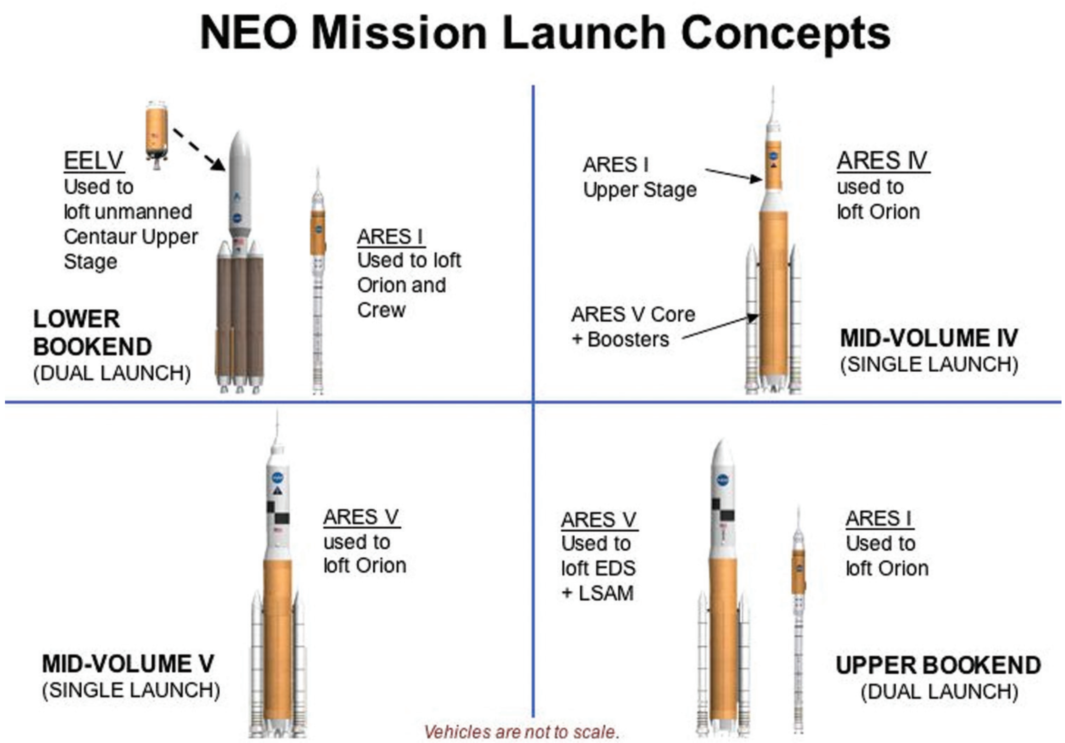


Fig. 3. The four types of NEO mission launch concepts considered for the Constellation NEO feasibility study.

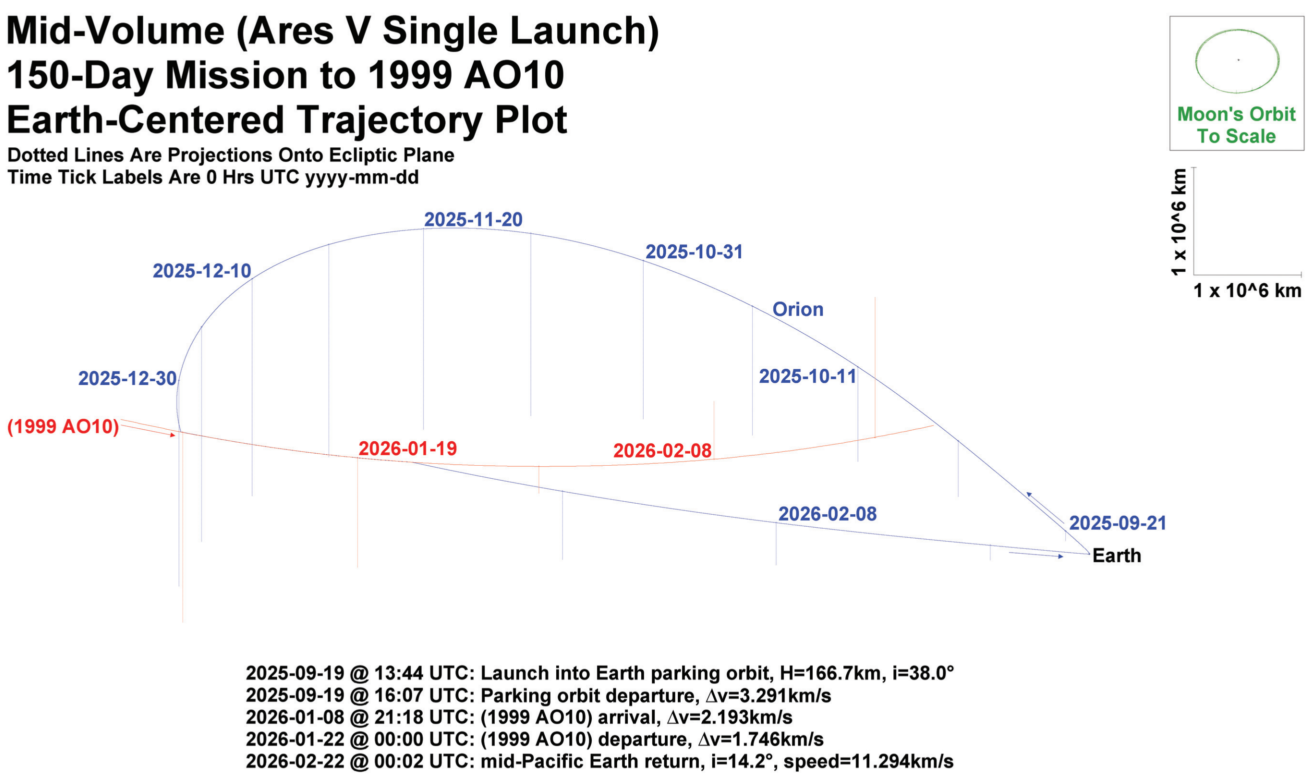


Fig. 4. An Earth-centered trajectory plot showing a possible 150-day mission profile to NEO 1999 $AO_{10}$ with the CEV on top of an Ares V launch vehicle. Atmospheric re-entry is similar to that of the Apollo missions returning from the Moon. The Moon's orbit is shown for scale.

Table 1. This table lists the nine NEOs which are accessible using Constellation hardware described in this feasibility study between the years 2020–2035. Note that three of these objects are listed twice depending on the flight time of the mission. The first row across the top denotes the object name, H magnitude (Mag), semi-major axis (SMA), eccentricity (Ecc), orbital inclination (Inc), launch date (LD), flight time (FT), Δv post-escape (DVPE), and Total Δv required for the mission (DVT). The italicized rows highlight three possible 150-day mission scenarios, whereas the remaining rows represent 180-day mission scenarios.

| Name | Mag | SMA | Ecc | Inc | LD | FT (days) | DVPE | DVT |
|---|---|---|---|---|---|---|---|---|
| *1999 AO10* | *23.9* | *0.912076* | *0.110731* | *2.62* | *2025-SEP-19* | *150* | *3.74* | *7.06* |
| *2000 SG344* | *24.8* | *0.977537* | *0.066916* | *0.11* | *2028-APR-25* | *150* | *3.67* | *7.00* |
| *2006 DQ14* | *27.0* | *1.027738* | *0.052967* | *6.30* | *2030-SEP-21* | *150* | *3.20* | *6.93* |
| 2001 GP2 | 26.9 | 1.037761 | 0.074018 | 1.28 | 2020-APR-06 | 180 | 3.69 | 7.01 |
| 2001 QJ142 | 23.4 | 1.062177 | 0.086275 | 3.11 | 2024-APR-24 | 180 | 3.40 | 6.89 |
| 1999 AO10 | 23.9 | 0.912076 | 0.110731 | 2.62 | 2025-AUG-22 | 180 | 3.54 | 6.85 |
| 2003 LN6 | 24.5 | 0.856814 | 0.209499 | 0.66 | 2025-DEC-21 | 180 | 3.69 | 7.02 |
| 2000 SG344 | 24.8 | 0.977537 | 0.066916 | 0.11 | 2028-APR-27 | 180 | 3.22 | 6.56 |
| 2006 UQ216 | 27.3 | 1.103814 | 0.162567 | 0.47 | 2028-AUG-15 | 180 | 3.55 | 7.26 |
| 2006 DQ14 | 27.0 | 1.027738 | 0.052967 | 6.30 | 2030-AUG-27 | 180 | 2.10 | 5.87 |
| 1999 CG9 | 25.2 | 1.061891 | 0.063564 | 5.16 | 2033-AUG-18 | 180 | 3.08 | 6.61 |
| 1999 VX25 | 26.7 | 0.901265 | 0.137967 | 1.67 | 2034-SEP-25 | 180 | 3.45 | 7.09 |

and return to Earth just prior to the NEO receding beyond the range of the CEV.

## GROUND-BASED TELESCOPE AND PRECURSOR SPACECRAFT INVESTIGATIONS

A detailed investigation/characterization effort should be undertaken prior to any launch of a human-led mission to a candidate NEO. This can be done by various ground-based observations and activities. Visible and infrared telescopes can refine the astrometric positions of a NEO, obtain detailed light curve information constraining NEO shapes and spin rates, and collect albedo and spectral data on basic physical properties. If a NEO has a relatively close approach to the Earth, the Arecibo and Goldstone planetary radars should be able to refine the orbit of the object and perhaps even "image" it. The radar data would reveal the basic shape of the object and would determine its size, its spin orientation, whether it was part of a multiple system (i.e., a binary or tertiary object), and possibly its surface characteristics. This information is similar to that obtained by a spacecraft flyby mission, but provided at only a fraction of the cost. Such detailed preliminary investigations of potential mission targets would help constrain the pool of potential candidate NEO targets for the CEV mission.

In addition to ground-based efforts to characterize potential NEO mission targets, small precursor spacecraft should be flown to collect even higher fidelity data. The precursor spacecraft's main objective is to perform basic reconnaissance of a target NEO under consideration for the subsequent human-led mission. As stated above, it will assess the NEO for any potential hazards that may pose a risk to the Orion vehicle, its deployable assets (e.g., surface science packages, rover system, etc.), and its crew. However, the information obtained on the basic physical characteristics during its reconnaissance will also be crucial for planning the operational activities of the crew and designing the in-depth scientific investigation of the candidate NEO. Ideally the robotic precursor would be able to determine and survey NEO physical parameters such as surface morphology, gravitational field structure, rotation rate, pole orientation, mass/density, and general composition. The spacecraft should also assess potential terrains for planning proximity operations and sample collection by the CEV and its deployable assets. An optimal NEO target will be one that has a relatively slow rotation rate, has an average diameter on the order of 50 m or greater, is composed of material that may be suitable for resource utilization, and is not part of a binary (or trinary) system.

If the NEO is found to be an appropriate target for the Orion vehicle, the robotic precursor spacecraft would also aid in the navigation of the CEV to the NEO. This would add a level of redundancy for the crew's assured arrival. During the CEV operational phase of the mission, the precursor spacecraft would observe the operational aspects of the Orion CEV from a distance, provide additional sensors for the scientific investigation of the NEO, and act as a communication relay if specific assets were out of the line-of-sight from the Orion CEV.

After departure of the CEV from the NEO, the robotic precursor could observe a high kinetic energy experiment at the NEO to investigate cratering excavation and formation, ejecta processes, seismic propagation, interior composition, and momentum transfer. Such information would not only be extremely valuable in terms of science, but would also provide crucial data relevant for hazard mitigation and planetary defense. The precursor spacecraft could also continue to relay data from any science packages left on the surface of the NEO, while at the same time monitoring the effects of the momentum transfer and refining the orbital motion (e.g., Yarkovsky effect), and rotation rate changes (e.g., YORP effects) of the NEO over time.

The precursor spacecraft does not need to be particularly sophisticated in terms of its instrumentation. A Deep Space Network transponder is essential for radio science data and refinement of the mass-to-volume ratio of the NEO and determination of its orbital motion over time. It should also have a visible camera for surface feature characterization and a spectrometer capable of obtaining surface spectra in both visible and infrared wavelengths for a general compositional investigation. Other instruments, such as a laser altimeter for surface topography, would also be useful for constraining additional gravitational characteristics of the NEO. It should be noted that the data from all of the precursor spacecraft's instruments would add to the current body of knowledge of NEO physical characteristics in addition to characterizing any potential mission targets for a human exploration mission.

## CEV SPACECRAFT CAPABILITIES

The CEV would require several basic capabilities in order to complete the scientific and technical objectives of the mission. These would involve equipment and techniques supporting remote sensing, deployment/re-deployment of surface experiment packages, and surface sampling. Previous ground-based observations and the precursor mission data of the NEO should have adequately characterized the surface and local space environment to reduce the risk to the CEV and its assets (i.e., crew and equipment). Hence, the majority of CEV operations should be able to take place in close proximity (~a few to several hundred meters) to the NEO. Such operations have been found to be challenging for remotely controlled spacecraft due to round trip light delay times of several tens of seconds or minutes, but should be much more tractable for the crew of the Orion CEV. Based on previous Apollo and Space Shuttle experience, the crew should be able to match the rotation of the NEO, or hover over its surface, while maintaining a stable attitude from which they can conduct a detailed scientific exploration of the NEO.

In terms of remote sensing capability, the CEV should have a high-resolution camera for detailed surface characterization and optical navigation. A light detection and ranging (LIDAR) system would be mandatory for hazard avoidance during close proximity operations and for detailed topography measurements. In addition, the CEV has in its current design a radar transmitter that could be outfitted to perform radar tomography of the object. This would allow a detailed examination of the interior structure of the NEO. Given that several NEOs appear to have a high degree of porosity (e.g., Itokawa is estimated to be 40% void space by volume [Fujiwara et al. 2006]), it is important to measure this physical characteristic of the target NEO. Such information not only has implications for understanding the formation and impact history of the NEO population, but may also have major implications for the development of future hazard mitigation techniques should an asteroid threaten Earth.

Another advantage of the CEV is the capability to precisely place and re-deploy relatively small scientific packages on the NEO's surface. Packages such as remotely operated or autonomous rovers/hoppers with one or two instruments could greatly increase the amount of data obtained, helping to refine site selection for subsequent sample collection, and enhancing the diversity of samples to be collected from the surface. In situ experiments designed to test such technologies as surface anchors/tethers, drills/excavation equipment, or resource extraction equipment could also be deployed. The CEV could also place a series of seismic sensors across the surface of the NEO shortly before departure, and then remotely detonate one or more small explosive charges on the surface once the crew is safely beyond the blast radius. Data from the seismic sensors would be relayed to the still-active robotic-precursor, which would help constrain physical properties of the NEO's interior structure.

Undoubtedly, the biggest scientific asset that the CEV will have to offer is its crew, which can adapt to specific situations and adjust experiments and operations with much more flexibility than a robotic spacecraft. The crew has the added advantage of EVA and sample collection capabilities during close proximity operations. The crew's ability to land, traverse the NEO, and collect macroscopic samples in geological context from several terrains (e.g., Muses Sea region or the Little Woomera terrain on asteroid Itokawa [Fujiwara et al. 2006]) would bring a wealth of scientific information on such physical characteristics as particle size, potential space weathering effects, impact history, material properties, and near surface densities of the NEO.

Although human missions are more expensive than purely robotic missions for in situ science and sample return missions, the overall science return from such piloted missions is vastly superior to anything that can currently be achieved via robotic spacecraft alone. As mentioned above, astronauts are much more flexible and adaptable to changing operational environments and able to cope with situations in real time far better than robotic spacecraft. The complex environments at and near the surface of a NEO present many challenges for both robotic and human missions, but in the end the human element will produce the most science return for any given investment, as evidenced by the Apollo astronaut EVAs and the quantity and quality of the samples they obtained. There were many instances during which the Apollo astronauts recognized the need to obtain interesting or important samples for collection, and performed tasks that a robotic spacecraft could not have achieved. For example, the Apollo astronauts obtained several samples by rolling over large lunar boulders to expose "fresh" surface materials. They were also able to obtain samples in complete geological context, preserving the depth profiles of the collected lunar material. Such activities are currently outside the realm of robotic capabilities, and are likely to be considerably more difficult in a NEO environment, as evidence by the Hayabusa mission to Itokawa. This is not to say that robotic missions should not be undertaken, but rather that certain scientific investigations are best enabled by a human presence. Ideally, future US exploration architectures should consider a combination of robotic and human exploration to destinations beyond LEO in order to maximize science return and improve overall mission efficiency.

## MISSION SCIENCE GOALS AND OBJECTIVES

There are several science goals and objectives in sending the Orion CEV to a NEO. The top priorities for this type of mission are sample return, internal structure measurements, crater formation observations, and characterizing the momentum transferred to the object by either explosive charges or a separate impacting spacecraft. Arguably the main goal of such a mission would be to collect macroscopic samples from various terrains on the NEO's surface via astronaut EVAs. This would enable sample collection to be obtained in geological context to ensure that profiles (i.e., top, middle, and bottom) could be maintained. Intact samples of the optical surface would also be used to evaluate space weathering/surface alteration effects in a deep space environment. In addition, supplemental telerobotic collection of samples from different or difficult to reach sites on the NEO could expand the sample suite. It would also be useful to identify and collect materials that may not be indigenous to the NEO, or which may have undergone significant alteration processes (i.e., black boulders on the surface of Itokawa [Fujiwara et al. 2006]).

Another primary goal of this mission would be to investigate and determine the interior characteristics of the target NEO. This would place some constraints on the macroporosities that may be found among this population of objects and help scientists understand the impact history of the early solar system. Such investigations could be combined with a detailed examination of any features/structures associated with crater formation in microgravity environments (crater morphology, crater internal structures, fractures, ejecta movement/secondary impacts, effects of surface topography/curvature on crater morphology, etc.) to further refine impact physics models appropriate for these primitive objects and understand NEO internal structures. Active detonation of a kinetic energy experiment after deployment of a seismic network would also serve to measure the interior of the NEO while gaining insights into the effects of crater excavation. In addition, the momentum transferred to the NEO orbit after charge detonation or a hypervelocity impact by a spacecraft could be measured, and any change in orbital motion of the NEO could be observed. Such information has important benefits for future hazard mitigation scenarios.

The information obtained from a CEV-type investigation of a NEO, together with ground-based observations and prior spacecraft investigations of asteroids and comets will also provide a real measure of ground truth to data obtained from the terrestrial meteorite collections. Major advances in the areas of geochemistry, impact history, thermal history, isotope analyses, mineralogy, space weathering, formation ages, thermal inertias, volatile content, source regions, solar system formation, etc. can be expected from asteroid sample return missions. Samples directly retuned from a primitive body would lead to the same kind of breakthroughs for understanding NEOs that the Apollo samples provided for understanding the Earth-Moon system and its formation history.

In addition, such a mission would allow the U.S. and NASA to gain operational experience in performing complex tasks (e.g., sample collection, deployment of payloads, retrieval of payloads, construction, etc.) with crew, robots, and spacecraft under microgravity conditions at or near the surface of a NEO. This has key potential benefits for future scientific exploration of other destinations beyond low Earth orbit, and development of more efficient exploration architectures. Discovering extraterrestrial resources that would enable more ambitious future human exploration is a desirable objective and one that has been identified in the 2003 National Research Council (NRC) decadal survey (p. 155). The cooperation of the robotic and human exploration programs to further the science objectives of NASA and the general science community has also been specifically mentioned in the 2003 NRC decadal survey report (p. 162–163), and will also be addressed in the next NRC decadal survey for the 2013 to 2022 time frame.

Knowledge of how asteroids and comets affect life on Earth, either through delivery of volatiles and organics or through devastating impact events, is one of the six continuing mysteries of the solar system that have been identified within the 2003 NRC decadal survey (see box 6.2, p. 160). Hence any scientific investigation that studies the physical characteristics of objects that may pose a threat to the Earth, or may have contributed to life's earliest beginnings, is directly relevant to the interests of the scientific community. A proposed Orion CEV mission to a NEO would be of high scientific value.

An asteroid lander/rover/sample return mission and support for continuing studies of NEOs have also been identified as part of a major recommendation by the NRC decadal survey's primitive body exploration group (p. 25–29). The survey states that NEOs are specifically identified as a source of key information both for pure scientific research and for the general public good. The survey also mentions that samples returned from near-Earth objects are a critical component to achieving the objectives for understanding the characteristics of the NEO population and their potential hazard (p. 29).

More specifically, an asteroid sample return mission is directly relevant to NASA's stated long-term strategic goals as adopted in response to the NRC's decadal survey and modified to fit the objectives of the USSEP. The 2006 Solar System Exploration Roadmap for NASA's Science Mission Directorate listed five fundamental questions that outline the major objectives for the NASA's exploration program:

1. How did the Sun's family of planets and minor bodies originate?
2. How did the solar system evolve to its current diverse state?
3. What are the characteristics of the solar system that led to the origin of life?
4. How did life begin and evolve on Earth and has it evolved elsewhere in the solar system?
5. What are the hazards and resources in the solar system environment that will affect the extension of human presence in space?

Each of these questions has aspects that could be addressed by the information collected by piloted CEV missions to NEOs.

While the scientific justification for such a human-led mission to a NEO is sound, it is important to point out that science is not the only rationale for undertaking this type of mission. There are several other valid reasons for the U.S. government and NASA, under the guidance of the USSEP, to mount a human mission to a NEO. Such rationales include, but are not limited to: increasing international participation and cooperation, sustaining NASA's programmatic momentum, gaining deep space operational experience, maintaining U.S. national prestige, demonstrating resource extraction and utilization, stimulating public interest, and developing hazard mitigation techniques. A human-led NEO mission will enable all of these goals, provide significant scientific advancement in understanding these relatively primitive bodies that formed during the earliest stages of the solar system, and identify the roles these objects played in the evolution of the Earth and its biosphere.

## MISSION COST, REQUIRED TECHNOLOGY DEVELOPMENT, AND RISK MITIGATION

The Constellation systems being developed under the auspices of the USSEP and ESAS provide a unique opportunity to enable human missions to NEOs. No other spacecraft system and associated launch infrastructure currently under consideration will enable both human and science exploration to destinations beyond low Earth orbit. Given that Constellation hardware is already under design and development for trips to the International Space Station and later to the lunar surface, the incremental development costs for the Orion CEV and the Ares family of launchers to be utilized for science missions to NEOs will be minimized.

Although a rigorous cost estimate was not part of this initial feasibility study, a brief examination of the associated costs for such a mission indicates that it would be similar to an extended lunar sortie mission. For the upper bookend NEO mission scenario, both an Ares I with Orion and an Ares V with an Earth departure stage (EDS) are assumed. There are, however, specific items required for lunar operation (e.g., lunar habitat, Altair lunar lander, etc.) that would not be required for a NEO mission and thus their costs should not be included. Additionally, only minor internal modifications were assumed for the Orion CEV even though there are only three astronauts for the upper bookend NEO mission compared to four on the lunar sortie. If the reduced costs associated with the lower bookend NEO mission are desired, then deletion of the Ares V vehicle and the inclusion of an EELV with an upper stage must be considered. The cost for a lower bookend NEO mission is expected to be somewhat cheaper due to the launch cost difference between an EELV and the Ares V, but the mission itself could happen much earlier and prior to the completion of the development of the Ares V launch vehicle. The mission length for any of the NEO options would be a minimum of 90 to 180 days. The ground-based mission operations would be similar to those needed for a lunar mission until the time delay for communications to the NEO mission made real-time support impossible. It is assumed that the mission operations costs for the first NEO mission would also be similar to that of an extended lunar sortie.

In terms of technology development, there is a relatively small amount of new technology that would be required for the optimum success of this mission. Some technologies associated with on-board operations automation, radiation shielding, microgravity EVA equipment (e.g., maneuvering units/tethers, sample collection tools, etc.), inflatable habitats, and NEO surface science packages would be required. However, most of these technologies are already being considered within NASA and the private sector for other space exploration missions. Hence the expected new technological development required for crewed missions to NEOs is minimal in terms of the overall cost of the Orion and Ares infrastructure.

Such human missions to NEOs using Constellation systems present significantly less operational and scientific risk than a full lunar mission. Given the very low gravity of the NEO, there is no need for a complicated scenario of descent, landing, ascent, and multiple docking and rendezvous of a crewed spacecraft outside of LEO within a significant planetary gravity well. This reduction in complexity also reduces the operational risks of a NEO mission. In addition, the Ares launch vehicles and Orion CEV will have undergone rigorous testing and will presumably have flown astronauts multiple times to the ISS and possibly already to the Moon. Hence, these missions will be using the best understood space transportation system infrastructure for human scientific and exploration missions outside of LEO.

## CONCLUSIONS

To date, the planetary science community has based much of its interpretation of the formation of asteroids and comets (i.e., parent bodies of the NEO population) on data from meteorites and interplanetary dust particles collected on Earth. These materials are known to come from such objects, but the exact location of the specific parent bodies within the solar system is not generally known. Because direct connections of these samples to specific objects cannot be made with any degree of certainty, scientists have only a limited ability to place their findings in a larger context. However, with pristine samples from known locations within the solar system, scientists can start to "map outcrops" and glean new insights into the compositions and formation histories of these NEOs. While such knowledge will aid in a better understanding of our solar system, it also has the potential for more practical applications such as resource extraction and utilization (e.g., water, precious metals, volatiles, etc.) and NEO hazard mitigation (e.g., determining material properties, internal structures, macro-porosities, etc.). These scientific and hazard mitigation benefits, along with the programmatic and operational benefits of a human venture beyond the Earth-Moon system, make a crewed sample return mission to a NEO using the proposed Constellation systems a compelling prospect.

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