Scientific Investigation of Near-Earth Objects via the Orion Crew Exploration Vehicle

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Abstract

NASA has examined the feasibility of sending the Orion Crew Exploration Vehicle (CEV) to near-Earth objects (NEOs) during the next decade and beyond as part of its future Human Space Flight program. 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. 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. The data collected 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 NEOs has been examined by several 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. An 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 compelling aspects of sending humans to NEOs 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 these objects 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 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. These data would also constrain the suite of materials believed to have been delivered to the early Earth, and identify potential source regions (*e.g.*, mainbelt asteroid and comet reservoirs) from which the NEO population originates (*e.g*., 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, 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; Mittlefehldt *et al*., 1998; Veverka *et al*., 2000; Britt and Consolmagno, 2003; Fujiwara *et al*., 2006). 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 (Δv) (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 Δv is required to brake into the vicinity of, and to depart from, a typical NEO. Several NEOs examined as potential human mission targets have total Δv requirements on the order of only ~5.7 to ~7.0 km/s. As a comparison, the last crewed mission sent to the Moon, *Apollo 17*, required a total Δv of ~9.1 km/s, which included injection from low-Earth orbit, descent, lunar landing, ascent, and return to Earth (Orloff, 2001; Adamo, 2007).

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 Yucatan peninsula ~65 million years ago was the cause of the massive K/T (*i.e*., dinosaur) extinction event. 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).

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 the NEO population. 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 facilities come on line, the detection rate of NEOs and potentially hazardous objects will increase by more than a factor of 50 (NASA report to Congress, 2007). 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.

Precursor Robotic Missions to NEOs

Although scientific exploration of NEOs can be accomplished by robotic spacecraft, more detailed investigations 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.

Ideally, a combination of robotic and crewed exploration of candidate NEOs would be planned since prior robotic reconnaissance would significantly reduce 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 small satellite(s) or 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.

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.

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. 1).

The total Δv capability of each of these configurations ranges from just over 4.5 km/s for the lower bookend to 7.25 km/s for the mid-volume Ares V single launch. The other two configurations have Δv capabilities of 6.0 km/s and 6.3 km/s, 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 Δv due to the extra payload mass being carried out to the NEO. These four total Δv 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. A 150-day trajectory plot to 1999 AO_{10} is shown in Figure 2 as an example of a mission profile that could be flown to these NEOs.

In general, the total mission Δv 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 and return to Earth just prior to the NEO receding beyond the range of the CEV.

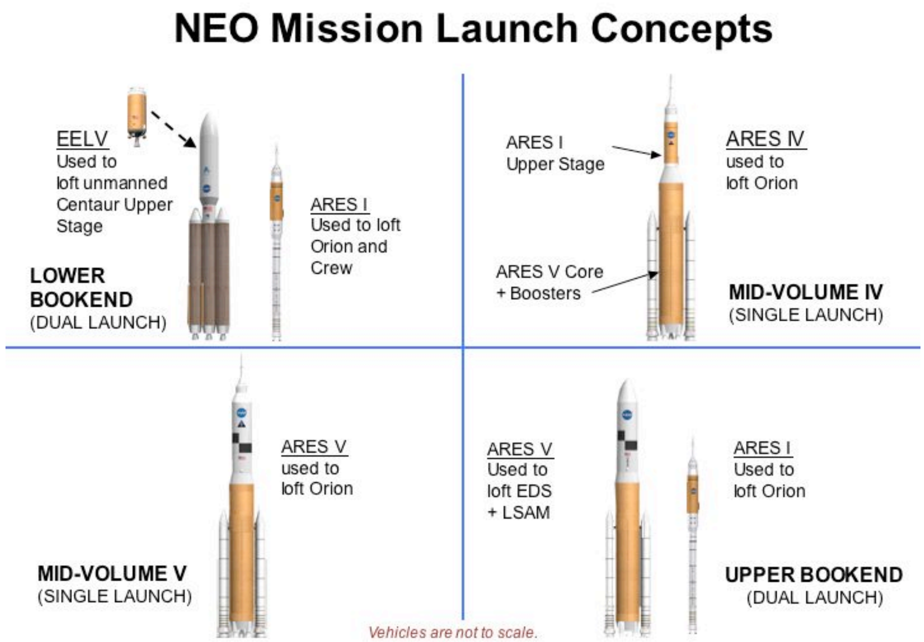

Figure 1: The four types of NEO mission launch concepts considered for the Constellation NEO feasibility study.

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.

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.

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.

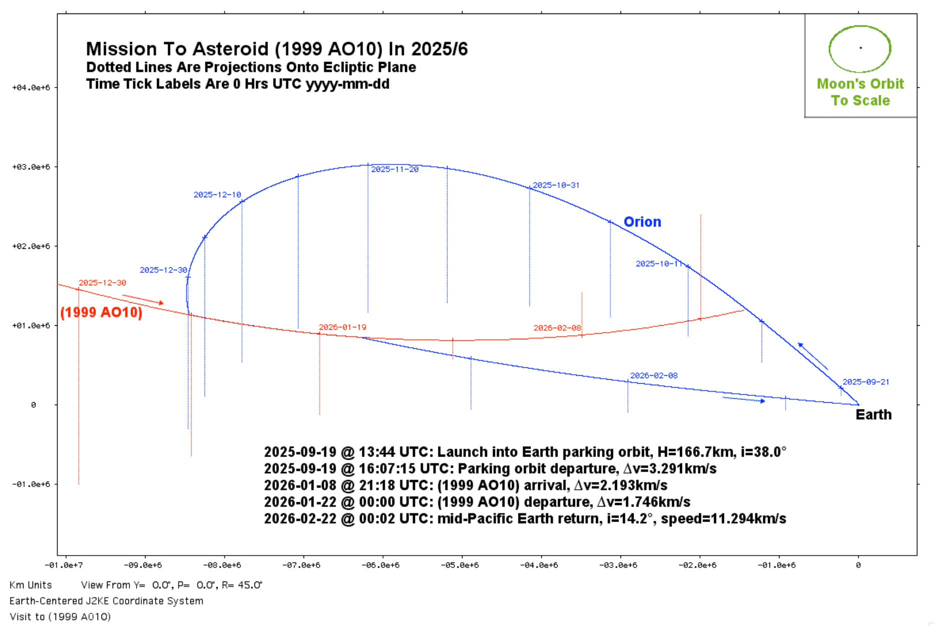

Figure 2: An Earth-centered trajectory plot showing a possible 150-day mission profile to NEO 1999 AO_{10} with the CEV on top of an Ares V launch vehicle. Atmospheric re-entry is similar to that of the Apollo missions returning from the Moon. The Moon's orbit is shown for scale.

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 by an impacting spacecraft. Arguably the main goal of such a mission would be to collect macroscopic samples from various terrains on the NEO's surface. Crew mobility during NEO proximity operations would enable sample collection 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. Such information also 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 missions 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 would 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 and has potential benefits for future scientific exploration of other destinations beyond low-Earth orbit.

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 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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