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INTO THE BEYOND: A CREWED MISSION TO A NEAR-EARTH OBJECT

David J. Korsmeyer, NASA Ames Research Center, Intelligent Systems Division, Moffett Field, CA, USA, David.J.Korsmeyer@nasa.gov
Rob R. Landis, NASA Johnson Space Center, Mission Operations Directorate, Houston, TX, USA Rob.R.Landis@nasa.gov
Paul A. Abell, NASA Johnson Space Center, Astromaterials Research & Exploration Science, Houston, TX, USA Paul.A.Abell@nasa.gov

ABSTRACT

Aside from the exploration of Mars, the objects that most capture our interest for a new human visit are the Near-Earth Objects (NEOs). These objects are ideal candidates for deep space operations and explorations as we extend the human presence out into the solar system. The notion of a crewed mission to a NEO was first discussed in the Apollo era. The most recent assessment has been undertaken by the Advanced Projects Office within NASA's Constellation Program. This particular study examined the feasibility of sending NASA's new Orion spacecraft (also referred to as the Crew Exploration Vehicle, or CEV) to a NEO. Depending on the specifications of spacecraft and integrated components, a mission profile would include two or three astronauts on a 90- to 180-day spaceflight; including a 7- to 14-day stay at the NEO itself. These missions to NEOs provide Exploration with an excellent suite of benefits: operational experience beyond cislunar space; risk reduction for space hardware; confidence building for future mission scenarios; *in situ* resource utilization evaluation; as well as a rich scientific return. This incremental step along the way towards Mars would mark humanity's first foray beyond the Earth-Moon system.

INTRODUCTION

In August of 2006, the Advanced Programs Office within NASA's Constellation Program decided to fund an initial set of concept feasibility studies. These were to assess the utility and opportunities for the developing Constellation infrastructure, particularly, the Ares Launch vehicles and the Orion crewed spacecraft, to be used for missions that were not directly in the design specifications (aka non-lunar missions). The Ares and Orion systems are designed to launch 4-6 crew to the International Space Station (ISS), and to eventually take 4 crew back to lunar orbit where a lunar lander would take the crew to the surface.

The NASA Constellation Program wanted to understand what are some other feasible, high-value uses of the Orion spacecraft and Ares launch system other than a lunar return. One of the key feasible uses was the notion of the Orion spacecraft taking astronauts to visit a Near Earth Object, most likely an asteroid. The results of this study[1] and its potential place in the manned exploration on the inner solar system are discussed in this paper.

WHAT ARE NEAR-EARTH OBJECTS?

Near-Earth objects (NEOs) include asteroids and comets whose orbits approach or intersect the Earth's orbit about the Sun (and are, therefore, distinguished from main belt asteroids which orbit the Sun between Mars and Jupiter). NEOs range in size from a few meters across to as large as ~30 kilometers (km) across, with smaller objects greatly outnumbering larger objects. Because of the volatiles they contain, near-Earth comets, while in Earth's vicinity to the Sun, would not make an attractive target for a crewed mission, so the study will focus on what we know to be near-Earth asteroids. However, the term 'NEO' will be used to refer to all near-Earth objects throughout this paper. From ground-based observations and the study of meteorites that have fallen to Earth, we know that the general makeup and structure of NEOs is wide-ranging – from those comprised of loose conglomerations of rock and stone to those consisting of mostly iron. Due to their small size and relative similarity of their orbits to Earth, many NEOs require significantly less Δv to access than is required to get to the Moon. The Moon is more frequently accessible due to its captive orbit around the Earth.

The orbits of many NEOs are quite similar to the Earth's heliocentric orbit, and therefore require a small Δv for rendezvous provided launch occurs near a close approach. In addition, due to their small size and consequent shallow gravity wells, only a very small Δv (~0.06 km/sec) is required to brake into the vicinity of, and to depart from, a typical NEO. For comparison, the Δv required to brake into or depart from lunar orbit is on the order of 0.8 km/sec, which when combined with the 3.2 km/sec lunar transfer Δv means that an *Apollo 8* type mission requires a Δv ~4.8 km/sec. For comparison, the *Apollo 17 mission* total Δv was ~9.1 km/sec[2]. So it can require less energy to get to a NEO than would take to land on the Moon.

Why then, have we not attempted to send crews to NEOs already? This is due in part to two things: the current lack of capable spacecraft and boost stages; and the difficulty in identifying when a NEO of interest will be passing by close enough to the Earth to enable reasonable travel times for a crewed spacecraft. To plan for a NEO mission, we would want to know that a NEO would be coming in close proximity to the Earth several years in advance. Knowing the relative positions of the NEO and the Earth requires a good characterization of the NEO trajectory prior to the NEO's close approach to Earth.

NEOs are often found when their orbits cause them to approach Earth and thus become a brighter magnitude object in the sky. The older surveying telescopes do not have the sensitivity to detect NEOs below 1km in size without the NEOs coming very close to the Earth. The current NASA NEO program assesses a new NEO to determine whether it is a Potential Hazardous Object (PHO) or not. Due to the nature of most NEO orbits, the phasing of NEOs and the Earth to meet occurs only every tens of years for most NEOs. At the time of most NEO discoveries, the NEO is likely already not in a position with respect to the Earth where a crewed mission could easily be sent to visit. It is likely that it will be several decades before the specific NEO returns close enough to the Earth for a mission to be sent.

In 1998, NASA accepted the mandate to detect and catalogue 90% of NEOs larger than 1 km. As of 9 August 2007, 4754 NEOs have been discovered and over 800 were identified as PHOs. A 2005 update to the NASA Authorization Act now directs NASA to detect and characterize NEOs down to 140 meters in size. The number of such smaller asteroids is vastly greater than the number of larger asteroids. This means that the discovery rate of NEO will increase greatly over the next ten years, even if only two new search telescopes begin operations. The two new telescopes are the Pan-STARRS (Panoramic Survey Telescope and Rapid Response System) and the Large Synoptic Survey Telescope (LSST). The number of known NEOs will grow especially if NASA is provided funds to perform the greater than 140 meter survey to 90% completeness by 2020. By the middle of the next decade we expect that there will be hundreds of possible new candidate NEOs accessible for a CEV mission.

Cumulative PHOs and NEOs 1990-2020		
Yr	#NEO>140m #NEO>100m	#PHO>140m #PHO>100m
1990	100 100	20 20
1995	300 300	60 60
2000	800 800	160 160
2005	3000 3000	600 600
2010	6000 10000	1200 2000
2015	30000 50000	6000 10000
2020	40000 80000	8000 16000

Table 1: Cumulative PHOs and NEOs

Past discovery rates of NEOs in Table 1 are from the NASA-JPL NEO Program Office website[3]. Future discovery rates are estimated from Figure 13 of the *NASA 2006 Near-Earth Object Survey and Deflection Study*[4]. Note that while the NASA metric for future surveys is defined for PHOs 140m or larger, the LSST will discover almost twice this number that are greater that 100m in size The estimates in Table 1 for the numbers >100m are accordingly just estimates, while the values for greater than 140m are from the NASA Report. These estimates are somewhat imprecise due to the different conversions between brightness (visible magnitude) and physical size. Note that all values in Table 1 are cumulative.

PREVIOUS NEO MISSION STUDIES

The idea of a human visit to an asteroid is as old as the human space program. Several studies have explored everything from Apollo system hardware to conceptual systems. To the authors' best understanding, the notion of a piloted mission to a NEO was first discussed in 1966 as an alternate follow-on utilization of the Apollo spacecraft and Saturn 5 hardware. The mission[5] would have been a flyby for the 1975 opposition of 433 Eros. During the 1975 opposition, Eros came within 0.15 AU of the Earth. The 1966 study examined the necessary capabilities to upgrade the Apollo/Saturn 5 hardware for a 500+ day round trip mission. More than 20 years later, NASA re-examined[6] the idea of visiting NEOs in greater depth as part of the Space Exploration Initiative in 1989. Since then, four other studies have examined the details of sending humans to NEOs[7,8,9,10].

The Advanced Projects Office within NASA's Constellation Program sponsored the most recent official NASA study. This six-month (Sept 2006 – Feb 2007) study was conducted by a team led from NASA Ames Research Center. That team included members from NASA Johnson Space Center (including astronaut Ed Lu), the Jet Propulsion Laboratory, NASA Headquarters, and former astronaut Tom Jones, the author of two previous NEO studies. The study examined the feasibility of sending a CEV to a NEO[11]. The ideal mission profile would involve a crew of 2 or 3 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 type of mission would be an ideal test flight prior to venturing out to Mars and would be on par technically (though not in flight time) to visiting the Martian moons Phobos and Deimos.

CURRENT CREWED NEO STUDY

The objective of the 2006-20007 NASA study was to examine the flight elements of the Constellation Program, such as the Orion manned spacecraft as well as the Ares launch vehicles, for suitability for deep space missions beyond the Moon, and in particular, missions to NEOs. These missions can test spacecraft systems, operational techniques, crew experience, and acquire practical knowledge of NEO physical characteristics (e.g., internal structure and composition).

Previous studies were reviewed as a starting point for establishing mission objectives and identifying candidate target bodies and mission profiles. Mission objectives would be updated in consultation with Constellation Program mission designers and NEO scientists. The existing database of NEOs was mined to identify candidate targets. The study used special software to identify candidate NEOs with short trip times and low Δv's in the appropriate time frame (late 2010s through the 2020s). Performance characteristics of the Orion spacecraft and Ares launch vehicles were analysed against the mission requirements for a selected set of candidate targets.

Study Results

At first order, the NEOs that are good targets of opportunity for initial piloted missions are those with the following characteristics:

- Earth-like orbits (low eccentricity and low inclination),
- close Earth approaches (i.e., ~0.05 AU of the Earth – a potentially hazardous object or PHO),
- slow rotation (i.e., rotation periods of ~10 hours or longer),
- single, solitary objects (nearly 1/6th of all NEOs are binary objects)
- asteroidal origin (i.e., not a cometary or extinct comet, or transition object)

Some 35 candidate NEOs for exploration by piloted CEV missions were found in the current NEO catalog. Four launch options were assessed. These ranged from using an Ares 1/CEV with an EELV to launch a Centaur-class upper stage for NEO orbit injection, to the full Ares 1 and Ares V launch systems. Several trajectories and

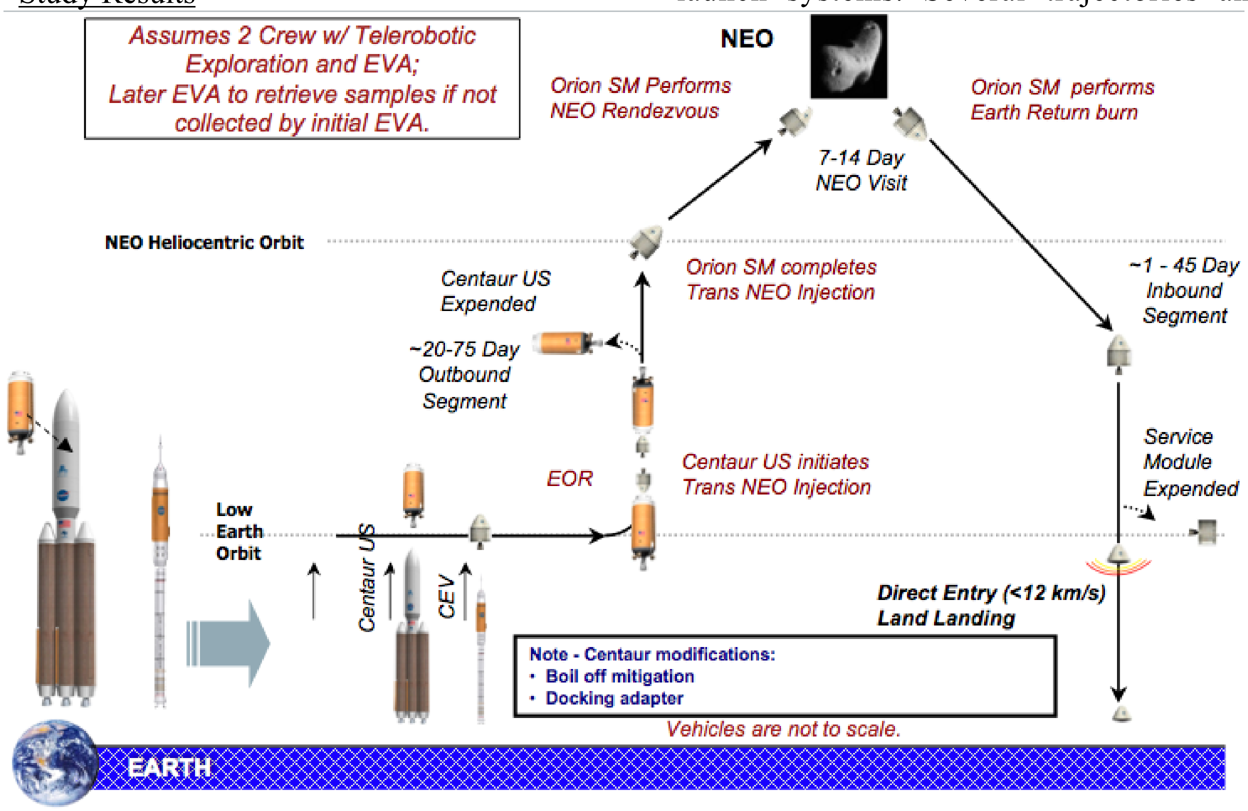

Figure 1: Crewed NEO Mission Concept

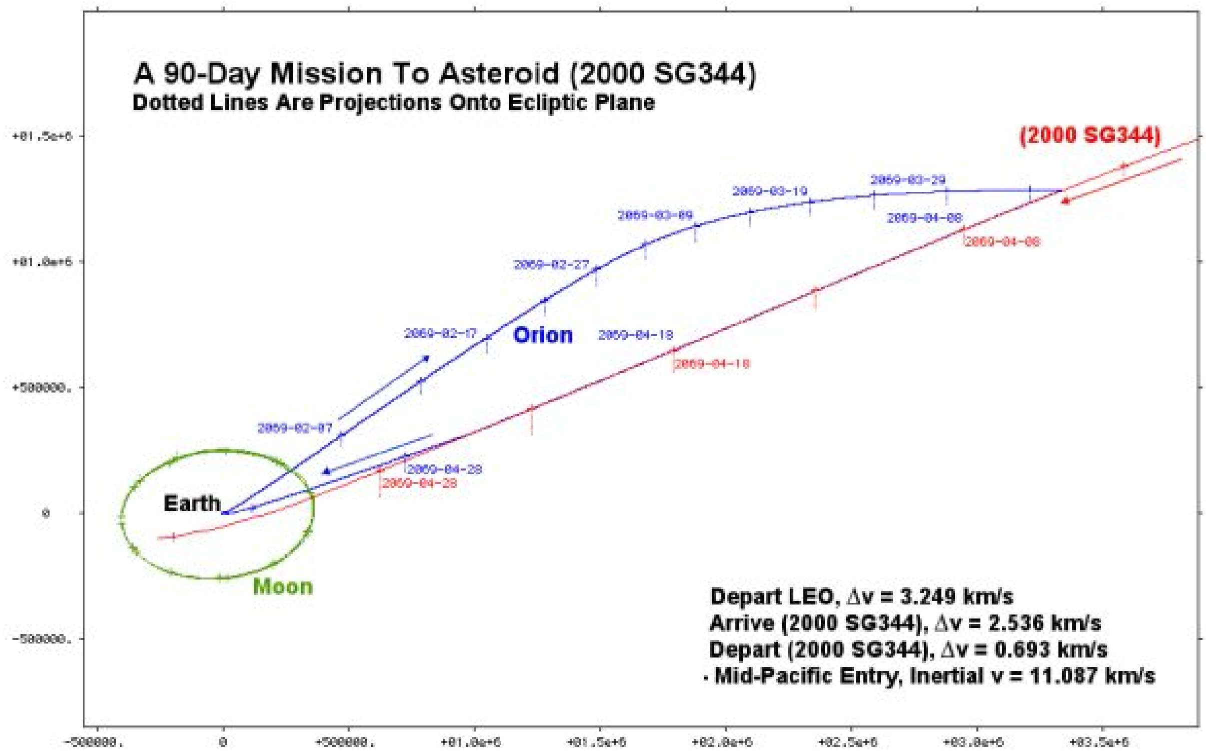

Figure 2: Notional NEO Mission Trajectory

mission lengths from 90 to 180 days were examined.

The current study performed a detailed analysis of a 90-day mission scenario to an asteroid. In order to minimize the impact to current CEV development and to maximize the applicability and validity of this NEO mission to Constellation test objectives, an unmodified Block II CEV and unmodified Ares launch vehicles were assumed. The asteroid 2000 SG_{344} was used as a placeholder for an appropriate mission target that has yet to be found from the NEO survey. This mission analysis was performed using a single Ares 1 launch of a CEV with an Evolved Expendable Launch Vehicle (EELV) launch of a Centaur-class upper stage to act as a NEO injection stage. The overall scope of the mission is shown in Figure 1.

The trajectories shown in Figure 2 show the orbital elements of the asteroid 2000 SG_{344} in 2069, which is representative of the proper relative position of the NEO to the Earth for the length of mission desired.

The most significant advantage of a piloted mission to a NEO is that it validates the Constellation Program system architecture and strengthens the foundation for the Vision for Space Exploration (VSE) in the run-up to the lunar sorties and lunar outpost development beginning at the end of the next decade (~2020). This crewed NEO mission can perform an early developmental test of exploration hardware and operations, potentially prior to the development of the full lunar architecture. Sending a human expedition to a NEO demonstrates the broad utility of the Constellation Program's Orion (CEV) crew capsule and Ares (CLV) launch systems.

CREWED NEO MISSION SCIENTIFIC AND PRACTICAL RATIONALE

Missions to NEOs reinforce the Constellation Program with a broad suite of benefits. Deep space operational experience (i.e., the manned CEV will be several light-seconds from the Earth) is critical for building a human presence in the inner solar system.

The NEO missions are a risk reduction for Constellation space hardware for lunar missions as well as Mars missions. This mission would provide great confidence building for future mission scenarios (e.g., lunar poles and farside, other NEOs, and eventually Mars). Additionally the early *in situ* resource utilization (ISRU) evaluation from a NEO would help to validate or disprove the ideas for using asteroids as material resources. Of course there is a rich scientific return for understanding how the solar system formed. Sending a human expedition to a NEO, within the context of the exploration vision, will help NASA in many ways as this is an exciting new mission class for the Constellation Program, marking humanity's first foray beyond the Earth-Moon system.

Piloted missions using the CEV to NEOs will not only provide a great deal of technical and engineering data on spacecraft operations for future human space exploration, but they will have the capability to conduct an in-depth scientific investigation of these objects. Essential physical and geochemical properties of NEOs can best be determined from dedicated spacecraft missions.

Although ground-based observations can provide general information about the physical properties of NEOs (rotation rates, taxonomic class, size estimates, general composition, etc.) spacecraft missions to NEOs are needed to obtain detailed characterizations of surface morphology, internal structure, mineral composition, topography, collisional history, density, particle size, etc. Such missions to NEOs are vital from a scientific perspective for understanding the evolution and thermal histories of these bodies during the formation of the early solar system, and to identify potential source regions from which these NEOs originated.

NEO exploration missions will also have practical applications such as resource utilization and planetary defense—two issues that will be relevant in the not-too-distant future as humanity begins to explore, understand, and utilize the solar system. A significant portion of the NEO population may contain water, an attractive source of life support and fuel for future deep space missions. The subject of planetary defense from impacting asteroids has garnered much public and Congressional interest recently because of the increasing discovery rate of asteroids with a small, but non-zero probability of striking Earth. NASA has already been directed by Congress in the 2005 Authorization Bill to report on options for deflecting a threatening asteroid. Many proposed deflection schemes critically depend on asteroid characteristics such as density, internal structure, and material properties – precisely the parameters that a crewed mission to a NEO could measure.

CEV Science Capabilities:

A CEV-type mission will have a much greater capability for science and exploration of NEOs than robotic spacecraft. The main advantage of having piloted missions to a NEO is the flexibility of the crew to perform tasks and to adapt to situations in real time. Robotic spacecraft have only limited capability for scientific exploration, and may not be able to adapt as readily to certain conditions encountered at a particular NEO. The Japan Aerospace Exploration Agency's (JAXA) *Hayabusa* spacecraft encountered certain situations that were a challenge for both it and its ground controllers during close proximity operations at asteroid Itokawa. A human crew is able to perform tasks and react quickly in a microgravity environment, faster than any robotic spacecraft could (rapid yet delicate manoeuvring has been a hallmark of Apollo, Skylab, and Shuttle operations). In addition, a crewed vehicle is 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 greatly enhance any scientific return from these types of missions to NEOs.

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 essential for hazard avoidance (during close proximity operations) and detailed topography measurements. In addition, the CEV should be outfitted with a radar transmitter to perform tomography, enabling a detailed look at 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), it is important to measure this characteristic of the target NEO. Such information on its internal structure not only has implications for the formation and impact history of the NEO, but also may have implications for future hazard mitigation techniques.

Another advantage of the CEV is the capability to precisely place and re-deploy relatively small scientific packages on the surface of the NEO. Such packages as remotely operated (or autonomous) rovers with one or two instruments could greatly enhance the amount of data obtained from the surface, and fine-tune the site selection for subsequent sample collection. Other packages that may be deployed could be *in situ* experiments designed to test such technologies as surface anchors/tethers, drills/excavation equipment, or material extraction equipment. The CEV could also deploy a transponder to the surface of the object for a long-term study of the NEO's orbital motion. This could be particularly useful for monitoring objects that have the potential for a possible future Earth impact.

The crew has the added advantage of EVA for sample collection during close proximity operations. The ability for the crew to traverse and collect one or more macroscopic samples from specific terrains on the surface of an NEO is the most important scientific aspect of this type of mission. Having a human being interacting in real-time with the NEO surface material and sampling various locales in context would bring a wealth of scientific information on such things as particle size, potential space weathering effects, impact history, material properties, and near-surface densities of the NEO.

ROBOTIC PRECURSOR MISSIONS

Currently there are no robotic precursor missions planned to visit NEOs that might one day be explored by human crews. Yet, a precursor mission would be required in order to maximize crew safety and efficiency of mission operations at any candidate NEO. Such an in-depth reconnaissance by small robotic spacecraft would help to identify the general characteristics of the potential NEO selected for study, and provide an important synergy between the robotic scientific programs and the human exploration programs of NASA. Knowledge of such things as the gravitational field, object shape, surface topography, and general composition would aid in planning for later CEV proximity operations at the NEO. Precursor missions would also be useful to identify potential hazards to the CEV (and any of its deployable assets) such as the presence of satellites, or non-benign surface morphologies, which may not be detectable from previous ground-based observations. The precursor spacecraft should ideally have a visible camera for surface feature characterization, and a spectrometer capable of obtaining surface spectra in both visible and infrared wavelengths for compositional investigation. Other instruments such as a laser altimeter for surface topography and an x-ray/gamma ray spectrometer for elemental distribution may also be useful for constraining additional characteristics of the NEO. It should be noted that the data from all of the instruments on the precursor spacecraft will add to the current body of knowledge of NEOs in addition to characterizing initial potential mission targets for the CEV.

Previous Robotic NEO Missions

To date, there have been only two spacecraft missions that have explored NEOs to any extent: NASA's *NEAR Shoemaker* spacecraft at asteroid 433 Eros in 1999 and the Japan Aerospace Exploration Agency's (JAXA) *Hayabusa* probe at asteroid 25143 Itokawa in 2005. Both of these robotic missions are considered to have been extremely successful and have generated much scientific interest in NEOs. Even though the scientific community has a better understanding of NEO physical properties and compositions based on the data from these missions, there are still many questions that remain unanswered. For example, data from the remote sensors on both spacecraft have been unable to identify the exact composition and internal structure of each asteroid after several months in orbit and a few landings (one for *NEAR Shoemaker* and two for *Hayabusa*). Therefore, even though both missions are considered to have achieved almost all of their scientific goals, they still 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 of the asteroid. It is still not clear if *Hayabusa* managed to obtain a sample of asteroid Itokawa. Preliminary indications are that it did not. Subsequently the science results that came from both of these missions, although extremely valuable, are still limited in terms of determining the compositions and internal structures of these NEOs.

Future Robotic NEO Missions

In October 2006, JAXA announced their intention to launch *Hayabusa 2* to the NEO 1999 JU_3, a C-type asteroid. The tentative plan is to launch in late 2010, rendezvous in 2013 and return samples to Earth ~2015. A next generation 'Hayabusa Mark 2' robotic spacecraft is planned to launch from Earth in 2015 and visit an extinct comet.

Don Quixote is a proposed European Space Agency (ESA) spacecraft to launch to a NEO in the 2013-2017 timeframe. *Don Quixote* is comprised of two spacecraft: *Hidalgo*, which will impact the NEO, and *Sancho*, which will orbit (station keep) above the NEO before, during and after Hidalgo impacts the target NEO. The NEO to visit has not been selected and the mission itself is pre-Phase A.

OSIRIS is a proposed NASA Discovery-class mission to visit a C-type NEO, 1999 RQ_{36}, launching in 2011. *OSIRIS* is also at the pre-Phase A stage and a selection decision on whether to go forward will be made in late 2007. Each of these planned missions will increase our knowledge of NEOs and better prepare mission planning for a crewed NEO mission.

MARS MISSION PRECURSORS

Crewed NEO missions can play a critical role in building valuable experience for a manned Mars mission. In a recent article[12] Durda made a good case for how a mission to a NEO would do much to capture the attention of the public with a new and exciting exploration goal. Additionally, a series of mission to NEOs, each one longer and more distant than the last, would provide very valuable and critical deep-space mission experience for astronauts, mission operations, and Mars-class spacecraft systems. It will be highly beneficial to test out and validate all of the systems necessary for a very long mission to Mars, and NEOs can serve that purpose in our own back yard.

Once we can visit NEOs at a total Δv of between 5 – 6.5 km/s, a mission to Phobos is very straightforward from an energy standpoint at ~7.9 km/s, and to Deimos ~ 7.5 km/s both depending on the method of capture into Mars orbit. Of course the trip times required for a martian moon mission is much greater, but overall it is a logical extension of the experience gained from a NEO mission. In comparison, a Mars surface mission the total Δv tally tops out at ~15.6 km/s.

As we look beyond the space station program and past the moon towards the exploration of the inner solar system, near-Earth asteroids offer a feasible, attractive stepping stones to Mars and beyond. Piloted human missions to NEOs prior to human exploration of Mars can provide unique opportunities to validate mission technologies and acquire deep space operational experience unobtainable elsewhere.

CONCLUSIONS

As new telescopes come on line in the next few years (e.g., Pan-STARRS in 2010 and the LSST in 2014), and/or as an expanded survey by NASA gets underway, the number of new NEOs detected is expected to grow exponentially. Depending upon their orbital parameters and geometries (relative to Earth), these newly discovered NEOs offer many targets for a visit using the Ares launch vehicles and Orion spacecraft, demonstrating and validating an early interplanetary capability of the Constellation hardware.

Finding the synergy between science-driven planetary missions, and the planned crewed space exploration has been challenging. While there is excellent science to be gained from a return to the Moon and Mars, there are new and exciting science opportunities with a NEO mission and no need to develop additional significant mission hardware.

Knowledge of the composition and morphology of NEOs will aid in a better understanding of our solar system, and in defining possible NEO hazard mitigation techniques due to an improved understanding of the material properties, internal structures, and macro-porosities of NEOs as a class. This knowledge also has the potential for more practical applications such as deep space in situ resource utilization of water, precious metals, oxygen, etc. These scientific, hazard mitigation and potential commercial benefits are all valuable attributes of a NEO mission. The operational benefits alone of a human venture into deep space, make a mission to a NEO a valuable prospect as a precursor to Mars missions. What is most compelling though is the cumulative benefits from all these together and the near term programmatic excitement and ability of using Constellation systems hardware already in development.

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