Plymouth Rock
An Early Human Mission to Near Earth Asteroids Using Orion Spacecraft

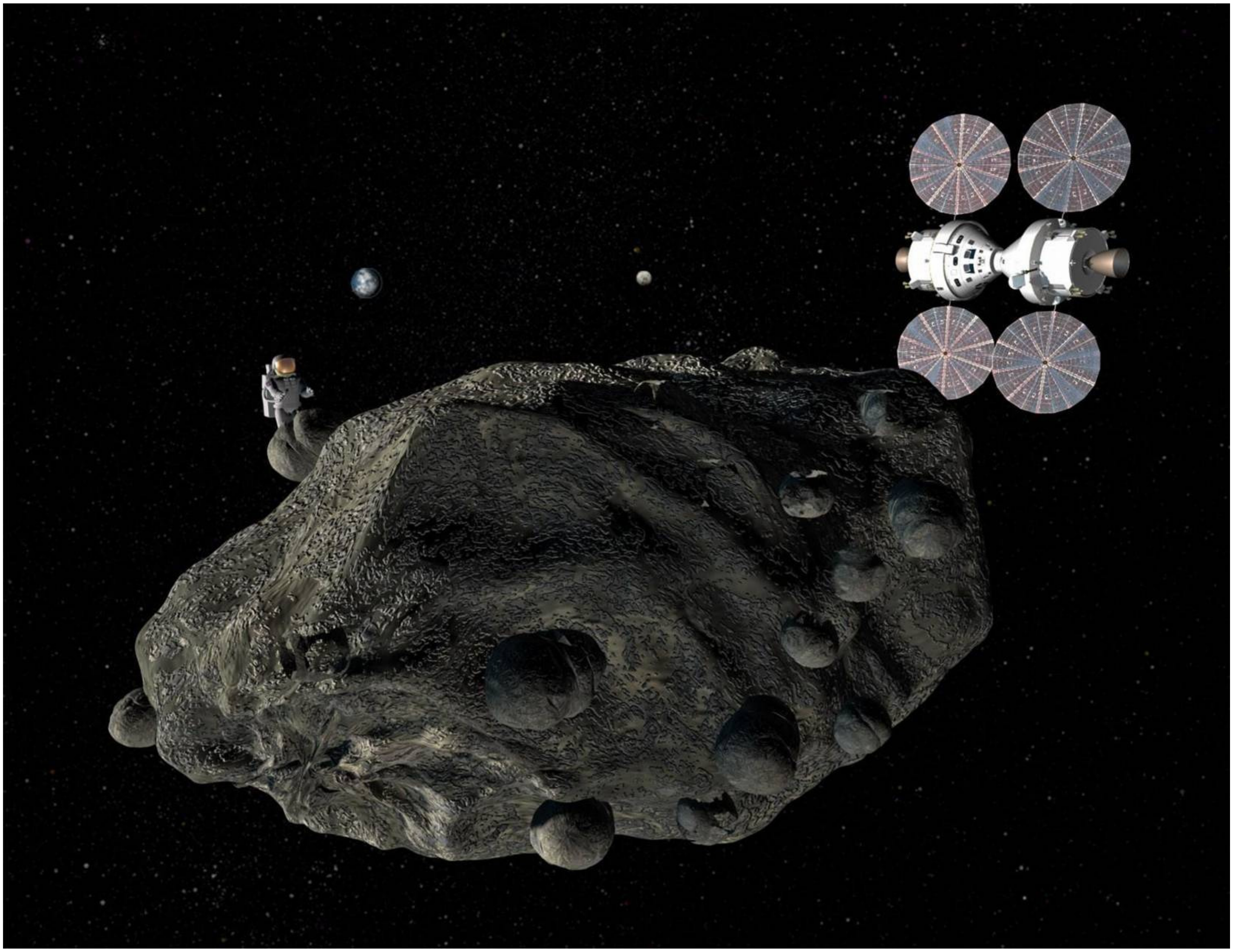

Image Credit: Lockheed Martin

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1. Executive Summary

In the last decade, the search for hazardous asteroids which might impact Earth has yielded an unexpected benefit. Astronomers have discovered a few dozen very small asteroids whose orbits around the Sun are similar to Earth's. Round trip missions to these asteroids are therefore much easier than to previously known Near Earth Asteroids, and roughly as easy as landing on the Moon. These asteroids represent a new potential destination for near-term human space exploration. Since favorable mission opportunities occur only a few times per decade, it probably would not be prudent to focus the human spaceflight program exclusively on asteroid exploration and develop new spacecraft customized for asteroid missions. Instead, asteroid exploration should be conducted in parallel with other missions such as Lagrange point visits or lunar landings, using common spacecraft designed for multiple types of missions. The authors have investigated the feasibility of conducting an asteroid mission that would complement NASA's lunar exploration architecture, using the launch vehicles and Orion spacecraft which would be used for lunar exploration. The proposed mission concept, called Plymouth Rock, combines a pair of Orion spacecraft with only modest modifications to provide the necessary propulsion, living space, and life support capability for two astronauts. Human asteroid missions have many of the same functional requirements as lunar landings, so that complementary asteroid and lunar missions may be feasible even if the lunar exploration architecture changes from the current plan.

We have concluded that the dual-Orion configuration can probably support deep space mission durations of five to six months. Longer missions are constrained by radiation exposure, volumetric packaging limits for life support consumables, and the small habitable volume available. There are at least three opportunities between 2015 and 2030 when such a mission could be performed. These occur in 2019-2020, 2028, and 2029. All of the asteroids in question are small, between 5 m and 50 m in diameter. The number of opportunities is increasing as more asteroids are discovered. A dual-Orion configuration probably represents the minimum capability necessary to perform an asteroid mission. Several additional mission opportunities to larger asteroids would be feasible for an upgraded spacecraft with a larger propulsion system. Desire for enhanced capabilities, such as a larger crew size and improved extravehicular activity (EVA) support may drive the need for a larger spacecraft. One of the two Orion spacecraft could be modified into an Orion Deep Space Vehicle with a larger habitat module suited for deep space operations rather than reentry.

By sending astronauts to explore these asteroids and bring back samples for study on Earth, we can learn about the formation and evolution of our solar system. We can improve our understanding of the threat to our planet from asteroid impacts, develop the practical knowledge needed to protect ourselves if necessary and even test this capability. We could also assess the feasibility of harnessing asteroid resources for a growing human civilization. If performed prior to the next lunar landing, a mission like Plymouth Rock can support lunar exploration plans by proving out the launch vehicles, spacecraft, and many of the operations for a lunar mission before the lunar lander is ready, much as the Apollo 8 mission did in 1968. A mission to an asteroid would also be valuable practice for a trip to Mars. Progressively more challenging asteroid missions provide an opportunity to incrementally develop expertise needed for long missions in deep space, without the leap in cost, complexity, duration, distance, and radiation exposure required for a Mars mission.

2. Introduction

In 2007 Lockheed Martin began a series of internal studies to explore how the Orion spacecraft now being built could be used besides its primary functions of transporting astronauts to the International Space Station and to the Moon. We investigated a variety of ideas, from artificial gravity test beds to satellite repair. One of the most intriguing was the potential to use Orion to explore a Near Earth Asteroid. Recently there has been increased interest in the idea of human visits to asteroids, particularly from the Review of Human Space Flight Plans Committee (known informally as the Augustine Committee). On April 15, 2010, President Obama announced that a human mission to an asteroid no later than 2025 would be one of NASA's new exploration goals. In order to contribute to the discussion on this topic, Lockheed Martin revisited our earlier studies to analyze some issues in more detail, and documented the results in this report. The work described herein was funded by Lockheed Martin and does not imply any programmatic intent or technical endorsement by NASA.

3. The Accessible Asteroids

In November 1991 astronomer Jim Scotti discovered a very small asteroid using the Spacewatch telescope at Kitt Peak. Based on the discovery date it was given the designation 1991 VG[*]. He quickly noticed that its orbit around the Sun was much more like Earth's than any other body known at the time. Other Near Earth Asteroids typically follow elliptical orbits which may approach Earth but range out towards Mars and the asteroid belt from which they came. The orbit of 1991 VG, shown in Figure 1, is nearly circular, and its average distance from the Sun is only 3% more than Earth's. Scotti and others immediately suspected that it might be a defunct spacecraft rather than an asteroid.[1] Many astronomers were initially skeptical that 1991 VG was simply a normal asteroid because objects in such orbits would make repeated close passes near Earth, and either be ejected to more distant orbits or impact our planet in less than a million years. 1991 VG must have reached its current orbit quite recently on the time scale of the solar system. Reverse propagation of the orbit showed it had last been in the vicinity of Earth in 1973, leading to speculation that perhaps it was the Titan Centaur upper stage from the launch of Helios A in 1974 (it isn't[†2]), or an S-IVB stage or Spacecraft Lunar Module Adapter panel from an early Apollo mission that had drifted into heliocentric orbit.[‡] However, the trajectory could not be matched to any known artifact.[3,4] No spectroscopic measurements which could have identified it were made before the asteroid last left Earth's vicinity in early 1992. For several years 1991 VG remained an enigma. Some thought its small size and Earth-like orbit might indicate it was material ejected from a recent crater on the Moon.[5,6] Astronomer Duncan Steel even suggested that if neither natural nor terrestrial origins were likely, then perhaps 1991

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[*] Asteroids are given provisional designations which include the year of discovery and an alphanumeric code which indicates the time period and order of discovery within that year. Eventually permanent numbers and names can be applied (e.g. 433 Eros) but in practice most small asteroids have not yet been given permanent names.

[†] Since very few large artifacts were sent on low-energy escape trajectories in the mid 1970s, this particular Centaur stage (TC-2) is often accused of masquerading as an asteroid when objects like 1991 VG are found. Nevertheless, it is innocent. It turns out that after launching the Helios A spacecraft into solar orbit the TC-2 Centaur stage was used for a series of experiments on in-flight restart of its cryogenic propulsion system. The stage performed two retro-burns which reduced its speed so that it stayed in Earth orbit, and according to US Space Command it reentered the atmosphere in December 1979. TC-2 has an airtight alibi, but its evil twin, TC-5, is still at large after launching Helios B in 1976.

[‡] Near Earth Asteroids are divided into Apollo, Amor and Aten classes depending on their orbits. One way or another 1991 VG is probably an Apollo, but it's unclear whether it is an Apollo *asteroid* or an Apollo *artifact*.

VG was an alien spacecraft.[7] Most astronomers took a more conservative approach and tentatively grouped it with the Small Earth Approachers, a then-newly identified group of small asteroids which pass near Earth but usually have much more elliptical orbits.

At the turn of the century, asteroid 2000 SG344 was discovered in a similar Earth-like orbit and again initial speculation focused on the space debris theory. However, 2000 SG344 is larger than anything humans have sent to deep space (30-45 meters across if it is as reflective as typical asteroids), so it provided the first convincing evidence that asteroids could exist in these orbits. Other discoveries followed. As of mid 2010 more than thirty similar objects have been discovered. As a result of both observational evidence and new theoretical modeling of how asteroid orbits evolve there is now a consensus that most of these objects are asteroids and not space junk. The list excludes a few deep space objects which have been positively identified as artificial, such as one dubbed J002E3 whose spectrum matches the titanium oxide pigment in white paint used on Apollo stages.

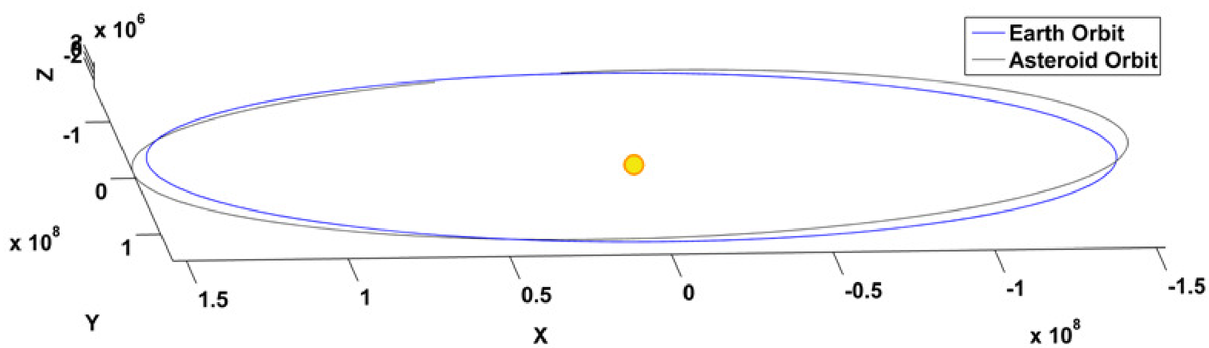

Figure 1: The Orbit of 1991 VG Nearly Matches Earth's Orbit Size and Inclination. Dimensions in km. Image Credit: Lockheed Martin

These asteroids are of particular interest for human space missions because they are the easiest objects in the solar system to visit and return from, with the possible exception of the Moon.[§] While other asteroids may occasionally come closer to Earth, such as the famous Apophis close approach in April 2029, the accessible asteroids pass Earth going nearly the same direction and speed, because their orbits are so similar to Earth's. This makes it possible to rendezvous with an asteroid and return to Earth with very low change in velocity (ΔV). The low velocity of the asteroid relative to Earth also makes it possible to visit and then return during a single conjunction, so that the mission duration is much shorter than a trip to Mars, in which the astronauts stay at Mars for 18-22 months waiting for the next return opportunity. However, since these asteroids have only been recognized very recently, their potential for human spaceflight is only beginning to be understood. The number of known asteroids in Earth-like orbits has more than quadrupled since the Vision for Space Exploration was formulated in late

[§] It's a common error to say that some asteroids are easier to get to than the Moon simply because the mission would require less ΔV than a lunar landing and return. However, ΔV is a poor measure of difficulty. In a lunar mission like Apollo or Constellation, the ΔV is not additive because the Earth return vehicle remains in lunar orbit and so no vehicle element - only the astronauts - undergoes both the lunar landing ΔV and the Earth return ΔV. In an asteroid mission, the total ΔV does apply to the return vehicle. A proper comparison of difficulty should also consider factors such as mission duration, the number of distinct spacecraft elements required, and functional complexity of the mission. Asteroid missions with ΔV only slightly lower than lunar landings may be harder due to much longer durations, but the very best asteroid opportunities do appear to be easier than lunar landing.

2003. It is likely that many more such asteroids will be discovered in the next few years as new survey telescopes such as Pan-STARRS come online. With this in mind, Lockheed Martin began a project in late 2007 to study human missions to asteroids.

The first step in such a mission study is to identify possible asteroid destinations. We have used three different filtering techniques to identify the few accessible asteroids among more than 6000 known Near Earth Asteroids. Each approach is intended only to identify candidate targets for more detailed analysis so all three techniques will catch some false positives. The simplest method is based on orbital elements and defines the population of the most easily accessible asteroids as those with orbital inclinations to the ecliptic less than 5 degrees, eccentricity less than 0.125, and semimajor axis between 0.9 and 1.1 Astronomical Unit (AU). The orbital elements of the 25 known asteroids which currently meet these orbital criteria are shown in Figure 2. Of these parameters, inclination is the most important, and near term feasible human missions probably require inclinations of less than about 2 degrees. The list of asteroids which meet these criteria is continually evolving, not only because of new discoveries, but also because close approaches near Earth or other planets can kick asteroids out of these orbits or capture new ones into favorable orbits. So, this simple filter of *current* orbit elements is less useful for planning missions more than a few decades in the future. Our second filtering technique is to identify asteroid orbits with a Tisserand parameter relative to Earth between 2.995 and 3.0. The Tisserand parameter can be used to estimate an asteroid's velocity relative to Earth, so it is better than the orbital element filter at identifying asteroids that are likely to have the necessary low approach speed. Also, the Tisserand parameter remains roughly unchanged before and after an encounter with Earth so it can be used over a longer

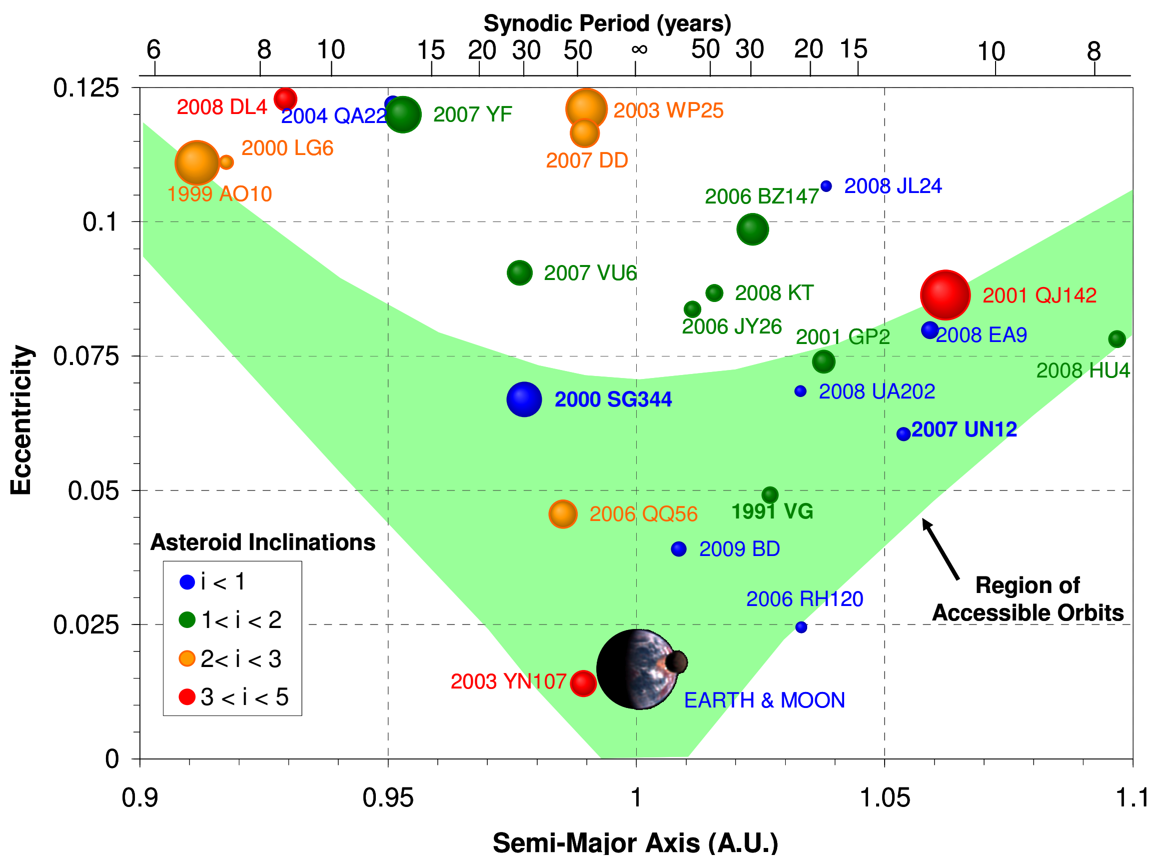

Figure 2: Orbits of Accessible Asteroids as of July 2009. Glyph Size Indicates Relative Size of Asteroids Over a Range of 5-75 m Diameter. Earth Is Not to Scale.

Figure Credit: Lockheed Martin

Earth-Moon Image Credit: Donald J. Lindler, Sigma Space Corporation/GSFC; EPOCh/DIXI Science Teams time scale to recognize asteroids which are not now in particularly favorable orbits but will shift into one after a future flyby of Earth. The region of orbits with favorable Tisserand parameters is shown as the green zone in Figure 2. The third and best technique is to select asteroids based on previously calculated close approaches to Earth. The JPL Small Body Database now provides predictions of future close asteroid approaches to Earth based on high precision orbit propagation which accounts for future orbit perturbations.[8] Asteroids which approach within about 20 million km of Earth with relative velocity less than 2.5 km/s merit closer examination. In these cases, low relative velocity is more important than a small distance at closest approach. Using these filters we identified 15 asteroids with Earth approaches between 2015-2030 for more detailed mission design analysis. End to end trajectory analysis identified the most accessible asteroids for near-term human missions, eight of which are described in Table 1. Not all of these asteroids can be reached using a dual Orion mission architecture. Mission design results are discussed in more detail in Section 8.

Table 1: Characteristics of Candidate Target Asteroids with Mission Opportunities in 2015-2030

Asteroid	Mission Year	Estimated Diameter	Orbit Semimajor Axis (AU)	Orbit Eccentricity	Orbit Inclination (deg)	Distance at Encounter (Million km)	Earth Impact Probability[9] (Next 100 yrs)
2008 HU4	2016	7-10 m	1.097	0.078	1.32	4.0 M km	-
1991 VG	2017	6-9 m	1.027	0.049	1.45	11.7 M km	-
2008 EA9	2019-20	8-12 m	1.059	0.080	0.42	12.2 M km	3 x 10^{-5} in 2068
2007 UN12	2020	5-8 m	1.054	0.060	0.23	19.2 M km	0.02% in 2075-2107
1999 AO10	2025	50-70 m	0.912	0.111	2.62	9.5 M km	-
2008 JL24	2026	4-5 m	1.038	0.107	0.55	19.6 M km	-
2006 RH120	2028	4-5 m	1.033	0.025	0.60	4.5 M km	-
2000 SG344	2029	30-45 m	0.977	0.067	0.11	8.0 M km	0.13% in 2070-71

The ideal orbit for an asteroid would have an inclination from the ecliptic of 0 degrees, and would be nearly circular (eccentricity close to 0). However, it isn't necessarily beneficial for the orbit to be the exactly the same size as Earth's (semi-major axis = 1.0 AU). The closer an asteroid's semimajor axis is to Earth's, the longer the time between close approaches to Earth. While launch windows to Jupiter (5.2 AU) occur every 13 months and to Mars (1.5 AU) every 26 months, mission opportunities are 10 to 40 years apart for many of these accessible asteroids. The asteroid 2003 YN107 has a semimajor axis of 0.99 AU but its next close approach won't occur until the year 2064.[10] As a consequence of their orbital similarity to Earth, there are only a few opportunities per decade to visit known asteroids. The number of opportunities will likely increase as more asteroids are discovered, but for now the limited number of opportunities has profound implications for asteroid mission planning. It drives the timing of a human asteroid program since it may not make sense to plan a program which provides an initial operational capability during a period such as 2021-2024 when there are no known mission opportunities. The small number of opportunities means that it may not make sense to design a spacecraft system dedicated to asteroid missions. Rather, asteroid missions would be performed occasionally by spacecraft that are also designed to perform other missions, such as going to the Moon or other deep space destinations. And finally, rare opportunities make good program management especially important. A delay in development or launch operations which causes a mission to miss its launch period by even a few weeks could postpone a mission for years.

Very little is known about the accessible asteroids. Because they are small, faint, and visible for only a few weeks or months, astronomers have not determined their spectral types, dimensions, or in most cases their rotation rates. Asteroid dimensions given in this paper are estimated from the known brightness (absolute magnitude) of the asteroid and assumptions about its albedo, so the dimensions are accurate only to within about a factor of two. All of the accessible asteroids discovered so far are quite small by the standards of the Main Belt or even the general Near Earth Asteroid population. Studies of asteroid orbital evolution as a result of perturbations from the planets suggest that the accessible asteroids are probably not from a unique source such as a lunar impact or the breakup of a single asteroid in an unusual orbit, but are normal Near Earth Asteroids whose evolving orbits become Earth-like for a few thousand years before shifting out of this accessible range. Therefore, the accessible asteroids are probably a diverse population including stony, iron, and carbonaceous objects generally similar to other observed asteroids. Other very small asteroids have been observed to rotate quickly, with rotation periods ranging from a few minutes to two hours.[11] They are therefore probably monolithic rather than loose "rubble piles" since centrifugal force would spin off loose materials. Spin rates have been measured for accessible asteroids: 2008 JL24 and 2006 RH120. Both were determined to rotate in 2 to 3 minutes. If better observation of other target asteroids shows that they too are monolithic fast rotators, that will pose challenges both for conducting EVAs near them and for removing samples from them, since they may not have loose material.

4. Reasons to explore asteroids: Security, Curiosity, and Prosperity

The Vision for Space Exploration states "The fundamental goal of this vision is to advance US scientific, security, and economic interests through a robust space exploration program."[12] An asteroid mission can address all three of these interests. Asteroids are scientifically interesting as remnants of the formation of the solar system. Unlike other objects in the solar system, they have direct implications for daily life on Earth because of the threat they pose from impacts. Asteroids therefore are also a national security issue. Asteroids have been suggested as a source of raw materials such as water or platinum group metals to supply a growing human economy. A human mission could evaluate the technical and economic feasibility of harvesting asteroid resources

Since past robotic missions have mostly been to large asteroids tens of kilometers across, it may seem anticlimactic to send the first human mission to an asteroid which is only the size of a building. However, there are good reasons to investigate smaller asteroids specifically. The small asteroids are the most numerous, and therefore are the most likely to impact Earth, the most likely to be in orbits we can reach, and the most likely to be harvested for resources. While there are estimated to be only about 1000 near Earth asteroids larger than 1 km, and perhaps 100,000 larger than 140 m, the number of 10 m sized NEOs may be as high as 10-100 million[13]. (These figures refer to the entire NEO population. The most accessible asteroids may number only a few hundred.) Asteroids in this size range are also the most likely to impact Earth, simply because there are so many more of them than the larger asteroids. There is roughly a 0.1% to 1.0% chance in any given year that a 50 m object will impact Earth, producing an explosion on the order of 1 megaton.[14,15] Determining the structure and composition of small near-Earth asteroids will have multiple practical applications for planetary defense or asteroid mining.

Security Value

Missions to asteroids would advance human knowledge required for planetary defense by addressing three gaps in our knowledge. First, astronomers could better predict the probability of asteroid impact if they better understood the small perturbations that affect asteroid trajectories, such as the Yarkovsky effect and YORP effect due to the emission of heat from the asteroid's surface. These perturbing effects are strongest on small asteroids. A mission to characterize the shape, spin state, and surface characteristics of an asteroid and tag it with a radio transponder for high precision tracking would improve the ability to predict whether other asteroids will hit Earth. Second, there is currently a large uncertainty in the destructive potential posed by a given asteroid because its mass, and therefore kinetic energy, must be inferred from its brightness by making assumptions about its size and density. Directly measuring the mass, density, composition, and possible internal voids of several asteroids would improve our future ability to determine whether a small asteroid on an impacting trajectory is actually dangerous. Finally, if it ever becomes necessary to deflect an asteroid, we will need to know more about the composition, internal makeup, and structural integrity of asteroids in order to select among several possible deflection methods. These types of measurements would be key priorities of an asteroid mission.

A decade ago the greatest asteroid impact risk was from undiscovered large asteroids which had a very low probability of impact but could cause very large amounts of damage, perhaps destroying civilization. Roughly 80-90% of the large (>1 km) Near Earth Asteroids have now been discovered and determined not to be on trajectories that impact Earth in the next century. Today the remaining threat is lower than previously thought, and is due primarily to smaller asteroids a few hundred meters across, most of which have still not been discovered. These mid-sized asteroids have a higher probability of impact than large ones because they are more numerous, but they would cause only local devastation.[16] The minimum size for asteroids to be considered dangerous is roughly 50 m in diameter. Both the Tunguska and Barringer Crater impactors are estimated to have been this size.[17,18] The specific asteroids we have identified as accessible are usually smaller than this, typically 10-40 m diameter, and are therefore considered mostly harmless. Because they are small and moving slowly compared to other asteroids, their impact energy would be low - a megaton or less - and they should break up in the upper atmosphere without doing much damage on the ground. For example, in October 2009 a small asteroid estimated to be 5-10 m across caused a 40 kiloton explosion in the upper atmosphere over Indonesia, but did no damage on the ground[**]. However, a few of the accessible asteroids are close to, or larger than, the 50 m threshold. 2000 SG344 is about 40 m across and one of the best candidates for a human visit. 1999 AO10 is probably 60-70 m across, and although it is not within reach of the Plymouth Rock mission architecture, it would be feasible to visit using an enhanced propulsion system. Several accessible asteroids have much higher than average probability of impact because they make so many close approaches to Earth. The set of accessible asteroids shown previously in Figure 2 includes four of the top five asteroids with the highest impact probability in JPL's Sentry database. Most of these are too small to be dangerous, but 2000 SG344 ranks seventh on the Palermo impact hazard scale. Past spacecraft flybys have mostly visited large asteroids several km across. Exploring smaller asteroids, whether with humans or robotic spacecraft, would improve our understanding of the objects that we are most likely to need to deflect.

Scientific Value

A crewed mission to an asteroid and the return of substantial samples would provide a dramatic increase in understanding of solar system and planetary formation. Asteroids are leftover remnants of the formation of the solar system. Their composition can teach us about how planets formed. Asteroids also created the enormous impact basins on the Moon and Mars in the early years of the solar system and have continued to influence planetary evolution through impacts and by adding water and carbon to the planets. Understanding these processes will aid our understanding of formation of other solar systems and the search for alien life.

[**] Even smaller meteorites do occasionally damage a building or total a car, but space agencies can reasonably ignore any asteroid risk which can be handled by your insurance agent.

Museums around the world have collected numerous meteorites, which are grouped into classes based on their chemical composition and structure. We know these meteorites are samples of asteroids, and asteroids are likewise grouped into families based on their spectra. However, it has proven difficult to conclusively determine which types of meteorites come from which types of asteroids. A sample return mission would allow material from a known asteroid type to be analyzed in the laboratory and would be key to correlating meteorites and asteroids. This could serve as a Rosetta stone which allows us to understand many other asteroids from their meteorites, not just the one sampled.

Economic Value

Asteroids have long been proposed as potential sources for resource extraction. Volatiles such as water could be gathered for use in space as propellant or life support supplies. Some asteroids are enriched in high-value platinum group metals[††] which might be worth the cost of transporting them to Earth if that cost can be reduced in the future. Both the cost of extracting these resources and their value once extracted are still mostly speculative. Human missions to a few asteroids could provide data to determine whether or not asteroid mining may some day be economically viable. Missions to asteroids could determine the abundance of these resources and investigate methods for operating on and near asteroids, including methods for extracting valuable material. Data on the chemical composition and geotechnical characteristics of asteroids would be as useful to engineers as to planetary scientists.

Value of Humans for Asteroid Exploration

Any human space mission should provide justification not only that the mission is worth performing, but that it is worth sending humans to perform it. Robotic missions can be simpler with a lower minimum cost threshold and don't expose astronauts to danger. Also, a much larger fraction of the asteroid population is accessible using robotic spacecraft, so scientists planning robotic missions can choose the most interesting asteroids to visit, while the targets for human missions will be chosen primarily for their accessibility with scientific goals as secondary criteria. Because of the diversity of asteroid sizes and types, it makes sense to send multiple robotic spacecraft to explore and characterize the population. But human abilities to operate in complex environments and react to unexpected situations still far exceed the capabilities of remotely operated machines. If the spin rate and complex gravity fields of asteroids make them difficult for remotely operated spacecraft to navigate, if they are geologically diverse, or if exploring them requires challenging operations such as drilling core samples or anchoring experiment packages on the asteroid, then developing advanced robotic spacecraft with these capabilities becomes quite expensive. A human mission can explore a small number of asteroids much more thoroughly than robotic missions and return many more samples. Robotic sample return missions typically return a few grams to a few kilograms of samples, whereas Orion is designed to return 100 kg of samples. It may therefore make sense to complement lower cost robotic exploration of the broad asteroid population with a few high value human missions.

Beyond the science objectives, a human asteroid mission can contribute in ways robotic missions cannot as an intermediate development step towards other exploration destinations such as the Moon or Mars. If performed prior to the first lunar return, an asteroid mission using

[††] The platinum group metals include iridium, osmium, rhodium and others. On Earth these metals mostly sank to the planet's core and are rare in the crust. Since some asteroids come from the cores of small differentiated proto-planets, they contain more of these metals. The discovery of a layer of rock enriched in iridium at the end of the Cretaceous period (the "iridium anomaly") was one early piece of evidence that an asteroid impact killed off the dinosaurs.

the same lunar exploration spacecraft and rockets can provide substantial risk reduction to the lunar exploration systems prior to the availability of the lunar lander. An asteroid mission would validate aspects of the lunar mission architecture including the launch profile and low Earth orbit (LEO) rendezvous, an Earth escape maneuver analogous to trans-lunar injection, and Orion reentry at lunar-like entry conditions. As a Mars mission precursor, an asteroid mission offers an opportunity to learn how to perform long duration missions in deep space beyond Earth's magnetosphere, without making the jump to multi-year Mars missions. Developing and performing an asteroid mission would provide experience with human mission operations affected by speed of light lag (on the order of 1-2 minutes), deep space radiation environments, and designing human missions without resupply or rapid return in contingencies. Since there is a large variety of asteroids in different orbits, an asteroid exploration program could explore progressively more difficult asteroids on longer and more distant missions to gradually build up to the capabilities needed to reach Mars.

5. Mission Concept

The fundamental requirements for a human mission to one of the accessible asteroids can be summarized as follows:

- A launch system and injection stage capable of delivering the spacecraft to an Earth escape trajectory with a C3 in the range of 1 to 5 km^2/s^2. This is an energy level just slightly above Earth escape velocity (C3 =0) or translunar injection (C3 = -1.8 km^2/s^2).
- Spacecraft capable of operating in deep space for a mission duration of 4-7 months.
- Sufficient habitable volume and life support consumables to support at least two astronauts and preferably three during this duration.
- A spacecraft propulsion system with at least 1.5 km/s of ΔV capability for major maneuvers in deep space. The propellants must be stored in space for months before the maneuvers take place. Very low-thrust propulsion (e.g. solar-electric ion or arcjet thrusters) is precluded by mission duration constraints.
- The ability to support at least one spacewalk at the asteroid.
- Reentry system capable of handling entry velocities of at least 11.1 km/s or higher.

An Orion spacecraft is one logical building block for a human deep space mission, in particular to perform the launch and reentry phases of the mission. Initially, we investigated an asteroid mission concept using Orion alone. However, a single Orion does not have enough habitable volume, life support consumables, or propulsive impulse to meet the mission requirements. Other studies of human missions to asteroids have therefore included additional spacecraft elements designed specifically for asteroid missions, or replaced Orion with an altogether different spacecraft. These approaches are possible, but we felt the development cost of either approach may make them impractical, especially since suitable mission opportunities occur infrequently. Instead, we sought a lower cost solution. The key feature of the Plymouth Rock mission is the use of a second Orion spacecraft to provide the additional capacity needed. A second Orion provides more pressurized cabin volume, life support, and storable propulsion. A second Orion is not as lightweight or capable as a dedicated new deep space spacecraft might be, but a pair of Orions provide just enough capability to perform a minimalist asteroid mission during the most favorable orbital alignments. A pair of Orions should be less expensive to develop than a new spacecraft, can be ready earlier, and provides substantial safety benefits by virtue of vehicle-level redundancy. One possible variation is to modify the crew module of the second Orion to increase its volume and life support capability, at the cost of giving up redundant return capability.

It may at first seem more logical to supplement Orion with a lunar lander such as Constellation's Altair, rather than a second Orion. The Altair descent module propulsion system has high Isp and very large total impulse, and Altair has an airlock. However, Altair is less suited than Orion for long duration missions. As presently conceived, Altair is designed to operate only for short durations, with limited life support capability. For example, it uses fuel cells for power instead of solar arrays. Also, the descent stage uses cryogenic LOX/LH_2 propellants which would boil off during the multi-month trip to the asteroid. The landing gear on a lunar lander are not useful for an asteroid mission, since the spacecraft won't really 'land' on such a small body. One of the strongest reasons to consider a dual-Orion asteroid mission configuration rather than an Orion-Altair approach is that the dual Orion mission can be performed before a lunar lander is developed. However, because Altair does have attractive features, its suitability should be reconsidered if its development progresses. If propellant boil off can be reduced to about 0.25% per day or less, or if asteroid missions are identified with short outbound durations, then Altair's propulsion capabilities could enable an Altair/Orion combination to reach asteroids that are too difficult for the dual Orion configuration.

The Plymouth Rock mission concept, shown in Figure 3, is similar to the Constellation lunar mission profile, substituting the second Orion for Altair, and an asteroid as the destination rather than the Moon. A heavy lift launch vehicle would deliver the Earth Departure Stage (EDS) and the Supplemental Orion to low Earth orbit without crew on board. A second launch using either an Ares I or a Delta IV rocket would deliver the crew in the Primary Orion. The Primary Orion would rendezvous and dock to the Supplemental Orion and EDS in Low Earth Orbit. The EDS would then fire to send both spacecraft out of Earth orbit into deep space. Upon approach to the target asteroid, the Supplemental Orion would use its Service Module propulsion system to match velocity with the asteroid. After several days exploring the asteroid, the astronauts would jettison the now-empty Supplemental Orion and use the Primary Orion's propulsion system to return to Earth.

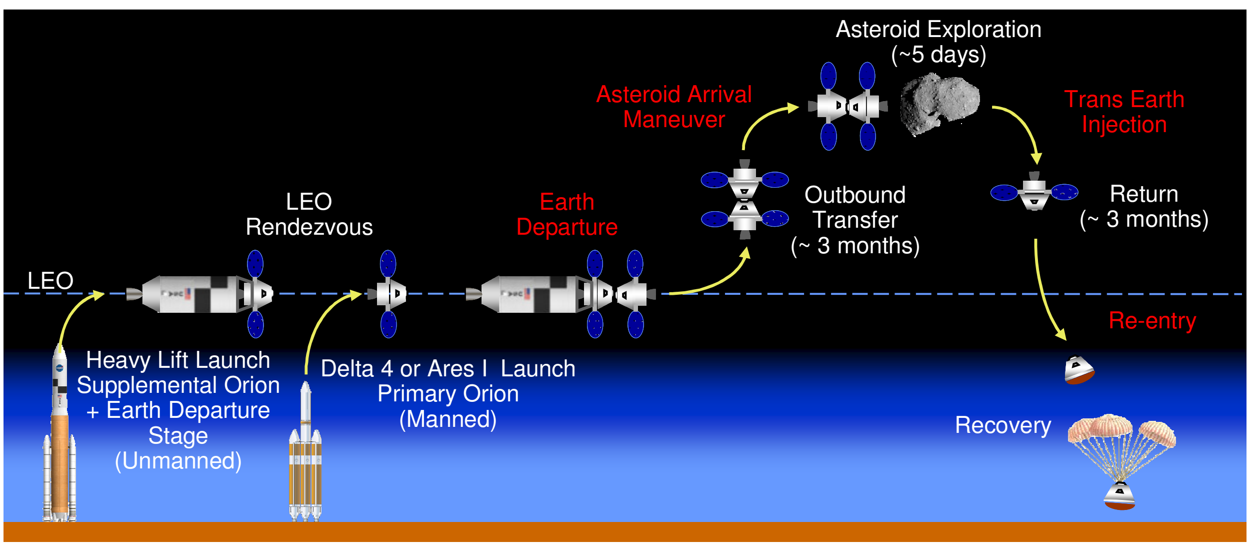

Figure 3: Dual-Orion Configuration for Asteroid Exploration Uses the Same Spacecraft and Launch Vehicles Planned for Lunar Missions. Image Credit: Lockheed Martin

The Plymouth Rock mission architecture described here is based on the current Constellation architecture because it is intended to complement a lunar exploration program, not replace it. However, the Constellation lunar mission architecture and launch vehicles are currently being reviewed and may change in the future. Should NASA change its exploration architecture, Plymouth Rock can be modified accordingly. The total system mass and many of the top level requirements for an asteroid mission are similar to a lunar mission, so it is likely that other lunar exploration architectures would also be capable of supporting asteroid missions.

6. Spacecraft Capabilities

The Orion spacecraft being developed for lunar missions has the capability to support a basic asteroid mission with some enhancements. Requirements, applicable capabilities, and necessary modifications are discussed in detail below.

Orion Overview

Orion consists of four major elements, show in Figure 4. The Launch Abort System (LAS) at the top is designed to pull the spacecraft away from launch vehicle in the event of an emergency during ascent. The conical Crew Module (CM) contains the pressurized living space for the astronauts, as well as most of the vehicle avionics. The Crew Module is the element which returns the crew to Earth, using a heat shield and parachutes. The CM has a docking adapter at the top to connect to other spacecraft. Below the crew capsule is the Service Module (SM) which provides most of the utility functions on the spacecraft. It contains the propellant tanks and main engine for propulsion, the tanks of water and oxygen for life support, solar arrays for power, a thermal control fluid loop with radiators to cool the capsule, and an antenna for long distance communication. A Spacecraft Adapter connects Orion to its launch vehicle. External jettisoned panels cover the solar arrays, radiators and thrusters during ascent.

Cabin Volume

The net habitable volume of the Crew Module is defined as the amount of open space in the crew cabin in which people could function. It is smaller than the total pressurized volume because it excludes space taken up by objects inside the pressure vessel such as subsystems and supplies. For long missions, NASA human factors standards recommend 9-10 m^3 of habitable volume per person as the "performance limit" and up to 20 m^3 per person is suggested as optimal.[19] Recommended volume as a function of duration is shown in Figure 5, taken from NASA STD-3000 Fig 8.6.2.1-1. A single Orion has about 9-10 m^3 of net habitable volume when configured for the lunar mission[20] – enough for only one astronaut on a long duration mission. This is one of the most pressing reasons why a single Orion is not sufficient for a long-duration mission. A pair of Orions can accommodate two astronauts, which is a more reasonable crew size for this mission. (For a six month mission the available volume in the spacecraft is reduced by about 2 m^3 taken up by

Figure 4: The Orion Spacecraft. From top, Launch Abort System, Crew Module, Service Module, Spacecraft Adapter.
Image Credit: Lockheed Martin

additional food and water, but some volume is freed up by the reduction in the number of seats and other equipment for the smaller crew complement). On the return trip, the Supplemental Orion is jettisoned, limiting the crew to about 4 m^3 per person in the Primary Orion. This is at the "tolerable limit" for a 90 day return trip, but meets the more comfortable "performance limit" if the return duration is 45 days or less. For comparison, 4-5 m^3 is comparable to the internal volume of a modern American minivan with its seats removed. This is much less volume than has been available to astronauts and cosmonauts on space station missions of comparable duration, but more room than has been available on some shorter free-flight missions. During the Apollo 7 mission (the longest Apollo mission without a lunar lander) the crew lived in under 2 m^3 per person for 11 days. The crew of Soyuz 9 spent 18 days in about 3 m^3 per person.[21] Gemini 7 made both flights seem spacious by comparison, but represents an extreme we hesitate even to compare to.

Determining the suitability of a given spacecraft volume is an inexact science especially for long missions. It is best done using real people in full-scale mockups rather than the parametrics and historical comparisons described previously. If it is determined that the dual Orion capsules provide insufficient living space, one solution would be to add a small pressurized module between the two spacecraft. Such a module could weigh as little as two to three tons (excluding the supplies which would be stowed inside it), and would be launched pre-mated to the top of the Supplemental Orion on the heavy lift launch vehicle. Its added volume would be especially useful during the return segment of the mission. Because this module would provide only living and storage space, and would not be required to generate its own power or provide life support or control functions, it would be relatively simple and inexpensive, comparable in complexity to a SpaceHab module or ISS Multi-Purpose Logistics Module. It might be a logical contribution for an international partner nation or commercial company interested in participating in the mission. Another alternative is to modify the second Orion to increase living space. This option is discussed in more detail below.

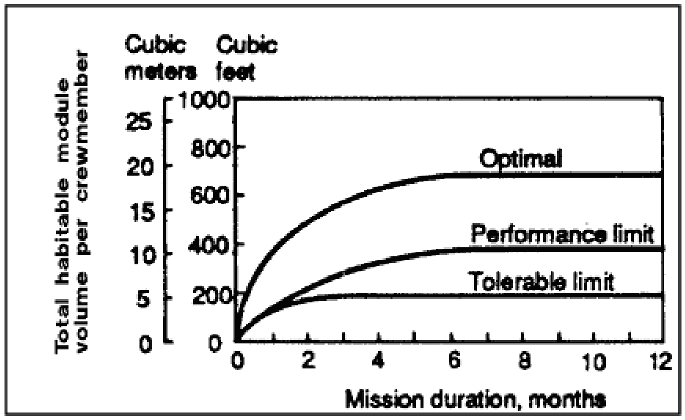

Figure 5: Habitable Volume Required Per Person, from NASA STD 3000 Image Credit: NASA

Mission Duration

Unlike Apollo or the Space Shuttle, the Orion spacecraft includes design features which support long missions, such as solar arrays rather than fuel cells for power, and regenerative amine beds rather than single-use lithium hydroxide canisters to remove CO_2. Orion is designed to support four astronauts for 18 days going to and from the Moon, with a 180 day unoccupied period in lunar orbit while the astronauts are at the lunar outpost, plus 30 days of contingency loiter capability for a mission extension. This built-in long duration capability is a critical enabler for an asteroid mission. Orion hardware is already designed for the same mission duration needed for an asteroid mission, addressing issues such as reliability, leak rates, hardware radiation tolerance, and micrometeoroid protection. Micrometeoroid and orbital debris (MMOD) protection has turned out to be one of the most challenging requirements to meet for long duration missions, since longer missions have higher cumulative probability of impacts. The Orion program has used extensive computational modeling to determine the effects of debris impact on thousands of different parts in 480 different regions of the spacecraft. The computer models are based on data from hypervelocity impact tests of the specific materials and configurations used on Orion. These tests resulted in a number of design changes to improve Orion's robustness, which are tailored depending on the mission environment and duration[22]. Kevlar/foam blankets are wrapped around propellant tanks and high-pressure oxygen and helium tanks, as well as the most vulnerable propellant lines. Radiator lines, exposed backshell thermal protection tiles, and some secondary structures are thickened to better withstand impacts. The outer surface of the service module extends forward to protect the exposed shoulder (the rounded corner) of the capsule heat shield. With these features Orion meets stringent MMOD requirements for the long duration lunar outpost mission. Since the micrometeroid environment for the asteroid mission is enveloped by the design environments for the lunar mission and ISS mission, we expect that Orion could meet MMOD safety requirements for asteroid visits as well.

The primary mission duration difference for an asteroid mission is that Orion has not been designed to be occupied for the full duration. The preliminary feasibility evaluation suggests it should be possible for a pair of Orions to support continuously occupied crewed missions of up to 6 months (180 days). Missions up to 7 months (210 days) might be feasible but packaging volume limitations become more challenging and must be analyzed in more detail.

Life Support

Despite Orion's long duration capability, a five to seven month mission requires more food, water, oxygen, and nitrogen than Orion is presently designed for. Reducing the crew size from four to two astronauts and pairing up two spacecraft quadruples the number of days the astronauts can be supported, to approximately 80 days. A further factor of 2 to 2.5 increase in consumables is required for a 6 month class mission. We evaluated ECLSS consumables for several mission durations using the consumption rate allocations shown in Table 2.[23] These calculations are based on Orion's baseline open-loop life support system. While a closed loop system would result in lower masses for supplies on long trips, its hardware would be heavier and it would be more complex and therefore less reliable. We expect that an open loop system is preferable for trips up to six months, but this should be investigated more carefully. Sufficient oxygen and nitrogen were included to perform two cabin depressurization/repressurization cycles for EVAs. We followed most Constellation program design practices for failed tanks, cabin leaks, and other contingency scenarios. However, Constellation has one requirement which can't be applied to an asteroid mission - to survive a cabin pressurization failure by returning from the Moon rapidly enough for astronauts to be able to stay in their spacesuits until landing. One goal of the dual-Orion approach was to provide redundancy for either spacecraft to perform the return in the event of a failure by the other. So, we sized the oxygen supply so that consumption is drawn from both spacecraft equally during the outbound leg and either spacecraft has enough oxygen to support a 90 day emergency return up to the time they reach the asteroid. This means that whichever Orion is jettisoned still has significant quantities of oxygen remaining in its tanks. There is no existing system on Orion which could transfer oxygen from the jettisoned spacecraft to the primary

Table 2: Life Support Commodity Consumption and Waste Production Rates

Rate (kg per person per day)	Nominal	Faulted
Food	1.83	1.83
Water	2.70	1.50
Oxygen	0.82	0.72
Nitrogen	0.06	0.06
Fecal Waste (production)	0.30	0.30

Table 3: Life Support Consumables Required for Two-Person Missions of Various Durations

	120 Day	150 Day	180 Day	210 Day
Water	698 kg	868 kg	1037 kg	1207 kg
Nitrogen	79 kg	86 kg	86 kg	86 kg
Oxygen	391 kg	454 kg	489 kg	542 kg
Food	450 kg	560 kg	670 kg	779 kg
TOTAL	**1618 kg**	**1967 kg**	**2282 kg**	**2615 kg**

Orion for return and so we have oversized the oxygen system compared to the nominal requirement. An oxygen transfer system would be a logical upgrade. Food and some water can be stored in the cabin and we assumed these could be transferred from a failed Orion into the returning vehicle in the event of a mission abort, so that surplus food and water were not required for aborts. Based on these assumptions, we computed the masses for required consumables shown in Table 3.

We also accounted for hardware to store these commodities (the storage tanks are almost as heavy as the supplies they contain) and addressed high-level packaging and layout concepts. The allocation of mass between the Primary and Supplemental Orions are driven by two requirements. First, since the Primary Orion launches with crew on board, its Crew Module mass at launch and at landing is limited to the current nominal mass. Exceeding the current design mass would require redesign of the launch abort system and the parachute landing system, both of which would be expensive. Second, the total spacecraft mass including the Service Module was assumed to be limited to the same launch mass as the Orion lunar mission, so that it could be launched on Ares I. Any increase in mass due to consumables must be offset by reducing the propellant load. Using a different launch architecture could relax this constraint. The Supplemental Orion is launched on a heavy lift vehicle without crew on board, so it is not subject to either of these mass limits and is the logical choice to carry most of the additional mass. Therefore, the only extra commodities added to the Primary Orion at launch are its full share of oxygen and nitrogen, since these can not be easily transferred between spacecraft. The Primary Orion would be launched with its normal capacity of water in the SM (roughly half its share or a quarter of the total for a 180 day mission) and a few days worth of food. The Primary Orion's share of extra water and nearly all of the food would be launched in the cabin of the Supplemental Orion and could be transferred between the spacecraft after rendezvous in orbit. The Supplemental Orion carries its half of the water, oxygen, and nitrogen in tanks in the Service Module.

Based on an initial packaging assessment, the Orion SM can probably accommodate additional standard water tanks sufficient for up to 180 day missions and perhaps 210 day missions by rearranging some existing hardware. Since the nitrogen budget is mostly driven by leak rates and contingencies and not by metabolic consumption the amounts required are not much more than the current design and could be readily accommodated. Oxygen tanks are more problematic, since the volume required is large and design rules require more protection from micrometeoroids for these high pressure containers than for the water tanks. Presently these oxygen and nitrogen tanks are located around the inside of the avionics ring of the Service Module where they are well protected (see Figure 4). It may be possible to accommodate enough oxygen by using different sizes and shapes of tanks in different locations to fit the space available, and by locating some of the tanks in areas closer to the vehicle skin which are less protected from micrometeoroids. Another approach would be to reduce the extra oxygen carried for abort return either by relaxing this design objective or by developing a system for oxygen transfer between the two Orion spacecraft. This would eliminate one or two oxygen tanks from each spacecraft. Such a transfer capability would also be beneficial for ISS and lunar missions. For all commodities, adding tanks has additional impacts, such as adding telemetry channels and heaters, and possibly causing changes in supporting structure. These issues are recognized but have not been addressed in this study.

The pressurized volume available in the Crew Module of the Supplemental Orion is sufficiently large to store the food and water allocated to it at launch. Food containers would take up roughly 10% of the habitable volume of the Supplemental Orion depending on mission duration, and could be mounted to the structural backbone in place of some of the crew seats. Orion is designed to carry both crew and cargo and has plentiful structural hardpoints for attaching cargo containers. Volumetric constraints are more challenging for the return trip when only one Orion is used, and packaging during this phase must be investigated further. For example, waste management may pose a packaging challenge for the return trip. Orion is capable of venting liquids overboard, but has no external dump capability for solid waste. Trash and human waste can be collected in the Supplemental Orion for disposal when the extra Orion is left behind at the midpoint of the mission. However, any waste generated during the return trip will remain in the primary Orion until landing. Containers for waste will total about 0.5 m^3 for a 90 day return trip. Internal packaging is one reason to limit the total mission duration to six months or less and in particular to minimize the duration of the return leg of the trip.

Propulsion

Orion is equipped with a main engine burning MMH and N_2O_4 propellants. The propellants are space-storable and the propulsion system is capable of multiple restarts. The propellant tanks on Orion are sized for a worst case lunar landing site location, lunar orbital geometry, and abort requirements, based on analyzing more than 2 million different trajectory cases[24]. However, loading all the propellant required for these worst case scenarios would exceed the performance capability of Ares I. Therefore, the nominal propellant loaded for a lunar mission is computed from a less stringent set of cases and is slightly lower than the full tank capacity. Two scenarios are considered in this study. In one, the launch mass of the Primary Orion is limited to the current performance of Ares I, in which case additional propellant must be offloaded to compensate for added mass of life support commodities. In the other case, it is assumed that the Primary Orion propellant tanks can be fully loaded, either due to performance improvements in Ares I or the use of a different launch vehicle such as the more powerful Delta IV Heavy. In either case we assume the tanks of the Supplemental Orion will be fully loaded because it is launched on a heavy lift system. After accounting for the mass of the modifications and extra consumables described above, we estimate that the dual Orion combination has the following ΔV capabilities for primary maneuvers after Earth departure.

- Supplemental Orion: 690 m/s when pushing the Primary Orion
- Primary Orion if launch mass is limited to Ares I performance: 990 m/s after jettison of Secondary Orion
- Primary Orion if tanks are fully loaded (not limited to Ares I performance): 1120 m/s

These values exclude the propellant consumed by the Primary Orion to reach low Earth Orbit and rendezvous with the Supplementary Orion, and the propellant allocated to RCS use, reserves, multi-day launch period coverage, and unusable residuals, all of which are accounted for separately. Ideally the required ΔV for the asteroid arrival maneuver would match the capability of the Supplemental Orion, but in practice the Primary Orion may have to perform part of the arrival maneuver, and thus push the mass of both vehicles. In this case, ΔV can be shifted from the Trans-Earth Injection maneuver to the Asteroid Arrival Maneuver at a ratio of 0.6:1. For example, using the Primary Orion to perform 60 m/s of the Asteroid Arrival Maneuver when both spacecraft are attached would reduce its capability to perform the Trans-Earth Injection burn flying alone by 100 m/s.

The engine thrust to vehicle weight ratio of the dual Orion configuration is sufficient for all deep space maneuvers. The Orion main engine thrust level of 33 kN (7500 lbf) is actually driven by ascent abort requirements rather than nominal maneuvers. During a launch abort late in ascent during ISS missions, Orion is required to have sufficient thrust to push its landing point away from the middle of the North Atlantic Ocean and either back towards Newfoundland or downrange to Ireland in order to ensure that the crew lands within range of land-based rescue forces. The thrust level required to adjust the trajectory prior to reorienting for reentry exceeds the thrust required for major in-space maneuvers. We have briefly investigated the possibility of using lower thrust electric propulsion, such as high-power arcjets, to increase the ∆V capability of Orion, but at any reasonable power level the thrust is too low and the trip time increases.

Reentry

Spacecraft designed for lunar return experience inertial velocities at atmosphere entry of about 11 km/s. The Apollo thermal protection system (TPS) was designed to a requirement for an entry inertial velocity of 11,074 m/s at atmospheric entry interface altitude of 122 km (400,000 ft), and the highest entry speed actually flown was 11,139 m/s on the unmanned Apollo 4 test.[25] This range brackets the minimum possible entry inertial velocity for a vehicle returning from beyond Earth's sphere of influence. The most benign asteroid missions have inertial reentry speeds of about 11.1-11.2 km/s. For comparison, entry speeds for LEO missions are on the order of 8 km/s, Earth returns from Mars missions will be in the range of 11.75 – 12.0 km/s or higher, and the fastest Earth entry velocity to date was the tiny Stardust capsule at 12.9 km/s.

Orion is capable of reentry at just over 11 km/s inertial velocity but the absolute upper limit of its reentry capability has not been defined. Orion is also designed to reach a coastal landing zone near San Diego during any time in the lunar cycle, in order to reduce the cost of recovery operations. Depending on the position of the Moon, this sometimes means that Orion must perform a skipping reentry to reach the landing site, which increases the total heat load during reentry. Though asteroid missions will have slightly higher inertial velocities, the thermal environments can be kept within Orion limits using two techniques. First, a shorter skip distance during reentry reduces heating. Second, the direction of flight can be selected to reduce heating. The relevant parameter for sizing TPS is not actually the inertial velocity, but rather the velocity of the spacecraft relative to the atmosphere, which is rotating along with the rest of the Earth. The asteroid mission reentry trajectory can be targeted to fly nearly due East, aligned with Earth's rotation, which reduces the airspeed. We estimate that Orion can withstand reentry inertial velocities of at least 11.4 km/s using appropriate trajectory shaping, but much more analysis is needed on this topic. At the upper end of this velocity range some landing site flexibility would be sacrificed and recovery near San Diego would not be feasible at all times. Lower velocity returns typical of the missions we have selected (11.15-11.2 km/s) should be compatible with US coastal landing.

For the Plymouth Rock dual-Orion mission architecture, mission opportunities are constrained mainly by propulsion and mission duration limits and not by the entry velocity limit. Some higher ∆V asteroid mission opportunities have entry velocities of up to 11.7 km/s, so an asteroid mission spacecraft with greater propulsion capability for more challenging asteroid missions might also need enhanced thermal protection. For higher reentry velocities, crew tolerance to higher g loading must also be considered.

Orion Enhancements for Deep Space Missions

The initial dual Orion concept for Plymouth Rock should meet basic mission requirements but is marginal in several aspects. Living space is very tight, packaging additional life support commodities is challenging, external stowage for EVA equipment and science is limited, and the low ∆V capability of the system limits the number of accessible asteroids. We have therefore considered enhancements to Orion which would increase capabilities for deep space missions.

In the basic mission concept the Crew Module of the Supplemental Orion would retain the heat shield, parachutes and other landing systems to provide a redundant return capability, even though nominally they would never be used. Alternatively, we have considered replacing the second Orion with a variant called the Orion Deep Space Vehicle which gives up reentry capability in favor of improved capability for extended missions. Removing subsystems needed only for reentry (thermal protection, landing systems, crew seats and impact attenuation, CM propulsion) reduces the mass of its Crew Module by several thousand pounds. Since the outer shape does not need to be aerodynamic, the crew cabin can be enlarged and life support supplies can be packaged outside the cabin rather than squeezed into the Service Module. Figure 6 shows a modified Crew Module design in which the crew cabin's upper conical section and docking tunnel are replaced with an extension of the cylindrical lower section at the same constant diameter. This modified module has about two thirds more pressurized volume than the standard capsule, but more than twice as much Net Habitable Volume because the internal systems do not increase in size. Although it is larger, the longer cabin structure actually weighs less than the standard structure because it does not need to withstand landing impact or launch abort loads. There is also room for external attachment of the EVA equipment and science payloads so that Orion can better support spacewalks at the asteroid, shown in Figure 7. Increased living space and storage for life support supplies would enable the Orion Deep Space Vehicle to support three, rather than two, astronauts for some of the lowest ΔV mission

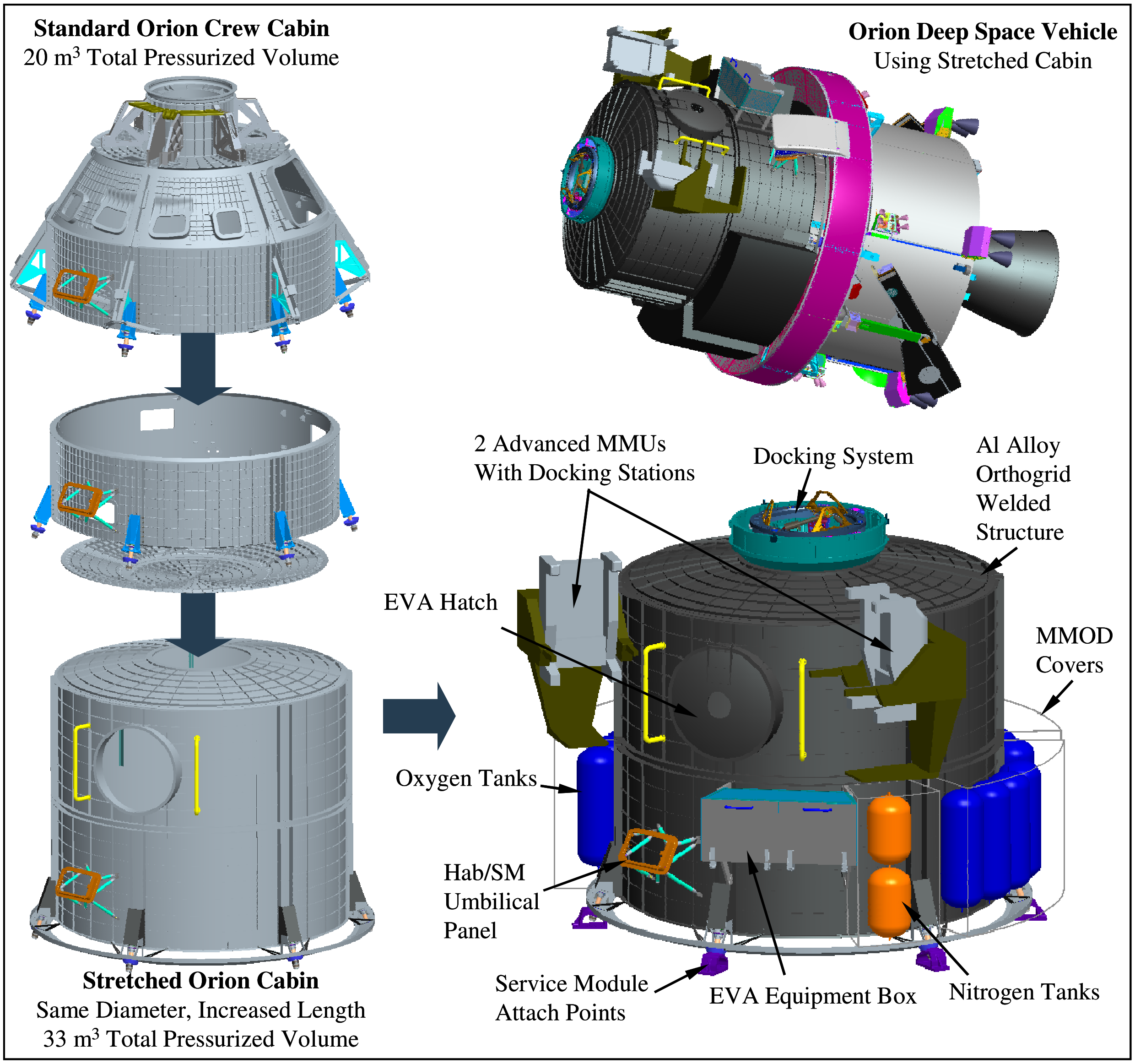

Figure 6: Orion Deep Space Vehicle with Larger Crew Cabin Image Credit: Lockheed Martin

opportunities, assuming that the crew module is retained during the return trip and only the Service Module is jettisoned from the Supplemental Orion. A small trash disposal airlock similar to the one on Skylab would be increase usable space during the return trip. Though the outward appearance of the Orion Deep Space Vehicle is very different from the standard Orion, it would share many internal systems, such as avionics, life support, and crew systems, and the Service Module would be essentially the same. For example, the oxygen and nitrogen tanks shown outside the habitat module are the same type used in the Orion Service Module today. The Orion Deep Space Vehicle provides an affordable way to enhance Plymouth Rock’s capability but at the cost of giving up redundant reentry capability.

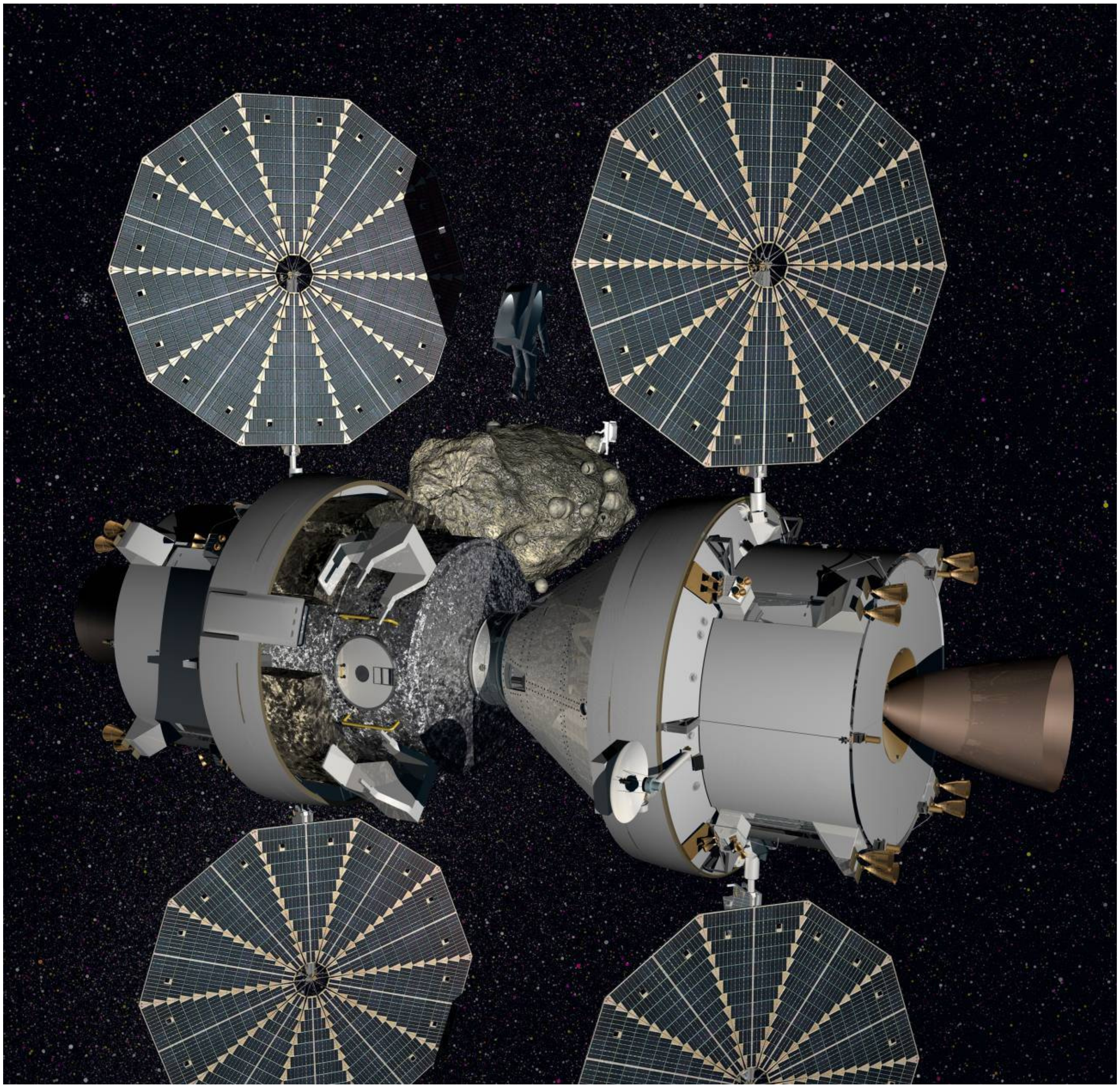

Figure 7: Orion Deep Space Vehicle Provides Better Capability for Spacewalks
Image Credit: Lockheed Martin

Another way to improve mission capabilities would be to upgrade the Orion Service Module propulsion system. The most useful improvement would be an increase in the tank size and propellant load. We have examined either stretching the tanks of the current 4-tank SM, or designing a larger 6-tank SM. The 6-tank approach is more effective, but requires a major redesign of the service module and the resulting spacecraft would be too heavy to launch on either an Ares I or Delta IV Heavy launch vehicle.

7. Launch Systems

The projected mass of the combined Orion spacecraft configured for an asteroid mission is between 43 and 47 metric tons depending on mission duration and other variables. This mass must be delivered to a C3 of 0 to 5 km^2/s^2 for the opportunities being considered. The mission lift requirement is very similar to the Apollo / Saturn V mission. Several possible launch approaches are feasible. For example, the Constellation architecture uses a so-called "1.5 launch" approach, combining one very heavy lift launch vehicle, Ares V, with a smaller launch vehicle, Ares I. The combination of an Ares V and Ares I is projected to have more than enough performance to deliver a pair of Orions to the desired Earth escape trajectory. The Ares V alone should be able to deliver 45 tons to a C3 of about 12 km^2/s^2.[26] So, a single launch mission would be possible in this scenario. However, to avoid modifying the Ares V for human launches, a Plymouth Rock mission using Constellation launch vehicles would likely launch the crew separately on an Ares I, as is planned for lunar missions. It would be erroneous to count any extra ΔV capability from these launch vehicles as being available for the Asteroid Arrival maneuver or Trans-Earth Injection, since the Earth Departure Stage is not designed for multi-month durations and would be jettisoned shortly after the Earth escape burn.

Other launch possibilities are also feasible. Simple variations on the Constellation baseline would be to maintain the 1.5 launch approach but use an existing Delta IV Heavy launch vehicle in place of Ares I, or a slightly smaller heavy lift system in place of Ares V. Another approach would be to use two identical launch vehicles of intermediate capacity. Each rocket would launch one of the Orion spacecraft with a cryogenic propulsion stage. The two Orion spacecraft would rendezvous in low Earth Orbit and use both propulsion stages instead of one larger stage to reach escape velocity. Launch vehicles with a capacity of about 55-60 tons to low Earth orbit would be sufficient to perform the mission this way. A launch approach with smaller, existing rockets may also be feasible using multiple propellant tankers or a propellant depot to fuel an Earth Departure Stage. The Plymouth Rock mission requires less than half the cryogenic propellant delivered to orbit that the Constellation lunar mission does. It would therefore be less difficult for a depot architecture than a lunar mission, with fewer launches and tanker spacecraft required and less boiloff due to the shorter assembly duration. However, a depot in an arbitrary LEO orbit plane will only be properly aligned for departure to an asteroid about once every three weeks due to orbit precession. This is potentially longer than the practical launch period. So, an asteroid mission may require a dedicated depot in a mission-specific orbit, rather than using a facility shared by other missions. Propellant depots at lunar Lagrange points have similar orbital geometry constrains. The depot architecture must be studied further to determine whether it is practical for an asteroid mission.

There is one area of possible risk for launch system performance. Missions in which the asteroid rendezvous takes place well above or below the ecliptic plane require that the Earth departure trajectory have a high declination (angle relative to the equator). In some cases, this requires that the LEO park orbit have an inclination greater than the maximum performance 28.5 degree orbit which corresponds to launching east from Cape Canaveral. For example, the minimum ΔV trajectory to asteroid 1999 AO10 launching in late August of 2025 requires an Earth parking orbit with an inclination greater than 50 degrees. The reduced performance of the crew launch vehicle to higher inclination park orbits would likely require that the Primary Orion be launched with less propellant, thus reducing the ∆V available for the Trans-Earth Injection (TEI) maneuver. Also, launches from Kennedy Space Center are limited to inclinations below about 55 degrees for range safety reasons, which would make some high-declination departure opportunities infeasible. Missions to 1999 AO10 departing a few weeks later have higher in-space ∆V requirements but can use lower inclination LEO park orbits. So, finding a true performance-optimum mission design will require trading the departure date, park orbit inclination, launch vehicle performance, and mission ∆V requirements.

8. Asteroid Mission Trajectories

The specific architecture proposed for the Plymouth Rock mission has some unusual implications for mission design. Because we propose to use pre-defined spacecraft, both the overall mass of the spacecraft and their propulsion capabilities are approximately fixed. Designing the mission then becomes a task of constraining the trajectory to match the required ∆Vs to the capabilities of the spacecraft, rather than optimizing the trajectory and determining how large the spacecraft would need to be. The Ares V has more than enough performance to deliver the dual Orions to the Earth escape trajectories identified for all of the cases studied. Therefore, if an Ares V or similar launch vehicle is used, the Earth escape C3 or ∆V is effectively unconstrained. Surplus propellant on the Earth Departure Stage can not be saved for later burns such as the Asteroid Arrival Maneuver, because the stage is not designed to retain its cryogenic propellants for multi-month durations. So, if Ares V class launch vehicles are used, the ∆V of the Earth departure burn is not a significant factor in this mission. Earth departure ∆V would be more important if the mission were launched using smaller launch vehicles, or if the departure stage had long-duration capability so that surplus performance could be carried over to the asteroid arrival maneuver. However, since the variation in Earth Departure ∆V is small and depends on the assumed park orbit, we have chosen to focus our optimization on minimizing the spacecraft ∆V (the sum of the Asteroid Arrival Maneuver and the Trans-Earth Injection) rather than the total mission ∆V, which includes the departure from Earth orbit.

In addition to ∆V, several other parameters are important. One is the balance between the durations of the outbound and return trips. Since the return trip is performed with only the Primary Orion, the astronauts have less habitable volume and less redundancy during the return trip than the outbound trip. The ideal mission would spend most of the mission duration on the outbound leg and have a very short duration return leg. This also increases the ∆V capability of the spacecraft slightly, since more of the mass of oxygen and water is consumed and vented overboard before the major propulsive burns at the asteroid. Some of the trajectories we have analyzed have return trips as short as 30 days, but most of the feasible trajectories are more evenly split in duration. The trajectory design must also constrain the return entry velocity to be within the capabilities of the capsule TPS. Missions to higher-inclination asteroids or to more distant rendezvous points tend to have higher entry speeds which may make them infeasible depending on the capsule capability. Reentry speed can be reduced at the cost of additional propulsive ∆V. Finally, we considered the ability of astronomers to recover the asteroid (that is, re-detect it) prior to launch. Since these asteroids are quite small they can only be observed when they are near Earth, and they do not pass near Earth frequently. Since these asteroids have only been discovered recently, an asteroid mission in the 2020s may occur during only the second observed approach of the target asteroid after a gap of a decade or more. We expect that additional telescopic observations as well as radar observations by the Goldstone or Arecibo planetary radars will be necessary several months before launch to provide accurate orbital data for mission planning. This provides a reason to seek the latest feasible launch date within a given mission opportunity in order to have more time for observations.

Using the criteria described above, and the asteroid selection methods described in Section 3, we have developed multiple trajectories for each of 15 asteroids between 2015 and 2030. The results of the mission opportunity search are summarized in Table 4. We used the JPL Horizons database for high-precision asteroid ephemerides[27] rather than simple Keplerian orbit elements to predict the asteroid's position because the orbits of the asteroids during the period of interest are perturbed by Earth's gravity enough to affect the results. Spacecraft trajectories were computed by solving Lambert's problem using a universal variables approach with a bisection solution algorithm. This is a simple method that is well suited to quickly computing large numbers of potential trajectories to examine a wide range of different start dates and trip durations. The primary drawback of this analytical approach is that it considers only the Sun's gravity and neglects the influence of Earth's gravity on the spacecraft trajectory. We have spot-checked our results with a more sophisticated trajectory code which accounts for gravity from Earth, the Sun, and the Moon, and found that ΔV results match within 2.5%.

We have analyzed trajectories using several different assumed sets of propulsion capabilities corresponding to different spacecraft configurations, five of which are shown in Table 4. The spacecraft ΔV capabilities for the two spacecraft in each option are as follows:

- Capability 1A: Primary Orion propellant constrained by Ares I performance: 690+990 m/s
- Capability 2A: Primary Orion fully loaded with propellant: 670+1120 m/s
- Capability 3C: Propellant capacity of both Orions increased 50%: 860+1630 m/s
- Capability 4B: Use low-boiloff Altair instead of supplemental Orion: 2000+960 m/s
- Capability 5A: Use Orion Deep Space Vehicle as the supplemental Orion, with the habitat retained during the return trip: 775+930 m/s

Asteroids which are not accessible using one of these performance levels are shown using a reference 180 day mission duration and unconstrained ΔV for comparison.

Our identification of favorable asteroids and the associated mission ΔV matches well with that reported by Landis et al. in 2007[28] with the exception that we have added asteroids which had yet not been discovered when Landis' team did their analysis, and identified an opportunity to visit asteroid 2000 SG344 in the year 2029 which is better than the 2028 opportunity described by Landis. We have also compared our results to a forthcoming paper by Adamo[29] and concluded that they are consistent.

Of 15 asteroid mission opportunities prior to 2030 which we have analyzed, three or four appear feasible using the dual-Orion approach of the Plymouth Rock architecture. These are 2008 HU4 in 2016, 2008 EA9 launching in late 2019, 2006 RH120 in 2028, and 2000 SG344 in 2029. Given the President's goal of sending humans to visit an asteroid by 2025, the most feasible known mission opportunity is to 2008 EA9, departing in late 2019. The most attractive mission opportunity before 2030 is to the asteroid 2000 SG344. Both of these missions are discussed in more detail below. The number of known opportunities which are feasible at this level of performance will probably double in the next five years as more asteroids are discovered, and the total number of undiscovered potential targets is much higher. A thorough survey could discover 10 to 100 times more possible destinations.

Table 4: Mission Parameters for the Best Round Trip Asteroid Mission Opportunities, 2015-2030

	TOTAL MISSION		EARTH DEPARTURE			ASTEROID ENCOUNTER		EARTH RETURN		
	Mission Duration	Spacecraft Delta V	Depart Date	Earth Escape C3	Outbound Duration	Arrival Delta V	Depart Delta V	Return Duration	Landing Date	Reentry Velocity
2008 HU4 Opportunity in 2016										
4 million km from Earth 7-10 m diameter										
Capability 1A	No Solution									
Capability 2A	195 days	1.78 km/s	8 Apr 2016	1.5 km^2/s^2	41 days	0.59 km/s	1.19 km/s	149 days	20 Oct 2016	11.09 km/s
Capability 3C	90 days	2.44 km/s	12 Apr 2016	1.8 km^2/s^2	31 days	0.74 km/s	1.70 km/s	54 days	11 Jul 2016	11.11 km/s
Capability 4B	70 days	2.90 km/s	9 Apr 2016	1.6 km^2/s^2	30 days	0.81 km/s	2.09 km/s	35 days	18 Jun 2016	11.14 km/s
Capability 5A	No Solution									
1991 VG Opportunity in 2017										
12 million km from Earth 6-9 m diameter										
Capability 1A	230 days	1.64 km/s	20 Jun 2017	1.1 km^2/s^2	125 days	0.61 km/s	1.04 km/s	100 days	5 Feb 2018	11.19 km/s
Capability 2A	215 days	1.77 km/s	27 Jun 2017	1.3 km^2/s^2	112 days	0.70 km/s	1.07 km/s	98 days	28 Jan 2018	11.20 km/s
Capability 3C	175 days	2.31 km/s	24 Jun 2017	2.5 km^2/s^2	80 days	1.06 km/s	1.25 km/s	90 days	9 Jan 2018	11.23 km/s
Capability 4B	150 days	2.90 km/s	28 Jul 2017	4.2 km^2/s^2	61 days	1.45 km/s	1.45 km/s	84 days	25 Dec 2017	11.25 km/s
Capability 5A	225 days	1.68 km/s	23 Jun 2017	1.2 km^2/s^2	120 days	0.64 km/s	1.04 km/s	100 days	3 Feb 2018	11.19 km/s
2008 EA9 Opportunity in 2020										
12 million km from Earth 8-12 m diameter										
Capability 1A	200 days	1.66 km/s	17 Nov 2019	2.8 km^2/s^2	93 days	0.46 km/s	1.20 km/s	102 days	4 Jun 2020	11.16 km/s
Capability 2A	195 days	1.72 km/s	18 Nov 2019	2.8 km^2/s^2	92 days	0.47 km/s	1.25 km/s	98 days	31 May 2020	11.17 km/s
Capability 3C	160 days	2.45 km/s	3 Dec 2019	4.2 km^2/s^2	76 days	0.80 km/s	1.66 km/s	79 days	11 May 2020	11.24 km/s
Capability 4B	145 days	2.91 km/s	4 Dec 2019	4.9 km^2/s^2	64 days	0.96 km/s	1.95 km/s	76 days	27 Apr 2020	11.25 km/s
Capability 5A	200 days	1.65 km/s	17 Nov 2019	2.8 km^2/s^2	93 days	0.46 km/s	1.20 km/s	102 days	4 Jun 2020	11.16 km/s
2001 GP2 Opportunity in 2020										
12-18 m diameter										
Infeasible	180 days	3.51 km/s	7 Apr 2020	1.5 km^2/s^2	145 days	3.01 km/s	0.50 km/s	30 days	4 Oct 2020	11.34 km/s
2007 UN12 Opportunity in 2020										
19 million km from Earth 5-8 m diameter										
Capability 1A	235 days	1.63 km/s	24 Jun 2020	3.8 km^2/s^2	119 days	0.41 km/s	1.23 km/s	111 days	14 Feb 2021	11.24 km/s
Capability 2A	230 days	1.71 km/s	27 Jun 2020	4.1 km^2/s^2	117 days	0.45 km/s	1.27 km/s	108 days	12 Feb 2021	11.25 km/s
Capability 3C	210 days	2.21 km/s	15 Jul 2020	6.2 km^2/s^2	95 days	0.93 km/s	1.28 km/s	110 days	10 Feb 2021	11.25 km/s
Capability 4B	195 days	2.77 km/s	1 Aug 2020	8.8 km^2/s^2	83 days	1.49 km/s	1.27 km/s	107 days	12 Feb 2021	11.25 km/s
Capability 5A	235 days	1.63 km/s	24 Jun 2020	3.8 km^2/s^2	119 days	0.41 km/s	1.23 km/s	111 days	14 Feb 2021	11.24 km/s
2001 QJ142 Opportunity in 2024										
60-90 m diameter										
Infeasible	180 days	3.25 km/s	27 Apr 2024	5.9 km^2/s^2	82 days	1.24 km/s	2.01 km/s	93 days	24 Oct 2024	11.34 km/s
1999 AO10 Opportunity in 2025										
50-70 m diameter										
Infeasible	180 days	3.22 km/s	21 Aug 2025	1.6 km^2/s^2	133 days	2.15 km/s	1.06 km/s	42 days	17 Feb 2026	11.39 km/s
2008 JL24 Opportunity in 2026										
4-5 m diameter										
Capability 4B	165 days	2.93 km/s	19 Feb 2026	7.2 km^2/s^2	64 days	1.33 km/s	1.60 km/s	96 days	3 Aug 2026	11.25 km/s
2006 RH120 Opportunity in 2028										
4.5 million km from Earth 4-5 m diameter										
Capability 1A	145 days	1.58 km/s	30 Jun 2028	0.5 km^2/s^2	64 days	0.84 km/s	0.75 km/s	76 days	22 Nov 2028	11.11 km/s
Capability 2A	135 days	1.69 km/s	3 Jul 2028	0.5 km^2/s^2	64 days	0.82 km/s	0.87 km/s	66 days	15 Nov 2028	11.12 km/s
Capability 3C	100 days	2.23 km/s	16 Jul 2028	1.1 km^2/s^2	46 days	1.10 km/s	1.13 km/s	49 days	24 Oct 2028	11.14 km/s
Capability 4B	80 days	2.79 km/s	23 Jul 2028	1.8 km^2/s^2	37 days	1.35 km/s	1.44 km/s	38 days	11 Oct 2028	11.17 km/s
Capability 5A	140 days	1.63 km/s	2 Jul 2028	0.5 km^2/s^2	62 days	0.85 km/s	0.77 km/s	73 days	19 Nov 2028	11.11 km/s
2006 UQ216 Opportunity in 2028										
10-15 m diameter										
Infeasible	180 days	3.47 km/s	17 Aug 2028	10.9 km^2/s^2	101 days	2.85 km/s	0.62 km/s	74 days	13-Feb-2029	11.73 km/s
2000 SG344 Opportunity in 2029										
8 million km from Earth 30-45 m diameter										
Capability 1A	150 days	1.65 km/s	17 Jul 2029	2.0 km^2/s^2	70 days	0.70 km/s	0.95 km/s	75 days	14 Dec 2029	11.16 km/s
Capability 2A	145 days	1.73 km/s	19 Jul 2029	2.2 km^2/s^2	67 days	0.74 km/s	0.99 km/s	73 days	11 Dec 2029	11.16 km/s
Capability 3C	120 days	2.34 km/s	29 Jul 2029	3.0 km^2/s^2	56 days	1.00 km/s	1.34 km/s	59 days	26 Nov 2029	11.21 km/s
Capability 4B	105 days	2.88 km/s	2 Aug 2029	3.9 km^2/s^2	48 days	1.22 km/s	1.66 km/s	52 days	15 Nov 2029	11.24 km/s
Capability 5A	150 days	1.65 km/s	17 Jul 2029	2.0 km^2/s^2	70 days	0.70 km/s	0.95 km/s	75 days	14 Dec 2029	11.16 km/s
2006_DQ14 Opportunity in 2030										
Capability 4B	155 days	2.83 km/s	16 Sep 2030	11.9 km^2/s^2	84 days	2.04 km/s	0.79 km/s	66 days	18 Feb 2031	11.67 km/s

All options assume a 5 day stay at the asteroid. ΔV values are deterministic only, and do not include mid-course corrections, flight performance reserves, or allocations for extended departure periods

2008 EA9 Mission in 2019-2020

The earliest feasible mission is the 2019 launch opportunity to encounter the asteroid 2008 EA9 in 2020. This asteroid is about 10 meters in diameter. Its composition and spin state are unknown. Considering the name selected for the mission, it is appropriate that the launch occurs around Thanksgiving in 2019 and the astronauts would return in 2020 in time to celebrate the 400th anniversary of the Pilgrims founding Plymouth Colony. Trajectory plots in heliocentric and geocentric coordinates are shown in Figure 8 and Figure 9. The mission would take the crew about 12 million km from Earth, which corresponds to about 32 times the distance of the Moon, or 0.08 A.U. At this distance, the speed of light lag is about 40 seconds each way. Maneuver ΔV and reentry velocities are shown in Figure 10 through Figure 12, referenced to the same departure date scale in each case for ease of comparison.

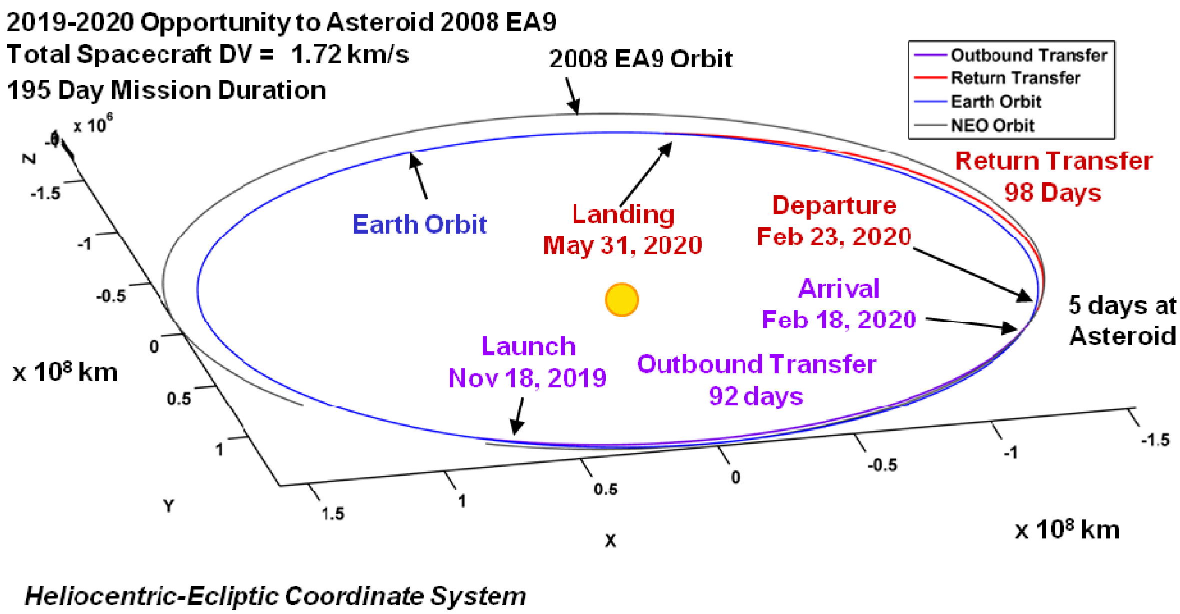

Figure 8: Missions To Accessible Asteroids Like 2008 EA9 Are Feasible Because Their Orbits Are Very Similar To Earth's

Image Credit: Lockheed Martin

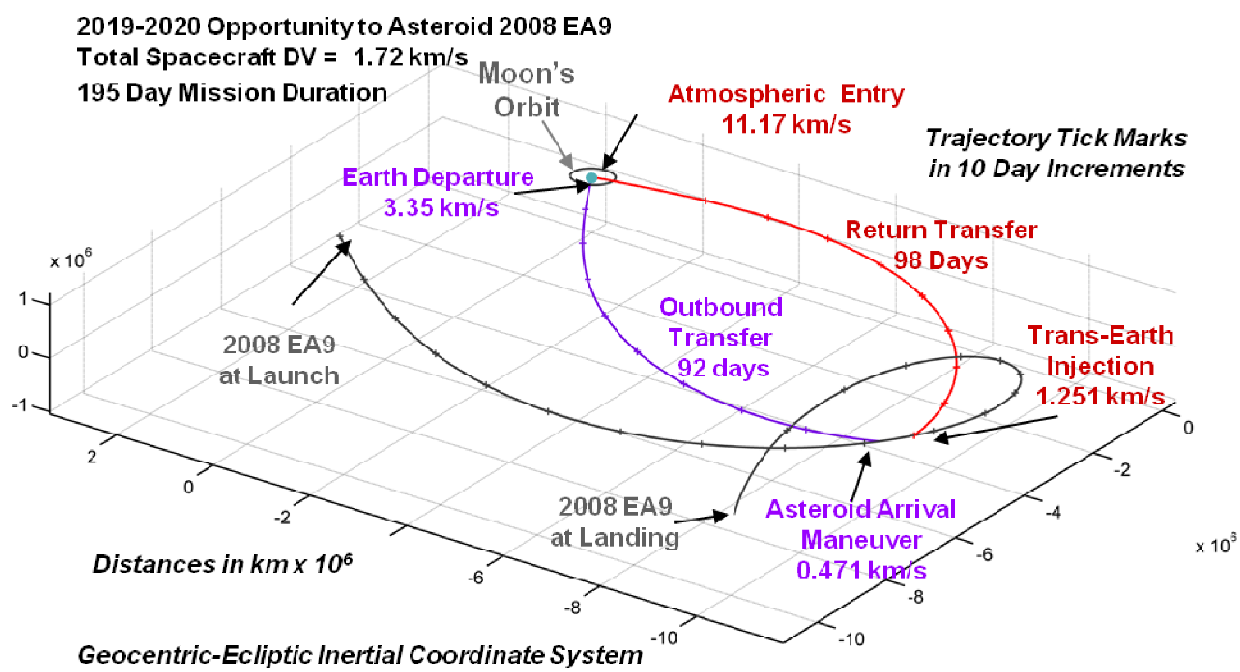

Figure 9: A Mission to 2008 EA9 Would Take Astronauts 32 Times Farther Than the Moon
Image Credit: Lockheed Martin

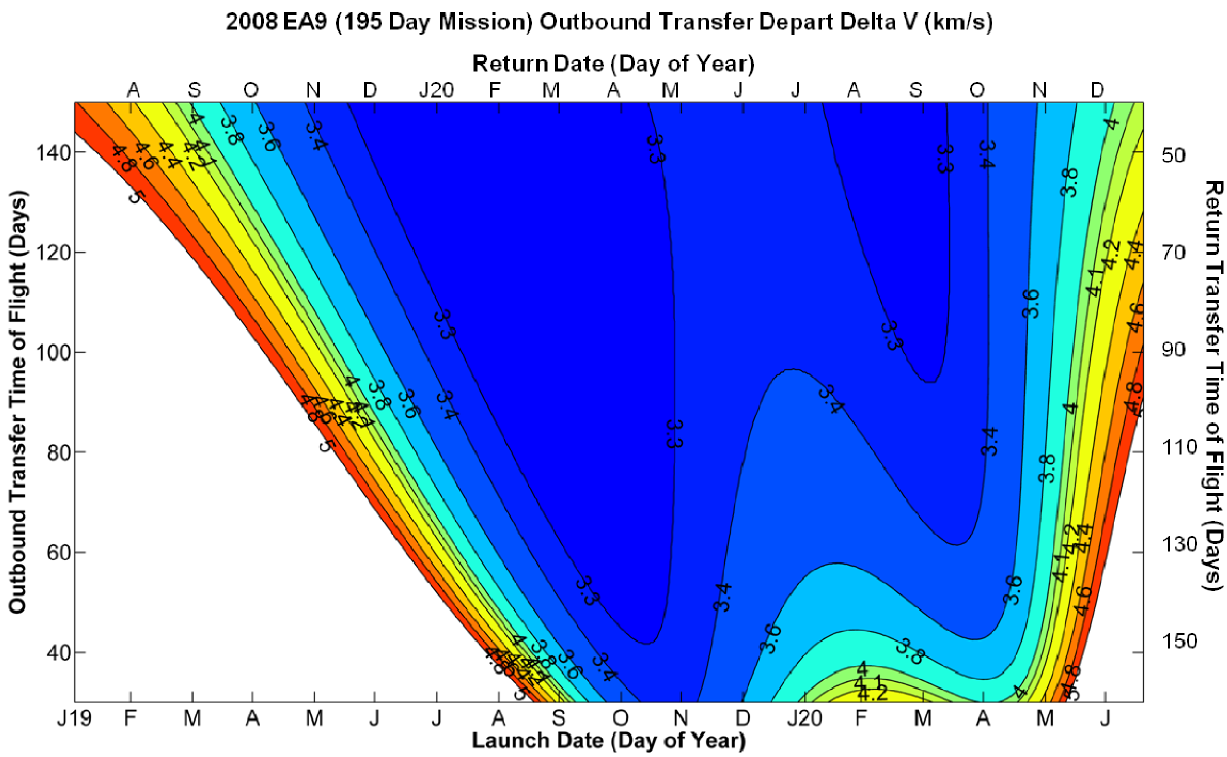

Figure 10: Earth Escape ∆V (km/s) from a 200 km Earth Parking Orbit as a Function of Departure Date for 2008 EA9 Opportunity in 2019-2020.
Image Credit: Lockheed Martin

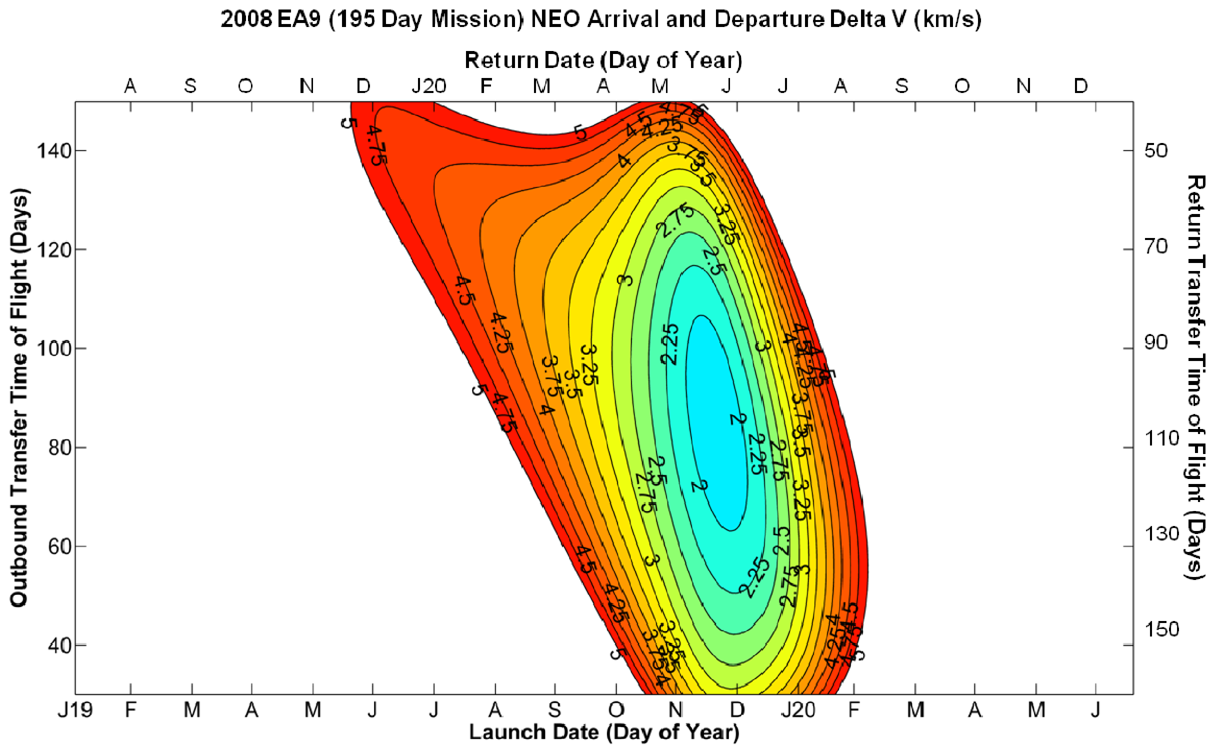

Figure 11: Combined ΔV (km/s) for Asteroid Arrival Maneuver and Trans Earth Injection for a 195 Day Total Mission Duration with 5 Day Stay at the Asteroid During 2019-2020.
Image Credit: Lockheed Martin

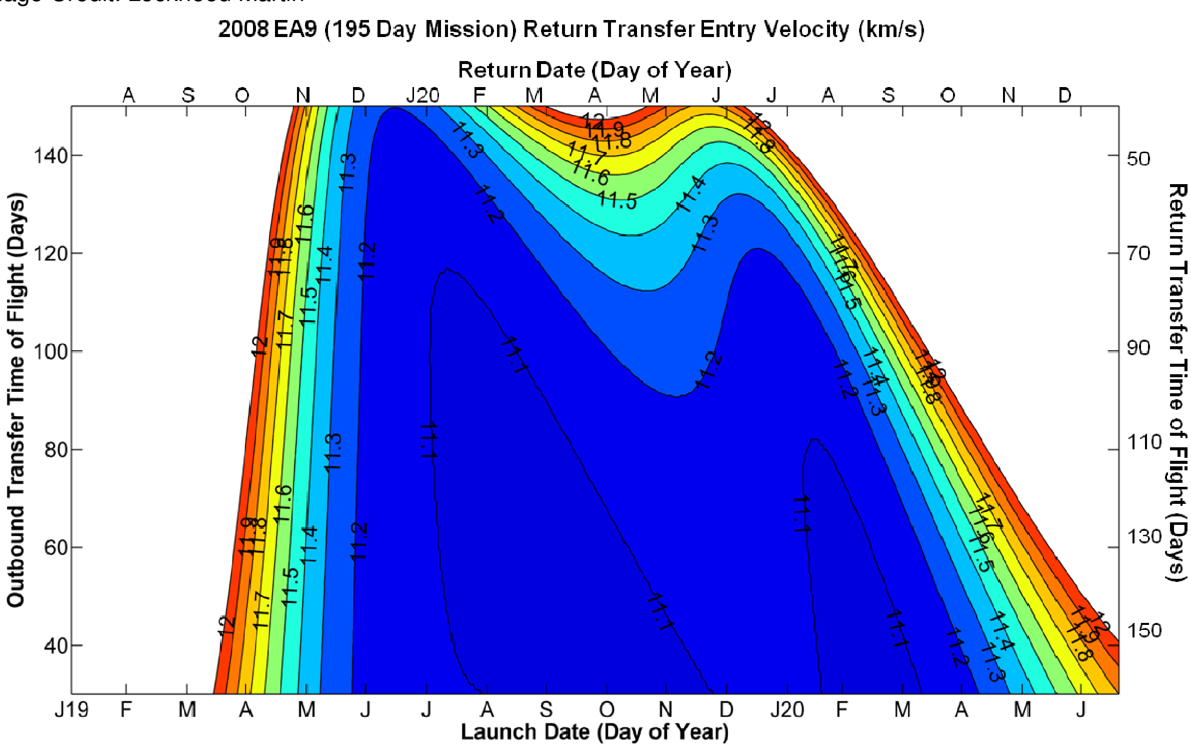

Figure 12: Inertial Velocity (km/s) At Atmosphere Entry Interface For 2008 EA9 Mission In 2019-2020. Launch And Return Dates Correspond To 195 Day Total Mission Duration.
Image Credit: Lockheed Martin

2000 SG344 Mission in 2029

The opportunity in 2029 to explore asteroid 2000 SG344 is perhaps the most favorable yet identified. Details are shown in Figure 13 through Figure 16. The asteroid's very low inclination (0.11°) and close approach (8 million km) make it one of the easiest opportunities energetically. So, the mission duration is shorter than most of the missions we have examined. The ΔV requirements are low enough that a mission using the standard Orion plus the Orion Deep Space Vehicle could carry three, rather than two, astronauts. The asteroid is larger than many of the other candidates, at 30-45 m diameter, and therefore perhaps more interesting. In contrast, the asteroid 2006 RH120 has an opportunity the previous year with similar low ΔV, but it is only 4-5 m across. 2000 SG344 makes a few close approaches to Earth beginning at least a year and a half before the selected launch date, providing chances for telescopic and radar observation prior to launch for improved characterization and orbit determination, and perhaps for a robotic scouting mission. Launch opportunities for this mission are in mid July 2029, coinciding with the 60th anniversary of the Apollo 11 Moon landing. Asteroids will be in the public consciousness because the "doomsday asteroid" Apophis will have made a close approach inside the geosynchronous belt a few months before, on Friday the 13th of April 2029.

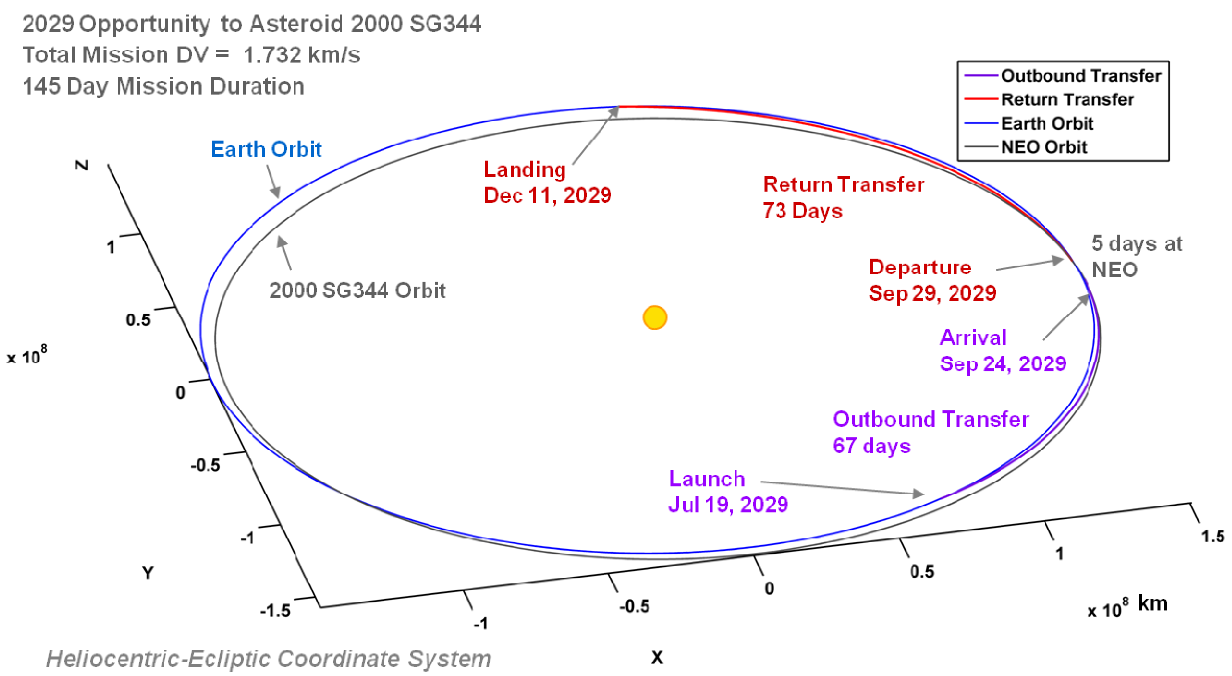

Figure 13: The Duration of a Mission to 2000 SG344 Is Shorter Than For Other Asteroids
Image Credit: Lockheed Martin

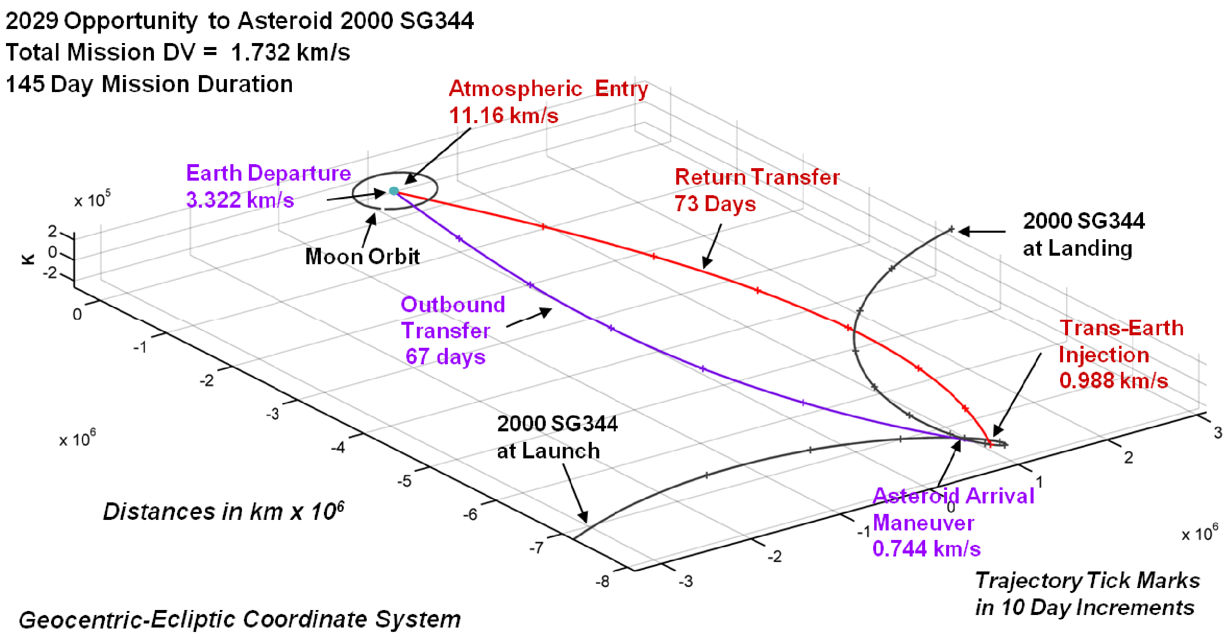

Figure 14: The Low Inclination And Close Approach Of 2000 SG344 Make It The Most Feasible Of Any Near-Future Asteroid Mission Yet Identified

Image Credit: Lockheed Martin

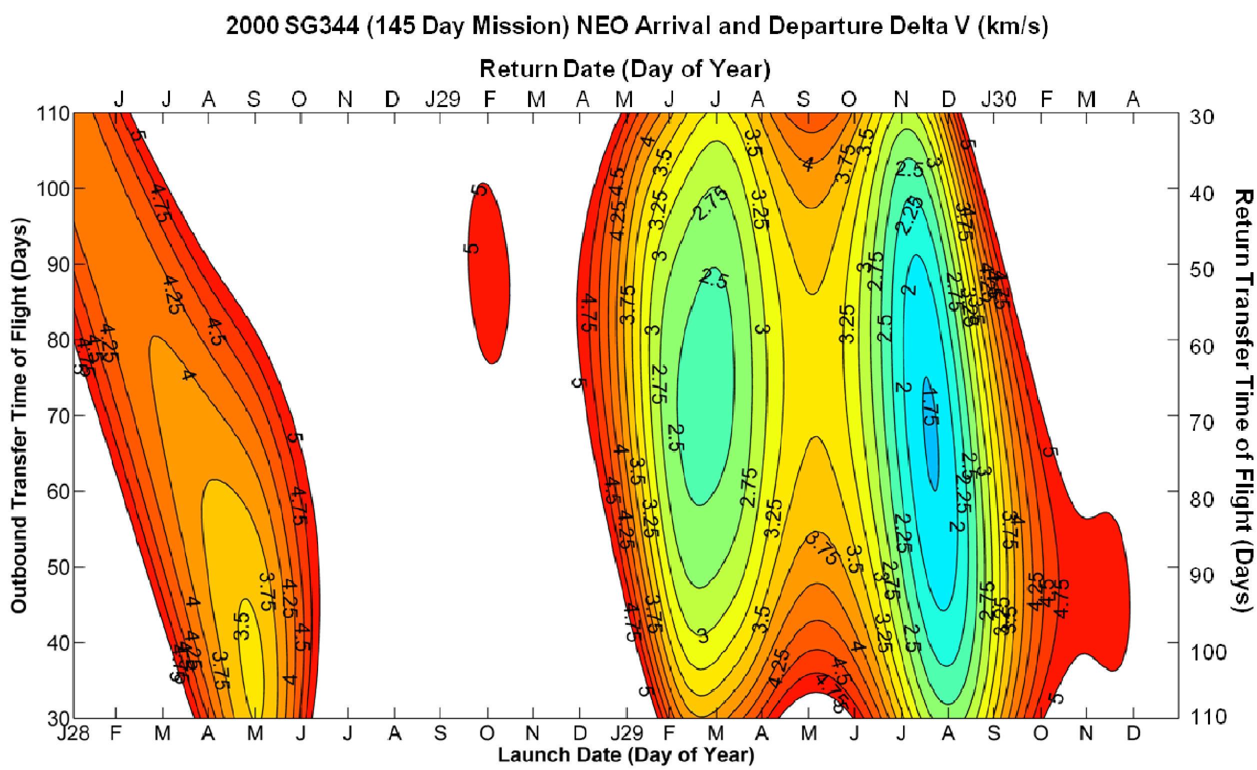

Figure 15: Combined ΔV (km/s) for Asteroid Arrival Maneuver and Trans Earth Injection for 2000 SG344 Opportunities in 2028-2029.

Image Credit: Lockheed Martin

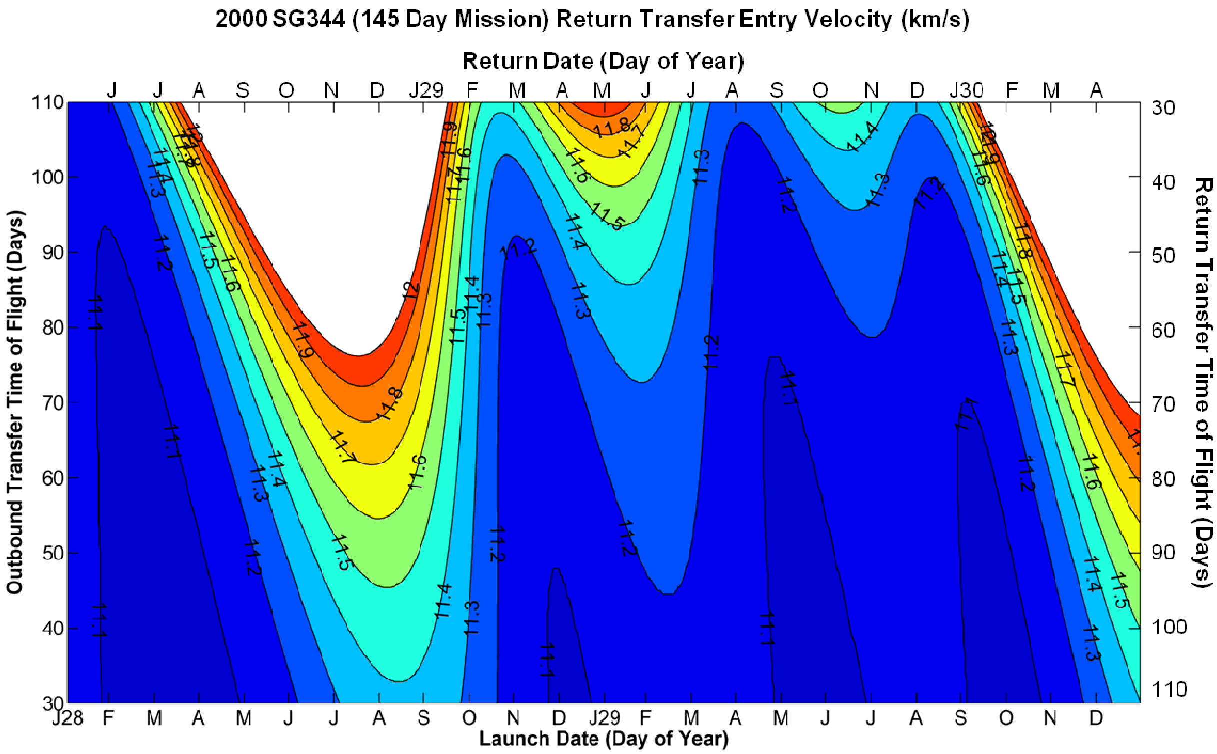

Figure 16: Inertial Velocity (km/s) at Atmosphere Entry Interface for Return From Asteroid 2000 SG344 for a 145 Day Mission in 2028-2029.
Image Credit: Lockheed Martin

9. Asteroid Exploration Operations

Many aspects of exploring an asteroid will be fundamentally different from our past experience with lunar and Earth orbit operations. For instance, both astronaut mobility around the asteroid and spacecraft maneuvering will need careful consideration given the negligible local gravity. The following description of exploration operations is only notional to illustrate options and capabilities and to highlight issues which should be studied in more depth in the future. This discussion assumes that no precursor robotic mission has visited the target asteroid before the human mission, but that Earth-based optical and radar observations have determined the spin rate and compositional type of the asteroid (e.g. stony, iron, or carbonaceous).

The asteroid exploration phase lasts about 5 days in the reference mission concept. Longer stays of one to two weeks are feasible either by increasing the ΔV budget or allowing slightly longer total mission duration. The exploration phase begins on the first day with the Asteroid Arrival Maneuver. This primary burn of the Service Module Main Engine on the Supplemental Orion empties the tanks on that module. The maneuver puts the Orions 20-50 km from the asteroid at very low relative velocity. The arrival position includes this standoff distance to manage the effect of trajectory dispersions and to allow for a slow final approach to the asteroid over the next several hours. During the rest of the crew day, the astronauts perform any post-maneuver spacecraft management tasks, and track the asteroid as they approach both to improve position determination and to watch for any co-orbiting moonlets or free floating debris which could pose a hazard. At the end of the first day the spacecraft would be a few hundred meters from the asteroid and the overall size, shape and spin state (i.e. not just its rotation rate but also the orientation of its axis of rotation) of the asteroid would be determined. It may be possible to visually determine whether the asteroid is monolithic or a collection of loose rubble. Direct measurement of the asteroid's mass by relative tracking of the spacecraft motion would be useful at the beginning of the stay, but we are not sure that rapid detection of such small accelerations (on the order of 10^{-6} to 10^{-8} m/s^2) would be feasible under these conditions.

During the second day the astronauts would photograph the asteroid at high resolution using both the rotation of the asteroid and the relative motion of the spacecraft to observe the entire surface at multiple lighting angles using both handheld cameras and sensors mounted on the Orion service module science instrument platform. Radar sounding to determine the internal structure of the asteroid would also be desirable to identify internal voids in the asteroid. Information downlinked to Earth would be used by the science team to plan spacewalks on the following days. Crew time would also be allocated to preparing EVA equipment and pre-breathing. At the end of the day the dual Orions would be 50-100 m from the asteroid.

The third and fourth days would be dedicated to spacewalks to explore the asteroid directly. Although some other recent asteroid mission concepts envision 'landing' a piloted spacecraft on the asteroid, we see no reason to do this. Landing or docking the spacecraft to the asteroid provides no obvious operational advantages and would require development of a contact and anchor system. Direct contact puts the spacecraft in danger of damage from free-floating surface material kicked up by the astronauts. It would also disturb the asteroid surface both with mechanical contact and thruster plume impingement. The asteroid would intermittently shadow the solar arrays and block line of sight for communications to Earth. Instead, we would prefer to safely station the dual Orions on the order of 50-100 meters from the asteroid (a few times the asteroid diameter), well clear of both the surface and the asteroid's shadow. At this distance, the gravitational and thermal influences of the asteroid on the spacecraft are greatly reduced. Instead of landing the spacecraft, free-floating astronauts would explore the asteroid using a propulsive backpack similar to the SAFER and Manned Maneuvering Unit (MMU) systems. Based on consultation with astronaut Bruce McCandless, it should be feasible to develop a modern equivalent of the MMU suitable for asteroid operations[30]. One of the design requirements for the original MMU was to rescue astronauts from a tumbling Space Shuttle, whose dimensions and assumed rotation rates were quite similar to the expected size and motion of the target asteroids. Though it never had to demonstrate that capability, astronauts using the MMU did successfully match rotation rates with spinning satellites. However, it has also been suggested to us by astronauts with ISS EVA experience that when working at one location for an extended period of time it is helpful to anchor oneself in place. Astronauts exploring an asteroid will want some means of temporarily attaching to the asteroid and then releasing, much like rock climbers.

Orion does not have an airlock, but is designed to support EVAs by depressurizing the crew module. For a two-person Plymouth Rock mission, both astronauts would enter the crew module of the Supplemental Orion and close the docking hatch to the Primary Orion. After venting the air in the Supplemental Orion, the astronauts open the side hatch, and one astronaut egresses to don his or her maneuvering backpack. If the supplemental Orion is a standard capsule, the backpack and other EVA equipment would be stored externally on the Service Module. (Some changes would be required, such as adding external handholds to the SM which are currently only included on the CM). The other astronaut remains inside the crew module, with the hatch open. This allows the second astronaut either to relatively quickly egress should the first astronaut require assistance with a task, or to remain inside and operate the spacecraft, such as to maneuver it to rescue the spacewalking astronaut in an emergency[‡‡]. By remaining high above the surface, the astronaut in Orion can provide a bird's eye view of the asteroid. For example, this would help the spacewalking astronaut navigate and provide the capability for overhead context photography to document the location of each sample collected. On the second day of spacewalks the astronauts can switch roles. The alternative Orion Deep Space Vehicle would be designed to accommodate two advanced MMUs as well as EVA tools and science payloads on the external surface of the habitat module rather than the Service Module. The larger habitat module also opens up the possibility for a three-person crew. In this case, two astronauts would perform spacewalks simultaneously while the third remained inside the pressurized capsule of the Primary Orion.

Once an astronaut reaches the surface of the asteroid and says something suitably historic, the first priority would be to collect samples capturing the diversity of the surface. These would include rocks, gravels, and fine soil or dust, assuming these are present on the asteroid. A magnetic sample collector would be used to collect loose metallic grains which may be present even on otherwise stony or carbonaceous asteroids. These samples will help determine the origin and history of the asteroid. Another area of focus will be measuring geotechnical parameters which will influence the design and feasibility of future hardware intended to operate on asteroids. Astronauts would measure bearing and shear strength, penetrability and electrical and thermal conductivity. Experimenting with different methods of anchoring to the surface will also be important. Ideas ranging from harpoons to adhesives have been suggested. Finally, astronauts could emplace experiments which would remain on the asteroid after they leave, similar to the Apollo ALSEP instruments. These could include a tracking transponder to improve tracking accuracy of the asteroid's orbit, instruments to measure long-term changes in the environment or rotation state of the asteroid, explosive charges to support seismic studies, or even an experiment to modify the orbit of the asteroid with light pressure using reflective film on one side of the asteroid. Though asteroid trajectory deflection may seem ambitious, it is not particularly difficult to move such small asteroids by a detectable amount.

The scientific success of the J-series Apollo lunar landings was due in large part to the geological training of the astronauts and the ability of the backroom scientists at mission control to advise the astronauts in real-time as discoveries were being made.[31] In recent decades, geology has not been relevant to Space Shuttle and ISS activities, and scientists have had little reason to look over the shoulders of spacewalking astronauts. If an asteroid mission can be conducted prior to the lunar landings, it offers the opportunity to rebuild geological knowledge in the astronaut corps and develop new procedures for real-time exploration with ground-based interaction, prior to the next lunar landing.

The last day of operations at the asteroid would be spent closing out the exploration phase and preparing the spacecraft for departure. All samples would be catalogued and stowed in the Primary Orion for return to Earth, while trash and any gear not needed for the return trip would be transferred to the Secondary Orion. Last-minute observations of the asteroid could be made to follow-up on discoveries by the ground science team. Finally, the astronauts would enter the

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[‡‡] Orion is designed so that astronauts in a space suit can operate displays and controls when the cabin is depressurized. This stems partly from the requirement that Orion be able to bring astronauts home safely from the Moon even if a failure depressurizes the cabin. The *Columbia* Crew Survival Investigation Report observed that although Shuttle astronauts have worn a pressurized suit to protect them during reentry since the *Challenger* accident, three *Columbia* crew members were not wearing their gloves because the gloves make it difficult to perform tasks. Orion engineers are designing the cabin to accommodate limited space suit dexterity to avoid problems like this in the future.

Primary Orion, separate the two spacecraft, perform the Trans-Earth Injection maneuver using the Service Module main engine and depart for Earth. After departure, the unmanned Secondary Orion might be used for continuing observations of the asteroid as an extended mission (see Figure 17). During this quiescent period it may be possible to perform measurements which require either more time or more stability than were available during the human visit, such as precision tracking of the asteroid or measurement of its gravitational attraction. The extended mission could also serve as a long-life test of the durability and reliability of the Orion spacecraft. The lunar architecture calls for the Orion spacecraft to remain untended in orbit around the Moon for up to six months during lunar outpost missions, a capability which could be validated as a secondary objective of the asteroid mission.

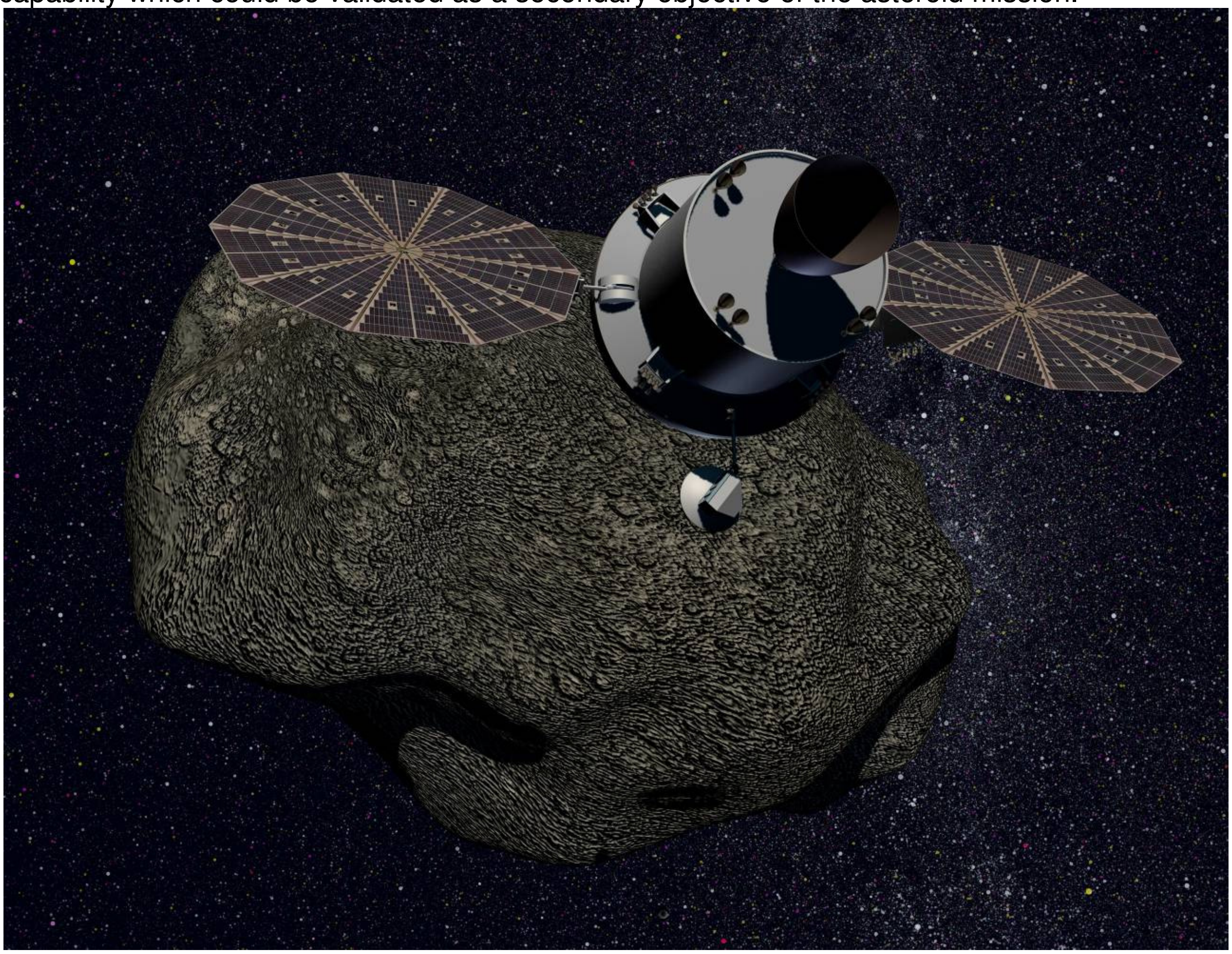

Figure 17: The Supplemental Orion Could Remain Behind at the Asteroid to Perform Long-term Monitoring After the Astronauts Return to Earth

Image Credit: Lockheed Martin

10. Safety and Health

Compared to the baseline Constellation lunar mission, the Plymouth Rock asteroid mission concept poses increased safety and health risks to astronauts due to duration and distance, but these risks are counterbalanced to some extent by safety benefits from mission simplicity and vehicle-level redundancy.

The astronauts will spend roughly six months in deep space. They must be provided with exercise options to mitigate the effects of microgravity, which is not provided by Orion in the nominal lunar mission because of the short time the crew spends in the spacecraft. They will be exposed to a more severe radiation environment, because they will not be shielded by the mass of the Moon. Perhaps the greatest added risk is a direct function of the greater distance inherent in an asteroid mission. In the event of an abort caused by a medical or spacecraft crisis, an emergency return to Earth will take anywhere from two to five months, compared to only a few days from the surface of the Moon. Given these enhanced risks, it is important to design the asteroid mission with mitigating safety features. First and foremost, the Plymouth Rock mission architecture provides vehicle-level redundancy. By using a second Orion rather than a simple habitat module to provide the necessary mission capabilities, Plymouth Rock can provide the crew with two fully functional independent spacecraft during the outbound trip, including redundant re-entry capability. However, once the Asteroid Arrival Maneuver is performed, only the Primary Orion Service Module has propellant remaining for the Trans-Earth Injection maneuver. Therefore, it is beneficial to design the mission so that the outbound leg is longer than the return leg, thus providing redundancy for as much of the mission as possible.

In addition to redundancy, the Plymouth Rock mission architecture is less complex than the planned lunar landing missions. It has fewer risky events, such as major propulsive maneuvers, rendezvous and docking events, and EVAs. It has no maneuvers similar to the lunar landing and ascent, during which propulsion underperformance can result in an imminent crash. A comparison between the asteroid mission and planned lunar missions is shown in Table 5.

Table 5: Safety Comparison of Asteroid Mission vs Constellation Lunar Mission

	Asteroid Mission	Lunar Sortie	Lunar Outpost
Nominal mission duration	~140-200 days	20-25 Days	180-200 days
Emergency return duration	2-6 months?	3-5 days	3-5 days
Primary propulsion events (post-launch)	3	8-10	8-10
Rendezvous and docking events	1 (in LEO)	2 (LEO + Lunar Orbit)	2 (LEO + Lunar Orbit)
Separation events (post-launch)	3	5	5
EVAs	2-4?	Dozens?	Dozens?

Radiation

Two sources of radiation pose significant health risks for exploration missions outside Earth's magnetosphere. Galactic Cosmic Rays (GCR) are highly energetic charged particles moving at relativistic speeds. They create a predictable background level of radiation which varies over the duration of the 11 year solar cycle. Cosmic ray radiation levels are 2-3 times higher when the Sun's magnetic field is weakest during solar minimum than during solar maximum. While daily doses incurred by astronauts from cosmic ray exposure are relatively small, the life-time probability for health detrimental radiation effects is cumulative and increases with mission duration. GCR exposure risks are low for short missions like lunar sorties which last only a few weeks, but become significant for asteroid missions of a few months or more, and even more so for multi-year missions such as to Mars. Because cosmic rays consist of extremely high energy particles, passive shielding is not very effective. The daily effective dose from cosmic rays for Orion astronauts beyond low Earth orbit is calculated to be 1.4 mSv (milliSieverts) during solar minimum and 0.5 mSv during solar maximum. In order to perform Lunar Outpost missions, Orion hardware is designed to tolerate space radiation environments for more than 210 days in lunar orbit – a similar environment and duration to the asteroid mission.

The other natural ionizing radiation risk is from Solar Particle Events (SPE). Their contribution to the background level of radiation is negligible, but strong flares occurring randomly several times per solar cycle can create very high levels of radiation for a few days. Solar Particle Events are more likely during solar maximum but can occur at other times during the solar cycle. Passive shielding protects against radiation from SPEs more effectively than against cosmic rays. Because the increased radiation environment lasts for hours or a few days, astronauts can use temporary “storm shelters” for augmented protection in a small section of the spacecraft. Orion has a design requirement to ensure that the tissue-averaged effective dose received by any crew member does not exceed 150 mSv for a design reference radiation environment based on the major solar flare of August 1972 as parameterized by J. King.[32] A flare of this magnitude might be expected to occur about once per solar cycle, but it is not necessarily a worst case. For comparison, had astronauts been in an Apollo Command Module during the August 1972 solar flare their effective dose would have been several times higher than this limit.[33]

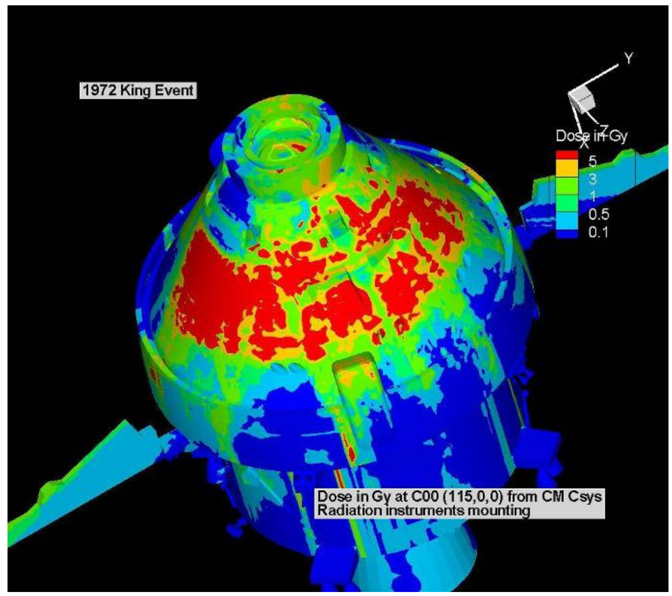

Figure 18: Radiation Penetration to a Reference Point in the Orion Cabin from Various Surface Locations.
Image Credit: Lockheed Martin

Meeting this requirement without adding substantial mass for dedicated radiation shielding has required extensive analysis and design effort. Based on National Research Council recommendations, the radiation protection effort was integrated into the spacecraft design engineering process early in the program. The Orion radiation analysis starts from the vehicle CAD solid model including mass density and material composition of each component on the vehicle. A ray tracing procedure is used to compute total radiation shielding provided by vehicle components along 10,000 different directions relative to several crew positions in the vehicle. An analysis is performed to assess astronaut body self-shielding at 600 organ point locations inside the body. The vehicle and body shielding data are then used to calculate the tissue-averaged effective dose that would be incurred by individual crew members during the design reference SPE using radiation transport modeling software. From this data, engineers can determine which areas of the spacecraft provide the most or least shielding, and adjust the locations of existing vehicle components to improve protection without adding mass. This process has progressively improved the spacecraft’s inherent shielding capabilities over the course of the development program.

Figure 18 shows a map of the directionality of radiation exposure relevant to a location near the center of the cabin, using a logarithmic color scale. The thin middle of the conical section of the cabin has the least shielding, but the cabin is well shielded from the bottom (i.e. aft) by the Service Module and the capsule heatshield, and from the top (i.e. the nose) by the docking adapter and parachutes. Though it may seem undesirable from a performance perspective to carry all the ‘dead weight’ of a capsule’s reentry systems on a deep space mission, the parachutes and thermal protection do provide valuable radiation protection. While material composition matters, the spacecraft mass is considered the most significant parameter predicting overall vehicle radiation protection capabilities. Since radiation exposure decreases non-linearly with shielding mass thickness, removing the TPS and other reentry system mass would lead to an exponential increase in astronaut exposure. The radiation exposure during a solar particle event inside a spacecraft designed only for in-space use is very likely to pose an unacceptable health risk unless substantial parasitic mass is included for dedicated radiation shielding.

To provide more protection during an intense Solar Particle Event, the crew would create a temporary storm shelter in the best-shielded section of the spacecraft. In the event of a severe flare, the crew would temporarily remove the items in the central stowage bays at the aft of the cabin and use this space as a shelter. Stowed items removed from the bays would be positioned in specific locations in the cabin identified to maximize shielding. This approach reduces radiation dose by more than a factor of two compared to the nominal configuration of the cabin. Determining the best arrangement required the Orion Radiation Protection team to develop new analytical methods given the large number of possible configurations and to coordinate with flight operations groups to ensure the cabin could be reconfigured quickly and still meet operational needs. The resulting solution meets radiation safety requirements and avoided the need to add heavy dedicated radiation shielding.

At the expected exposure levels for both cosmic rays and solar flares the threat from radiation is primarily an increased probability of cancer, cataracts, and other effects later in life, rather than immediate illness or death during the mission. However, acute effects can occur if astronauts are poorly protected in thinly shielded vehicles or during EVA when a Solar Particle Event occurs. NASA applies a safety requirement that an astronaut's cumulative career radiation exposure should not cause more than a 3% chance of Radiation Exposure Induced Death (REID) using a 95% confidence interval to bound the large uncertainties in exposure effects. Since no amount of radiation is considered safe, exposure is governed by the ALARA principle (As Low As Reasonably Achievable) which requires that rather than treating a particular threshold as acceptable, reasonable effort should be made to reduce risk to the lowest achievable level.

While official career and short-term effective dose limits have been established for astronauts operating in LEO in NCRP report 132,[34] these limits explicitly do not apply to missions beyond LEO due to uncertainties about the long term effects of cosmic rays and the unknown design tradeoffs for such missions. Also, the effective radiation dose on an Orion asteroid mission is uncertain, depending on factors such as mission duration, solar flare activity, and required design assumptions. Our preliminary estimates indicate that radiation safety will be a significant design and operational issue but that asteroid missions are probably feasible within reasonable safety limits. Based on data developed for Orion lunar missions, a best case effective dose on an asteroid mission (150 day mission during solar maximum with no significant flares) would be roughly 75 mSv. This is comparable to a 6 month mission on ISS. A medium case would be a 180 day mission during solar minimum with no major flares, resulting in a mission effective dose around 250 mSv. This is somewhat higher than the doses received on the longest Skylab and US Mir missions. A severe case effective dose would be around 400 mSv, for a 210 day mission during solar minimum with one severe 1972-reference solar flare. The worst exposure over a 30-day period that includes both the flare and cosmic rays would result in organ dose equivalents to eye, skin and blood-forming organs of 0.52 Sv, 0.72 Sv, and 0.17 Sv, respectively. For comparison, 30-day LEO deterministic limits according to NCRP 132 are 1.0 Sv, 1.5 Sv, and 0.25 Sv, respectively. These limits are larger than the predicted values by factors of 1.5 – 2.1. Large solar flares aren't very likely during solar minimum. However, it may be appropriate to design for at least one significant solar flare even during solar minimum no matter how unlikely this is. It may even be appropriate to design for the possibility of more than one major flare, since flares can be correlated and astronauts can't quickly return to Earth after one major flare occurs as they can in a LEO or lunar mission. Determining appropriate deep space radiation effective dose limits and design criteria is one area in which an asteroid mission can help lay the ground work for a Mars mission.

Radiation exposure during a 180 day asteroid mission may well exceed the exposure on any prior US space mission. However, it would be much lower than has been estimated for Mars missions, and well within the career dose limits established for LEO missions. It should be possible for an astronaut with prior flight experience (and therefore prior radiation exposure) to perform an asteroid mission without exceeding career dose limits, so that they would not be prevented from flying additional space missions in the future. The estimated radiation dose for a Plymouth Rock asteroid mission is compared to other radiation doses and dose limits in Table 6.[§§]

Table 6: Asteroid Mission Radiation Exposure Compared to Other Sources

Exposure	Effective Dose (E) or Skin Dose (D_{skin})
Chest X-ray	E ~ 0.1 mSv
Typical US annual exposure (natural background plus medical imaging)	E ~ 3-6 mSv/yr
Computed Tomography (CT) Scan	E ~2-8 mSv
Apollo mission average [37]	E = 12 mSv
Regulatory limit for US terrestrial radiation workers	E = 50 mSv/yr
ISS Expedition 1-10 average[37]	E = 68 mSv
Skylab average[37]	E = 95 mSv
NASA Mir mission average[37]	E = 115 mSv
Orion requirement (Aug 1972 King SPE)	E ≤ 150 mSv
Orion asteroid mission (estimated range)	**E ~75-400 mSv**
Skylab highest measured dose (Skylab 4 skin dose)[35]	D_{skin} = 178 mSv
Career dose limit for 45 year old female astronaut in LEO[36]	E =900 mSv
Mars mission (estimate)[37]	E ~1000 mSv?
Career dose limit for 45 year old male astronaut in LEO	E =1500 mSv
Apollo Command Module during Aug 1972 equivalent solar flare	D_{skin} ~3500 mSv

As previously stated, radiation exposure should be managed to the lowest reasonable level rather than to a specific threshold. Design changes such as additional supplemental shielding can reduce exposure, but some of the most promising improvements are operational. Older astronauts have lower cancer risk for a given effective dose than younger astronauts, so it may be possible to reduce risk by considering each person's individual risk during crew selection, though other non-cancer radiation effects must also be considered. Radiation risk will vary during the solar cycle, with higher background dose during solar minimum, but a higher risk of a Solar Particle Event during solar maximum So, radiation risk may be managed by selecting asteroid mission opportunities during favorable times in the solar cycle. The lowest ΔV opportunities we have identified coincide with solar minima in 2019 and 2028, while the President's 2025 deadline for an asteroid mission corresponds to solar maximum. The other means of reducing risk is to reduce mission duration. Given that shorter missions provide not only benefits for radiation dose but also other time-dependent risks as well as ECLSS mass and volume, we believe it is worth considering propulsion enhancements like larger propellant tanks for Orion or dedicated propulsion stages to enable shorter missions.

[§§] Radiation exposure is a very complex subject which has been greatly simplified in this table. Different types of radiation produce different effects and a given dose received in a short time, such as a solar flare, can be more dangerous than the same dose spread over a year or a lifetime. Also, the table combines exposure information from different references which are expressed in terms of different radiation quantities (skin dose, or tissue averaged effective dose). These quantities should not be directly compared. For more information on this subject, see Reference 32 and 34.

Redundancy and Abort Return

One goal of the Plymouth Rock dual-Orion mission architecture was to provide redundant spacecraft, each with the ability to return a crew safely to the Earth in the event of a failure of the other spacecraft during the outbound leg of the trip. This would provide a safe return capability similar to the Apollo 13 scenario. As reported in the previous section on life support, it appears feasible to provide enough life support consumables to enable this, if reasonable abort trajectories are possible. However, the preliminary abort trajectory assessment was not as favorable. We computed the ΔV vs trip duration for abort return trips branching off the nominal outbound trajectory at different times during the nominal mission. An example for a 145 day mission to asteroid 2000 SG344 is shown in Figure 19. Out of six asteroids examined, only one (2006 RH120) had any period when the abort return ΔV was low enough for a single Orion to return within 90 days, and this safe period lasted only for the first six weeks of the outbound leg. For several other asteroid opportunities the combined ΔV of both spacecraft was sufficient to return in less than 90 days at any point during the outbound leg of either of these missions, if both spacecraft propulsion systems were operational. Much effort has gone into making the Orion propulsion system reliable to prevent the scenario of being stranded in lunar orbit, including adding auxiliary axial thrusters which are sized to provide backup to the main engine. So, it is plausible that the propulsion system of the faulted Orion would still be operational for at least some classes of spacecraft failures. However, for two of the five asteroids (2007 UN12 and 2008 EA9) even if both spacecraft propulsion systems were functional it would only be possible to perform an abort return at the end of the outbound trajectory, essentially mimicking the nominal mission. If a major malfunction were to occur during the middle of the outbound leg, the crew would have to wait several weeks before they could perform a propulsive maneuver to return home at approximately the nominal return date. Having redundant Orion spacecraft may not help the crew survive a major failure in these cases.

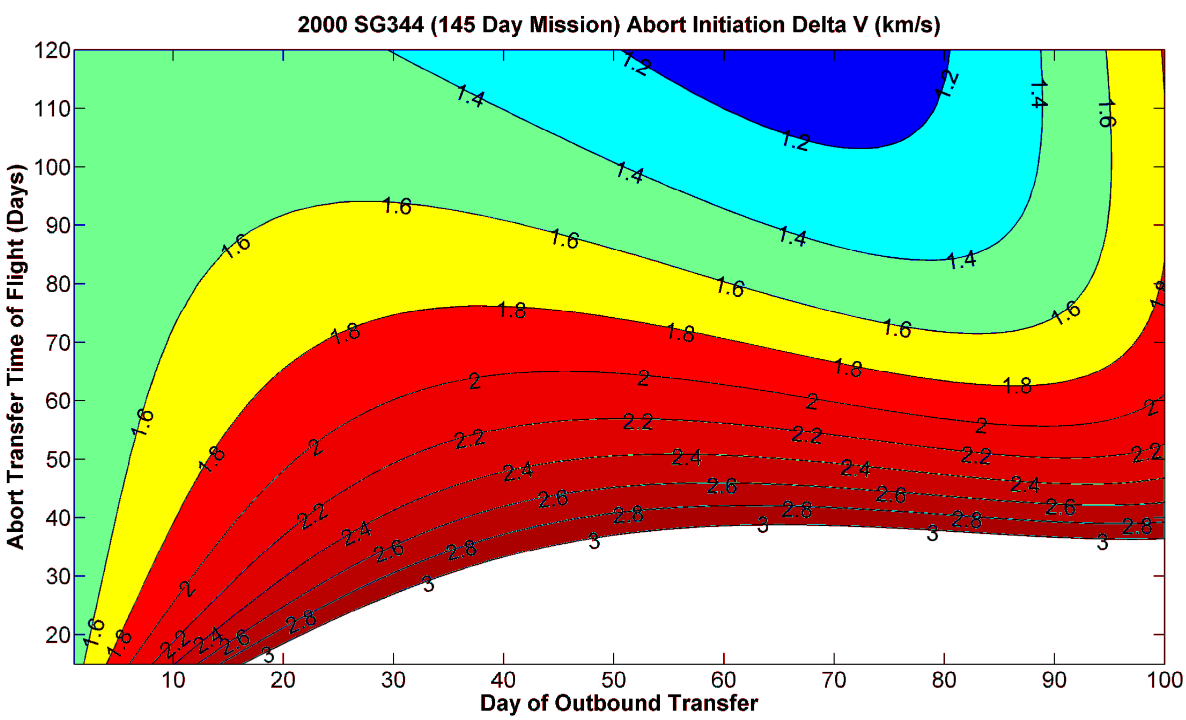

Figure 19: ΔV required to abort to Earth at various times in the outbound trip to asteroid 2000 SG344
Image Credit: Lockheed Martin

These abort results are only preliminary and further mission design work should be performed in an effort to improve abort options for asteroid missions. For example, it may be possible to design the nominal trajectory differently, in ways that make abort return trajectories easier at some cost in increased ΔV or trip time for the nominal trajectory. This would be analogous to the hybrid free return trajectories used during later Apollo missions, which accepted some constraints on the translunar trajectory in order to enable low ΔV Earth return aborts. Designing for aborts would be especially important for a mission architecture with dissimilar vehicles. For example, combining a large cryogenic propulsion stage with a single smaller spacecraft like Orion may result in nominal trajectories which are only feasible as long as the cryogenic stage functions properly, because the return spacecraft may not have enough propulsive capability to abort if the much larger stage failed. Abort assessments will also influence the decision whether to use two standard Orions with redundant reentry capability, or a standard Orion plus an Orion Deep Space Vehicle which would not offer redundant reentry, but would be better equipped for long abort return trajectories.

11. Next steps

The assessments documented in this report, though encouraging, are only preliminary and there is still much work to do in order to verify the feasibility of human exploration of the asteroids. Key areas for future work should include: a more detailed assessment of Orion capabilities and design modifications, the development of an operational concept at the asteroid destination, refinement of the mission trajectory, and an increased focus on asteroid characterization.

The first-order assessment suggests Orion can meet the major requirements for an asteroid mission, such as duration and life support consumables. However, there are many other details to be considered. Additional investigation is needed to determine whether the current Orion design is compatible with long-term continuous habitation and operation by only two astronauts. The mating of two Orions nose-to-nose has implications for both the structural design and operational interaction of the two spacecraft which require additional analysis including GNC/RCS, consumable sharing, and thermal management. For example, we have not yet investigated thermal management or power issues because for the most part the deep space environment is more benign than orbiting either Earth or the Moon. However, since the two Orions face in opposite directions there may be situations where it is not possible to point both in the optimum attitude for thermal management and power generation. Additionally, the missions occur at much greater distances from Earth than previous manned experience so communication link budget and signal delay need to be addressed. The Orion communications system includes a high-gain Ka band antenna but will probably need a higher power amplifier depending on data rate requirements. Enhanced capabilities such as the habitat module should also be considered in more detail.

Mission operations concepts for the spacecraft and spacewalking astronauts in close proximity to the asteroid should to be further developed to determine whether an asteroid mission is truly practical. Topics to be addressed include stationkeeping, depressurization, EVA activity and external equipment accommodation on Orion, design of a spacesuit propulsion system similar to a modern MMU, and development of techniques for EVA mobility on the asteroid including sample collection and emplacing equipment. Planning for these activities is complicated by the lack of definite knowledge of the asteroid body motion and surface composition. The approaches for these capabilities need to be robust enough to tolerate the uncertainties about the asteroid environment and also allow for contingency operations which may be complicated for a small crew size.

While the trajectory analysis methods used to date are appropriate for large scale searches of mission opportunities and estimation of basic propulsive requirements, more fidelity is required to confirm these findings. More analysis of the reentry phase is needed, and should include aerothermal considerations and targeting of specific landing zones. Deep space abort trajectories should be studied further. These mission design activities should also be repeated for new asteroids as they are discovered.

Designing a deep space mission will require that appropriate safety criteria and design standards be developed. Mission-specific design criteria for aborts and contingencies have been design drivers for recent human spacecraft programs such as CRV, OSP, and Constellation and likely will be for asteroid missions as well. Careful consideration of these requirements is needed, because implementing them well protects astronaut safety, but poor requirements can force onerous design choices which do not really improve safety much. Radiation dose requirements and exposure assumptions are examples of safety requirements which will be unique to deep space missions and which may determine whether or not it is practical to pursue this mission. A more advanced understanding of the biomedical effects of the deep space radiation environment may be needed in order to define these requirements.

Finally, and most important, if an asteroid mission is going to be a goal of the space program more funding should be allocated to astronomers who detect, track, and characterize near Earth asteroids. The President's 2011 Budget Request makes a good first step in this direction. Much of the effort needed to discover destinations for future missions would be complementary with projects to identify potentially hazardous impactors. However, more attention must be paid to asteroids which are determined not to be an impact risk but which are potentially accessible. Also, while impact hazard assessment focuses primarily on determining asteroid trajectories, exploration will require that we determine other characteristics of the asteroids as well, such as composition and spin rate. Since the opportunities to observe these asteroids occur several years apart, the next few years are the best time to discover asteroids which could be the destinations for missions in the 2020 timeframe. The necessary investment in ground based observation capability would be on the order of tens of millions of dollars per year. This is quite small compared to the reduction in mission cost that would be enabled by discovering more favorable asteroid destinations. A space based asteroid survey spacecraft would require a larger investment but would detect more asteroids more quickly. Ground based observation, space based surveys, and precursor robotic spacecraft visits are good opportunities for international collaboration.

12. Conclusion

Several clusters of small islands lie off the Atlantic coasts of Europe. While they are mostly unremarkable destinations in their own right, they served important roles in European exploration as training grounds to develop the skills and technology for transatlantic voyages, and as stepping stones to more distant destinations. The Norse settled the Faroe Islands north of Scotland around 650 AD, using primitive boats. After two hundred years sailing the North Atlantic, they had developed the experience and shipbuilding technology necessary to reach to Iceland in 870, then push on to Greenland and then Newfoundland. Prince Henry the Navigator sent early Portuguese explorers and colonists to the Madeira Islands around 1420, a generation before they were ready to press along the coast of Africa to India and the Spice Islands. The Canary Islands were a resupply stop for expeditions from Columbus to Magellan to Darwin. In 1609 the *Sea Venture* was struck by a hurricane on a voyage to resupply the new settlement at Jamestown. Her passengers survived only by beaching it on the uninhabited island of Bermuda, where the plentiful wildlife was unafraid of hungry castaways and there was enough lumber to build new ships. The Bermuda survivors who made it to Jamestown included John Rolfe, who introduced the tobacco that made the colony viable, and Stephen Hopkins, whose experience at both Bermuda and Jamestown came in handy when he later sailed on the Mayflower. Atlantic islands would be used as supply stops until as recently as the 1940s, when aircraft landed in the Azores to refuel, enabling practical air travel between Europe and America before airliners with true trans-Atlantic range were developed.

In the twenty-first century, the most accessible asteroids may well serve a role similar to that of the Atlantic Islands. Asteroids like 2008 EA9 and 2000 SG344 can be the easier intermediate destinations on which we practice deep space exploration, before we are ready to attempt longer trips to Mars. But like the Atlantic islands, we won't explore asteroids simply for practice. Rather, if we go it will be because these asteroids are attractive enough on their own merits to justify the expeditions. We will go to the asteroids to learn how to protect our planet from hazardous impacts, to find answers to fundamental scientific questions about the formation and history of our solar system, and perhaps for economic reasons, searching for valuable metals or water.

The Plymouth Rock study shows that the first visits to asteroids can be easier and earlier than we have previously thought. The United States does not need to wait for more advanced technologies or develop expensive dedicated deep space vehicles. We can explore the asteroids within a decade, using spacecraft already being developed and tested.

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