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Ares V: Application to Solar System Scientific Exploration

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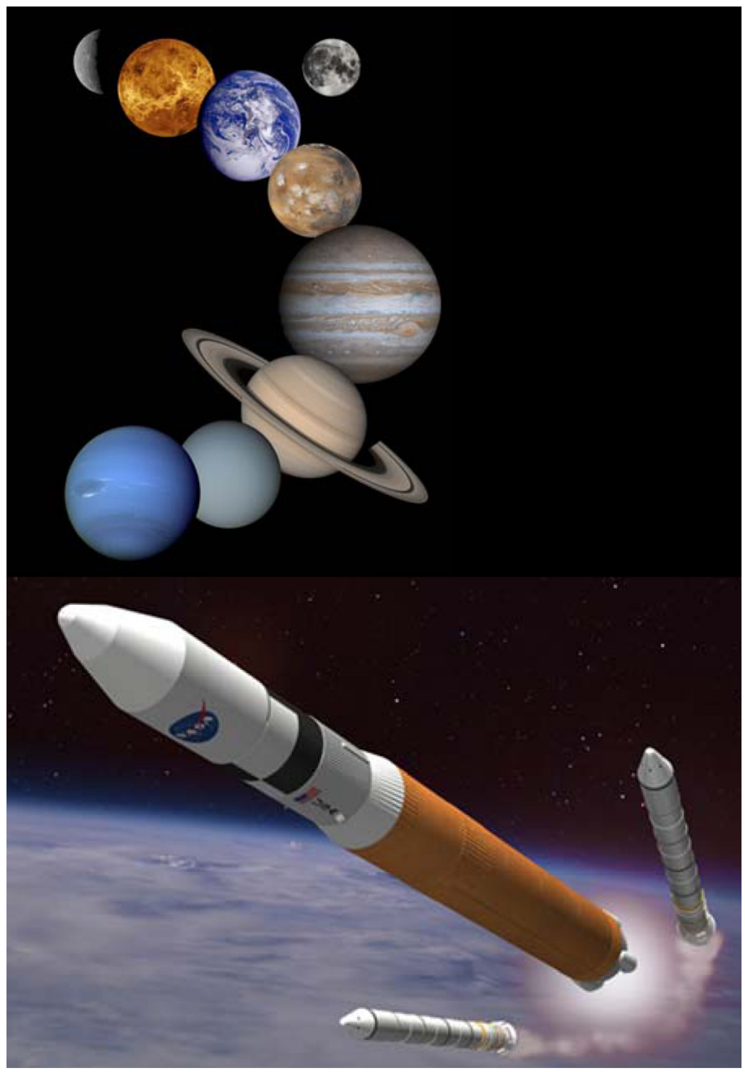

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1. Introduction

While the primary use envisioned for *Ares* V is to deliver large-scale cargo to the moon and supply needed staples to sustain a human presence beyond Earth orbit including Mars, the NASA administrator has asked what new science opportunities would be enabled by the capability of the *Ares* V launch vehicle. The general approach to addressing this question includes an estimate of vehicle performance over a wide range of C_3s (hyperbolic excess speed over escape, squared) and an examination of science missions that would be enabled by the increased capability of the *Ares* V.

Preliminary performance assessments indicate that *Ares* V could deliver 5 times the payload to Mars as compared to the most capable US launch vehicle available today, the Delta IV Heavy (Delta IV-H). Beyond Mars, the outer planets offer a number of high-priority investigations with compelling science as identified in the National Research Council (NRC) Decadal survey [1] and Solar System Exploration Roadmap [2]. Presently, missions to these destinations are only achievable using indirect flights with gravity assist trajectories and, in many cases, suffer from long flight times. An *Ares* V with an upper stage could capture these missions using direct flights with shorter interplanetary transfer times that would enable extensive *in situ* investigations and possibly the return of samples to Earth.

The following sections describe *Ares* V performance and its payoff to a wide array of potential solar system exploration missions. Application to potential Astrophysics missions is addressed in Reference 3.

2. *Ares* V Performance

Quantification of *Ares* V performance is based on the following assumptions derived from open literature [4].

- *Ares* V stage pre-ignition mass (total payload capability to LEO) is 131,800 kg in a 160-km parking orbit
- J-2X Upper Stage Specific Impulse (Isp) = 451.5s
- Lunar mission payload capacity = 54t (metric tons)
- *Ares* V final stage empty mass = 13.2t
- Burn assumptions:
  - Direct burn from circular parking orbit
  - *Impulsive with 10% gravity loss

*Due to the lower thrust-to-weight ratio, and longer burn time, a high gravity loss is assigned to discount the assumed upper stage Centaur flight for high C_3s.

Estimated performance for the *Ares* V launch system with and without the use of a Centaur upper stage relative to Delta IV-H capability is shown in Figure 1.

2.1 Moderate C_3 Range

Based on the current configuration and performance estimates for the *Ares* V, the maximum payload lift capability, when stacked with a fully loaded Earth Departure Stage (EDS), is 54t to

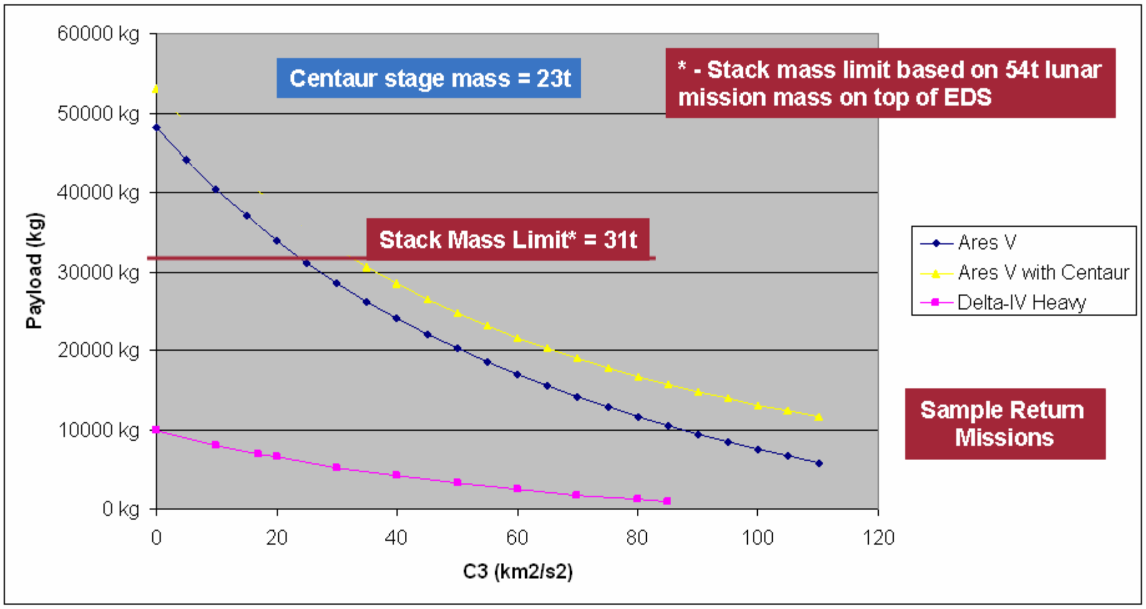

Figure 1 ***Ares*** **V high energy performance with/without an upper stage**

Low Earth Orbit (LEO). Given a fully fueled Centaur upper stage mass of 23t, a practical limit on payload mass when using an additional upper stage is 31t, as shown in Figure 1. Based on this limit, it is clear from the figure that any mission below a C_3 of about 35 km^2/s^2 could be launched using the *Ares* V without requiring an upper stage and yet delivers up to 5 times the mass of the currently available Delta IV-H. This C_3 is consistent with conventional outer planet missions that use multiple gravity assists, e.g., JPL's Europa lander [5], which would have traveled to Jupiter via multiple (three) Venus gravity assists.

Studies have shown that chemically propelled sample return missions to Mars, using Delta IV Heavy capability, could deliver ~8t to Mars at a C_3 of 10 km^2/s^2. This capability is estimated to be adequate to return ~10 kg of surface samples from two different sites. It can be seen from Figure 1 that the *Ares* V could deliver up to 40t, or a factor of five-fold improvement with an attendant increase in science return at this C_3. Furthermore, it has been shown that in the same C_3 range (9–18 km^2/s^2), the outer planets could be reached via multiple Venus gravity assists. It is also evident from performance comparisons between the Delta IV-H and *Ares* V that the latter can provide an additional launch mass capability of up to ~32t for the above C_3 range. Without an upper stage this comes at the cost of long-duration interplanetary transfer times associated with multiple inner planet gravity assists, for example VVVGA (Venus, Venus, Venus Gravity Assist) or VEEGA (Venus, Earth, Earth Gravity Assist). For chemically propelled missions these trajectories would take up to 10 years to reach a destination moon in the Saturnian system [6] without using Jupiter gravity assist.

2.2 High C_3 Range

For science missions to planetary systems and small bodies at the outer reaches of the Solar System, high launch energies (high C_3) are required to reduce cruise time and thus produce practical mission life times. This could be accomplished by significantly limiting the spacecraft mass or by adding an upper stage booster. For example, previous studies have estimated that 12t is a reasonable quantification of injection mass for outer planet sample return missions. As shown in Figure 1, the *Ares* V without an upper stage would open up direct sample return missions from the moons of Jupiter requiring a C_3 of ~80 km^2/s^2, while significantly shortening cruise durations. Sample return missions that would use a direct trajectory to Jupiter and its moons are estimated to take approximately 5 years round trip. In comparison, a sample return mission using a low-C_3 VEEGA trajectory would take about 9 years.

Even more dramatic are comparisons of direct missions (without gravity assist) to the Saturn system requiring a C_3 of ~110 km^2/s^2. Using an *Ares* V with an upper stage, a direct atmospheric/plume sample return round trip to Titan or Enceladus could be accomplished in approximately 10 years. In comparison, a plume sample return from Enceladus using a Delta IV-H launch vehicle has been estimated to take 18–25 years to complete [7].

3. Payoff to Solar System Scientific Exploration

In order to understand the potential benefits of *Ares* V capability in terms of compelling science, we first look at the enabling capabilities of the *Ares* V launch vehicle and then explore relevant solar system science mission concepts. The following subsections describe enabling capabilities of *Ares* V, application to solar system missions, and implications on *Ares* V requirements.

3.1 Enabling Capabilities

The *Ares* V launch vehicle brings opportunities to solar system exploration in a number of areas. First and most obvious would be the increased mass that such a vehicle could deliver to a target destination as discussed in Section 2.1. Alternatively, the expanded capability could be used to reduce transit times significantly, bringing a number of previously too-distant destinations within reach and opening up opportunities for mission architectures such as sample return from locations previously thought impractical. Another benefit of the *Ares* V is the significantly increased volume available inside the large payload fairing currently planned. This extra fairing size opens up possibilities for large aeroshells or other structures, or multiple element payloads, as well as reducing complex deployments associated with expansive spacecraft appendages.

The extra mass capability of the *Ares* V can be exploited in a number of ways. First is the opportunity to increase science capability. This can be accomplished through the accommodation of more complete instrumentation making use of a larger payload mass allocation. Additionally, the extra launch mass can allow a much more capable spacecraft with greater power and higher performance telecommunications to greatly increase data return from distant targets. Increased launch mass can also enable an increase in mission return through greater spacecraft delta-V capability. The ability to carry fuel sufficient to perform additional maneuvers at the destination can greatly expand the science missions that can be accomplished, including, for example, a single flight system that can access multiple targets. Additionally, the choice of target destinations can be expanded to include those with harsh environmental conditions through the ability to carry mass sufficient to shield against hazards such as radiation or debris. A side benefit of extra launch mass is the ability to simplify space system design, trading higher mass for lower-complexity solutions that can both reduce cost and increase robustness.

In conjunction with the ability to deliver higher mass, the performance of the *Ares* V can be used to significantly reduce trip times to distant destinations. The first benefit of this would come in earlier science return. This becomes a distinct advantage when considering missions to outer planets that might not be able to reach their destinations until more than a decade after launch if limited to current launch capabilities. In addition, taking advantage of shorter flight times to and from a target body could enable a whole new class of sample return missions: those that require mission durations that would be prohibitive with a less capable launch vehicle. For nearer targets the reduction in flight time can provide lower costs as well as lower risk by shortening the time spent in cruise operations. Shorter cruise durations also enable extended science mission duration once the target is reached. This feature becomes especially important when considering single missions to multiple targets.

Finally, the large fairing volume available with the *Ares* V (~10m diameter) enables a number of new opportunities. One important capability would be the accommodation of large flight system elements such as large-aperture antennas and optical systems. Large aeroshells up to twice the diameter currently possible on evolved expendable launch vehicles could be accommodated, enhancing delivered mass capability to planetary surfaces and/or opportunities for aerocapture. In all cases the larger volume available could result in simplification of packaging for complex deployables and greatly enhance the capability for multi-element missions, such as orbiter/lander combinations.

3.2 Application to Solar System Missions

The *Ares* V vehicle could enable a variety of mission types to the outer solar system. This includes orbiter missions to the farthest giant planets, the ice giants Uranus and Neptune; planetary networks in the outer solar system; sample return missions to a variety of outer solar system destinations; complex missions involving multiple diverse flight elements; and missions requiring large propulsive delta-V. This section briefly examines each of these categories and gives scientifically relevant examples.

Ice Giant Orbiters

Ice giant planets are so named because their most abundant constituents are not the gases hydrogen and helium, but rather compounds usually found as ices in the outer solar system, such as water. The two examples in our solar system, Uranus and Neptune, are also its most distant giant planets. It is this distance that leads to difficulty in inserting into orbit after a transfer from Earth of reasonable duration. Design lifetimes of radioisotope power systems drive the transfer trajectories to ones significantly faster than quasi-Hohmann trajectories, so the V-infinity of approach must be high, driving up the delta-V required for orbit insertion. Typical orbit insertion delta-V for a 12- to 13-year transfer to Neptune is in excess of 7 km/s. With current or even envisioned chemical propulsive orbit insertion, the inserted mass fraction is less than 10% of the approach mass. For current launch vehicles this yields far too little mass in orbit for a scientifically justifiable mission. Aerocapture has promised to increase that inserted mass fraction to 50% or more, so that orbit insertion technique has been emphasized in most recent studies [8, 9]. But the aerocapture method would not be used for a science mission until it has some kind of flight demonstration, and currently there is no firm plan for such a demonstration. The *Ares* V would allow launching sufficient mass to Neptune to support a scientifically worthwhile mission using chemically propulsive orbit insertion. The same scenario applies to Uranus.

Planetary Networks in the Outer Solar System

Shifting focus from the planets themselves to their satellites, multiple destinations of high scientific interest would benefit from various types of networks emplaced there, including such systems as geophysical networks, meteorological networks (possibly combined with the geophysical networks), and even navigational/communications constellations equivalent to Earth GPS and communications satellite constellations. Current launch vehicles would allow emplacing only one or two such assets into orbit at a time, where an *Ares* V would allow emplacing an entire capable network from a single launch.

Sample Return

Outer planet icy satellites are also prime candidates for sample return missions, as are some active comets. Satellites of Jupiter and Saturn—namely, Europa, Titan, and Enceladus—are objects of intense scientific interest for their astrobiological potential. But the most productive of sample return missions to those destinations would require very large launch masses if the missions are to be accomplished within reasonable mission durations as mentioned in Section 2.2, or in some cases at all. For Enceladus, it might be possible to fly to the Saturn system with a fairly standard Earth-to-Saturn transfer trajectory, perform a high-energy flyby through the south polar plume (Enceladus approach V-infinity >10 km/s) and capture a sample, and then return the sample to Earth via a free-return trajectory, with a Delta IV-H or even the largest of the Atlas V family. But the duration of such a mission would be at least 18 years [10], and the high-energy capture is likely to destroy some of the most important aspects of the sample, especially details of any organic constituents. To reduce the mission duration, and also to reduce significantly the flyby speed for a sample capture pass, requires far more delta-V and thus propellant than could be launched with one of the vehicles mentioned. This is partly due to Enceladus' location deep within Saturn's gravity well and partly due to Saturn's remote location, averaging ~9.5 AU from the sun. Return of a well-documented surface sample from Enceladus is even more demanding, requiring the addition of the capabilities and thus equipment for a soft landing, plus the increased delta-V above needed for the low-energy flyby scenario.

Europa is a high-priority destination for a surface sample return. Despite being closer than Enceladus, with Jupiter's heliocentric distance averaging ~5.2 AU, Europa is well into Jupiter's even larger gravity well, so the delta-V requirement for a well-documented surface sample return of reasonable duration would be quite large. Europa has no known eruptive plumes such as those on Enceladus, so there would be no opportunity to return a sample without a soft landing on its surface.

A surface sample return from Titan would also be extremely important scientifically, but its location at Saturn and its dense atmosphere make it as demanding a destination as Enceladus. The Titan atmosphere, ~4 times as dense as Earth's at the surface and highly extended such that orbiting at altitudes below ~1400 km is difficult, aids the entry, descent and landing by allowing an aeroshell and parachute to supply the ~6 km/s delta-V (minimum) needed to go from hyperbolic approach to landed on the surface. But it seriously complicates the ascent back into space for escape from both Titan and Saturn, again requiring a delta-V of ~6 km/s. Current studies are addressing the question of whether a simple Titan orbiter that uses chemical propulsion instead of aerocapture for orbit insertion could be launched on a Delta IV-H. A Titan surface sample return mission would be much more demanding than that. It is clearly infeasible on current expendable vehicles, but would likely be enabled by an *Ares* V [11].

Return of a cryogenic sample from an active comet might be accomplished with less delta-V than an icy satellite sample return, but would require a massive two-stage refrigeration system and power system One of the highest-priority objectives of such a sample return mission is to maintain the icy components in their natural crystalline (or amorphous) form. If the sample to be returned is expected to contain amorphous ice, preventing that ice from reverting to a crystalline form (an exothermic alteration that can affect other constituents) requires maintaining it at temperatures no higher than 130 K. Maintaining such temperatures would require at least a two-stage refrigeration system that is fairly massive, and the large power requirements of such a system call for a massive power system. For the final phase of the mission, i.e., descent through Earth's atmosphere for sample recovery on Earth's surface, that refrigeration system might have to maintain a fairly large reservoir of a cryogenic phase-change material such as liquid nitrogen. The need for all this heavy equipment drives a large launch mass.

Complex Missions with Multiple Diverse Elements

Another class of missions that can require a large launch capability is complex missions, especially when they involve multiple flight elements, such as combinations of orbiters, landers, and/or aerobots [12]. One immediate example would be a mission to Europa consisting of a capable orbiter and one or more capable soft-landers. Current studies [13] indicate such an ambitious mission would be too massive to launch on a Delta IV-H. Another recent example is the TandEM mission proposed to the European Space Agency Cosmic Vision 2015–25 Program. TandEM proposes to deliver two medium-sized spacecraft to the Saturnian system. One spacecraft would be an orbiter with a large host of instruments that would perform several Enceladus flybys and deliver penetrators to its surface before going into a dedicated orbit around Titan alone, while the other spacecraft would carry the Titan in situ investigation components, i.e., a hot-air balloon (Montgolfière) and possibly several landing probes to be delivered through the atmosphere.

Demanding, High-Performance Missions

Ice Giant orbiters, sample return missions, and complex missions are not the only ones needing a large lift capability. Some seemingly straightforward missions simply require very large delta-V, and that drives launch mass. An Io orbiter needs the large delta-V due to its location far down in Jupiter's gravity well. The Saturn ring observer concept can use a fairly simple spacecraft for its science mission, but the delta-V for insertion into its science orbit at Saturn is 10–11 km/s. Once in that orbit the spacecraft can never cross the ring plane, so it must maintain a non-Keplerian orbit propulsively, adding to the mission delta-V requirement. Other missions that target multiple destinations with a single flight element have large delta-V requirements. Examples include a chemical-propulsion precursor mission concept for a non-fission Jupiter icy moon tour, studied as a precursor to Project Prometheus studies [14]. Each spacecraft of this two-spacecraft mission concept would orbit two of Jupiter's Galilean moons. The delta-V requirements for this ambitious mission profile require a launch mass of more than 17,000 kg, far more than a Delta IV-H could launch to a reasonable C_3, but within the envelope for an *Ares* V. Another multi-destination example is a large nuclear electric propulsion mission such as the Jupiter Icy Moons Orbiter (JIMO), which could be launched on a single *Ares* V to a

C_3>0. Another mission class that would naturally require very large delta-V includes missions that would achieve extreme heliocentric distances within a reasonable mission duration; the Extrasolar (1000 AU) Explorer and the Thousand AU (TAU) mission are examples. Sometimes a large propulsive mass does not immediately translate to large delta-V, notably when the mass accelerated is very large. One such case is a mission to significantly alter an asteroid's orbit in order to demonstrate the capability to divert an Earth-impacting body.

Limitations of Ares V Capability

Despite the appearance of almost miraculous capability from the preceding examples, there are scientifically interesting missions that appear (though these have not been studied in detail) to be beyond the capabilities of even the *Ares* V. One class of such missions is orbiters at very distant small bodies, such as Pluto or other trans-Neptunian objects. To reach these destinations in a reasonable amount of time they must arrive with very high approach V-infinity, and due to the bodies' small sizes the delta-V for orbit insertion is essentially that approach V-infinity, typically 12 km/s or higher; the approach V-infinity for New Horizons at Pluto is 14 km/s. Sample return missions from such objects, and even somewhat less demanding objects such as Neptune's moon Triton, appear beyond the *Ares* V capability.

Summary of Potential Application to Solar System Missions

The *Ares* V launch vehicle could enable a large range of scientifically exciting missions in the outer solar system and beyond. The missions enabled would use a variety of combinations of the basic advantages offered by the *Ares* V launch capability: larger mass, for use in large delta-V, to enable heavier but available-technology solutions to problems previously calling for exotic technologies, or to provide expanded science capability (such as multiple synergistic flight elements); shorter trip times; and systems of larger physical dimensions than current 5-meter fairings will accommodate. But despite the appearance of limitless capability one might infer from the list of enabled missions and mission types, there do appear to be scientifically interesting outer solar system missions beyond even the *Ares* V capability. The best examples are orbiter or sample return missions to the most distant outer solar system small bodies, such as ice giant moons and trans-Neptunian objects.

3.3 Implications for *Ares* V Requirements

The envelope for solar system exploration and the achievement of major science goals would be expanded significantly by making use of the *Ares* V heavy lift capabilities. Key to enabling the effective application of *Ares* V to challenging solar system missions is the identification of requirements that if considered during development, would enable its broader use beyond lunar and Mars exploration. Requirements specific to planetary and small body exploration systems derive from areas such as pre-launch flight system cleanliness driven by planetary protection, ability to survive the launch environment, accommodation of spacecraft configurations that minimize post launch deployments, payload and spacecraft thermal control in the launch configuration, launch vehicle interface (e.g., electrical, mechanical, thermal), special needs for handling and integrating nuclear payloads, launch targeting and transfer stage to achieve interplanetary trajectory and preparation of a comprehensive Payload Planner's Guide. Quantification of requirements can be achieved by undertaking studies to assess in more detail (1) representative mission system designs (spacecraft and science payloads) specifically enabled by *Ares* V, (2) key driving requirements that solar system missions place on *Ares* V, (3) design impacts on the *Ares* V system(s) necessary to launch solar system missions, including supporting systems (e.g., specialized transfer stages, modifications of the fairing), and (4) cost estimates and cost trades for the *Ares* V systems necessary to launch exploration missions. Results of these studies would couple directly to the *Ares* V development activity to ensure that its capabilities are targeted to the broadest application space and in turn increase return on taxpayer investment.

4. Summary and Conclusions

In summary, there appears to be a wide range of science missions that could be launched by *Ares* V that would not be possible otherwise. *Ares* V capability is expected to open up lunar, Mars, near Earth and solar system missions for heavy payloads, and might even enable reasonable sample return missions from the far reaches of the Solar System. Furthermore, *Ares* V, configured with an upper stage, could enable vastly more capable missions that could bring the search for habitability at far reaches of the solar system much closer.

It is an obvious conclusion that in order to make maximum use of this capability, design requirements specific to challenging solar system exploration missions must be identified for consideration during *Ares* V development. Follow-on studies should be considered to examine in detail the capability of the *Ares* V vehicle to enable large, complex solar system exploration missions, the results of which will be valuable to NASA's programs for both human and robotic exploration.

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