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Synergies of Robotic Asteroid Redirection Technologies and Human Space Exploration

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This paper summarizes the results of a 2014 KISS workshop that identified a wide variety of ways that the technologies (and their near-term derivatives) developed for the proposed Asteroid Redirect Mission (ARM) would beneficially impact the Nation's space interests including: human missions to Mars and its moons, planetary defense, orbital debris removal, robotic deep-space science missions, commercial communication satellites, and commercial asteroid resource utilization missions. This wide applicability of asteroid retrieval technology is, in many ways, is just as surprising as was the initial finding about the feasibility of ARM. The current Asteroid Redirect Mission concept consists of two major parts: the development of an advanced Solar Electric Propulsion (SEP) capability and the retrieval of a near-Earth asteroid. The improvement in SEP technology required by ARM provides an extensible path to support human missions to Mars, is applicable to <u>all</u> planetary defense techniques, could reduce the time required for the LEO-to-GEO transfer of large commercial or military satellites, would enable new deep space robotic science missions, and could enable affordable removal of large orbital debris objects. The asteroid retrieval part of ARM would greatly improve the understanding of the structure of rubble-pile asteroids necessary to evaluate the effectiveness of primary asteroid deflection techniques, demonstrate at least one secondary asteroid deflection technique, greatly accelerate the use of material resources obtained in space to further space exploration and exploitation, and further planetary science.

I. INTRODUCTION

The Asteroid Redirect Mission (ARM) concept was developed in a Keck Institute for Space Studies (KISS) study in 2011/2012. The idea of capturing and moving a small (5-10 meter) asteroid was shown to be feasible with technology available in this decade and offered an important way to advance human exploration beyond low-Earth orbit. It would be simultaneously more interesting and beneficial than merely flying astronauts in lunar orbit, and more feasible and of lower cost than crewed missions to a near-Earth asteroid in its natural orbit. Importantly, it would advance key transportation technologies needed for future human missions to Mars. It would also expand planetary defence and in situ resource utilization endeavors, and further near-Earth asteroid science. ARM would thus represent both an enabling technical step and a programmatic solution to advance human spaceflight.

A key feature of the ARM technology is its potential to significantly improve the affordability of human missions to Mars. It would accomplish this primarily by furthering the development of high-power solar electric propulsion (SEP) technology. The proposed ARM vehicle represents a 30-fold improvement in SEP technology relative to the state-of-the-art. A further factor of 2 or 3 improvement would lower the cost human missions to the moons of Mars and a factor of 5 improvement significantly improves the affordably of human missions to the Martian surface. ARM, with its manageable risk and cost, would be the right-sized step to these higher-power capabilities. The improvement in affordably for Mas missions results from the remarkable fuel efficiency of solar electric propulsion —ten times better than the best chemical rockets—and the corresponding reduction in the mass of propellant required to be lifted from the surface of the Earth for these missions.

A more surprising possible benefit of ARM technology is its potential to provide a path for protecting astronauts against galactic cosmic ray (GCR) radiation on their long interplanetary voyages to and from Mars. Asteroids could provide the hundreds of metric tons of material that may be necessary to shield a deep-space habitat against GCRs enabling astronauts to make more than one round trip to Mars in their lifetimes. The skills for turning asteroids into habitat radiation shielding could be perfected using the ARM asteroid in lunar orbit with crewed mission durations of a couple of months at a time. During these missions to the ARM asteroid, another asteroid could be robotically redirected to an orbit matching the Earth's period. In this orbit astronaut crews in six-month-long missions could use it to provide radiation shielding for their deep-space habitat using the techniques learned in lunar orbit. The resulting multi-hundred-ton, radiation-shielded, deep-space habitat could then be transferred to a Mars cycler orbit using a combination of the Earth gravity assists and SEP thrusting. Astronaut crews could now travel to Mars in an environment shielded from galactic cosmic rays.

Finally, ARM breaks the ISRU paradigm of resource utilization at the destination by instead bringing materials to the point departure. This risk-lowering approach may be the key to unlocking the potential of wide-spread ISRU.

II. ARM-DERIVIATIVES FOR MARS MISSIONS

One version of the Asteroid Redirect Mission under consideration would deliver a multi-hundred-ton, near-Earth asteroid to a lunar DRO for subsequent investigation by astronauts in the mid 2020s. Once this capability has been demonstrated, many new and innovative variations on this theme become possible.

Human missions to Mars face multiple difficult challenges including: life support systems that must function reliably for years; the ability to land large masses on the Martian surface; the need for lots of equipment, supplies, and propellant to be brought from Earth; and the need to maintain the health of the astronauts for years including protecting them from galactic cosmic rays (GCRs). Derivatives of the ARM vehicle (ARV) and of the ARM mission itself provide potential pathways for addressing two of the most difficult problems facing human missions to Mars: (1) How to significantly reduce the enormous amount of propellant required for each mission, and (2) How to protect astronauts against GCRs.

II.A High-Power SEP Tugs

High-power electric propulsion has long been recognized for its potential to significantly reduce the mass of propellant required for a human mission to Mars thereby reducing launch costs considerably making the whole endeavor more affordable. Solar power in space has advanced much more rapidly than in-space nuclear power as demonstrated by the International Space Station (ISS) that has approximately 260 kW of solar array power (at beginning of life). With modern triple junction solar cells at 29% efficiency a solar array with the same area as the ISS arrays would generate over 600 kW of power at 1 AU from the sun. The near-term potential for very high-power solar arrays makes solar electric propulsion (SEP) the leading advanced propulsion candidate for improving the affordably of human exploration missions to Mars.

Much lower power solar electric propulsion is being used successfully on commercial communication satellites and NASA's Dawn mission to the main belt asteroids (4) Vesta and (1) Ceres. Dawn's ion propulsion system has already provided a record-setting

ΔV of over 10 km/s. In contrast, the greatest ΔV provided by any chemical propulsion system in deep space is less than 3 km/s. ARM would improve the total impulse capability of SEP systems by a factor of 30 relative to the current state of the art.

Human missions to Mars would require SEP vehicles with power levels of order a few hundred kilowatts [1]. SEP systems could be used both for the transportation of cargo and supporting infrastructure, and directly for carrying human crew. The highest power SEP systems flying today process a maximum of 9 kW to do some of the orbit-raising for large GEO comsats. Dawn, the highest power SEP system ever flown in deep space, processes a maximum power of 2.5 kW. The ARM ARV would process 40 kW providing the right-sized stepping stone to the higher power SEP vehicles needed to support human exploration of Mars. This step up in power provides meaningful risk reduction for the development of these higher-power vehicles while also being readily achievable, as well as useful in its own right.

ARV-derived 100-200 kW SEP systems can roughly double cargo payload delivered to high-Earth orbit (HEO), lunar distant retrograde orbit (LDRO), Mars orbit, Phobos, and Deimos. Such ARV-derived tugs could transfer cargo from a lower elliptical Earth orbit to a HEO, LDRO, or other orbit in Lunar vicinity. The key design parameters are array power, specific impulse (*Isp*), and maximum useable propellant (typically Xe). In Figure 1 the mass delivered to a lunar-crossing orbit and corresponding trip time are provided for various power levels and using up to 25 metric tons (t) of propellant. For reference, the baseline ARV provides a maximum SEP power of 40 kW (assuming a 50-kW solar array), a specific impulse of 3000 s, and up to 10 t of propellant. The ARV may be considered a stepping stone to the higher power, more capable vehicles assumed in Figure 1. The propellant contours for each power level are driven by allowing the specific impulse to vary between 1500 s and 5000 s, where lower *Isp* generally produces shorter flight times, and higher propellant mass and high *Isp* corresponds to longer flight times and less propellant. The launch vehicle assumed is a single block 2 SLS with estimated performance capable of lofting 130 t to LEO or 47 t to lunar orbit without a SEP stage.

To deliver masses in the range 60–70 t to a lunar crossing orbit, the SEP spiral ΔV is relatively low since the launch vehicle can perform most of the transfer by launching to an elliptical orbit with a high apogee. In these cases the propellant mass is low and spiral times are shorter. For higher delivered masses in the range 90-100 t, which effectively doubles the performance capability of the SLS to a lunar crossing orbit, the SEP stage performs most of the transfer ΔV, requiring more propellant and spiral time.

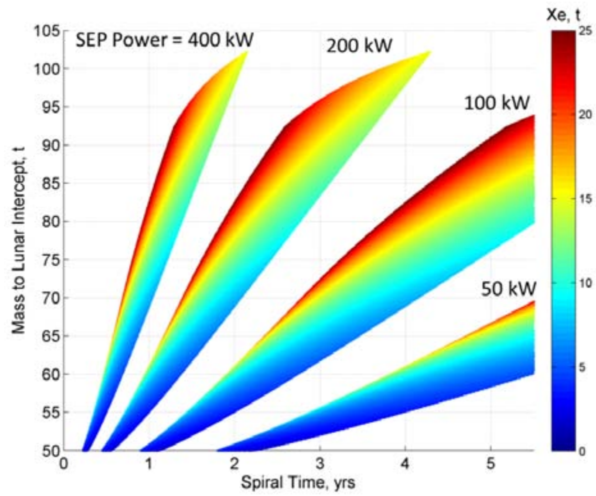

Figure 1. SEP can roughly double the mass delivered to lunar-crossing HEO from a single SLS launch. The specific SLS assumptions to recreate this figure are 241 km LEO, 140.8 t in LEO with 23.6 t inert upper stage, 462 s *Isp*. SEP spiral to 384000 km circular orbit for Lunar intercept, 44% efficiency at 1500 s, 67% efficiency at 5000 s.

II.B SEP Cargo Delivery for Mars Missions

Very large payloads could be delivered to an elliptical Mars orbit with an ARM-derived, high-power SEP vehicle combined with lunar gravity assists to escape Earth and chemical capture at Mars. For example, a cargo transfer trajectory is shown in Figure 2 where 77 t are delivered to a 250-km altitude periapsis

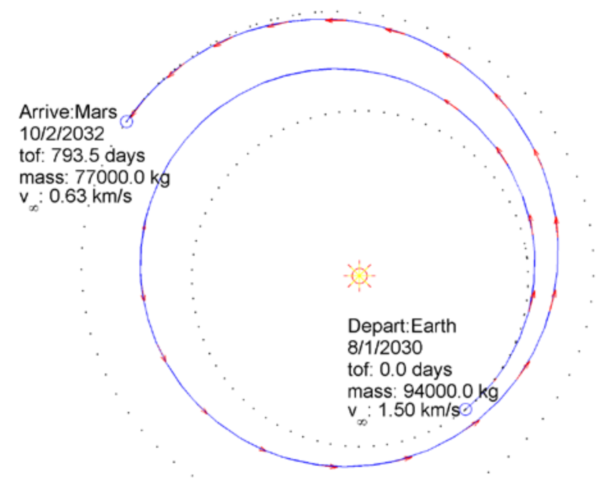

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Figure 2. A 270-kW SEP vehicle can perform a 1.5-revolution transfer to Mars (preceded by a geocentric spiral and lunar-assisted escape) and combined with a high-thrust capture maneuver at Mars would deliver a 70 t of payload to a 1-sol orbit from a single SLS Block 2 launch.

by 1-sol period Mars orbit. The assumed propulsion systems are a 270-kW SEP system operating at 3200 s Isp, and a bi-prop system with 323 s *Isp* for capture at Mars. The transfer begins with a 2.4-year Earth spiral to a lunar-crossing HEO requiring 22.0 t of Xe. Then lunar gravity assists inject the vehicle to an Earth escape V_∞ of 1.5 km/s. A 2.2-year interplanetary transfer to Mars expends another 10.2 t of Xe and a bi-prop maneuver captures the cargo from a 0.63 km/s V_∞ at Mars. Making the reasonable assumption that the combined dry mass of the SEP and bi-prop systems is 7 t, this leaves an impressive 70 t of cargo delivered to Mars orbit from a single SLS block 2 launch. A system based entirely on chemical propulsion would deliver only 26 t to this Mars orbit using aerocapture (and assuming a good Mars launch year). The value of high power SEP for support of human missions to Mars is obvious.

II.C. Intermediate Heliocentric Orbits for Stepping Stones into Deep Space

The step from cis-lunar to a human Mars missions would require major advances in several areas. ARM-derived technology enables several intermediate steps of increasing duration and challenge. A couple of especially interesting possibilities that build to human exploration of Mars are described below.

II.C.1 Earth-Resonant Orbits

The baseline ARM concept requires the identification and characterization of asteroids with very Earth-like orbits in which the Earth-encounter V_∞ is less than about 2 km/s. For asteroids that have higher energies (higher V_∞) with respect to Earth, a flyby of the Moon does not provide sufficient leverage to capture them and additional lunar flybys or more SEP thrusting would be required to eventually capture these objects into the Earth-Moon system at the expense of significantly increased time and/or propellant expenditure.

Alternatively, such high-energy asteroids could be redirected to Earth flybys where gravity assists then place them on heliocentric trajectories that repeatedly encounter Earth [2]. Such Earth-resonant orbits would make potentially ideal locations to take attractive asteroids (scientifically and/or commercially) that are otherwise too fast to practically capture into the Earth-Moon system. Especially useful is an Earth backflip orbit (i.e. a 180 degree transfer) that would match the Earth's period, but inclined so that the asteroid encounters the Earth twice a year.

Asteroids placed in backflip orbits become accessible targets for deep-space crewed missions with a total mission duration of six months. The crewed mission would launch when the asteroid has an Earth flyby and ride with it on its backflip trajectory in which the crew is never farther than 0.2 AU from Earth (for asteroids with V_∞ less than 6 km/s) and only minimal ΔV (10s of m/s) is required to return the crew after launch. Such a mission provides a potentially attractive, affordable next step beyond the lunar DRO into deep space and the first step beyond the Earth-Moon system. It would be an intermediate step to an asteroid in its natural orbit or to Mars, one that is likely to be far more reachable and consistent with affordable human interplanetary transportation capabilities.

But it's what the crew could be doing for those six months that makes this even more interesting. The crew could spend its time dismantling the asteroid turning it into radiation shielding to protect against galactic cosmic rays (GCRs). This is a skill that could initially be developed and matured using the first asteroid returned to lunar DRO and then subsequently applied to another asteroid redirected to an Earth-resonant orbit. In this way, the astronauts would be creating a deep-space habitat shielded against GCRs. Subsequent Earth gravity assists could transfer the asteroid-shielded habitat to a 1-year resonant orbit, enabling more ambitious missions with 12-month durations taking astronauts up to 0.8 AU from Earth as a further step toward Mars. Crew activities for these longer stays could include science experiments with and analysis of asteroid materials, mining and ISRU experiments (possibly with commercial sponsors), astronaut EVA and surface operations experience, and deep space synoptic observations of Earth.

An initial search indicates that there are over four hundred near-Earth asteroids of the right size with orbital characteristics that would enable them to be redirected onto an Earth-resonant orbit. On each orbit 1–10 m/s of ΔV is required to target a flyby of Earth and maintain the resonance. The resulting gravity assist from Earth modifies the asteroid's trajectory and allows for a wide range of orbits as depicted in Figure 3.

II.C.2 Mars Cycler

If the asteroid redirected to an Earth-resonant orbit has a V_∞ greater than 3 km/s then additional Earth gravity assists could be used to transfer it onto a Mars crossing orbit that returns to Earth. This type of orbit can then be further modified to repeatedly encounter Earth and Mars resulting in the asteroid being on a Mars cycler trajectory. Similarly, a deep space habitat shielded against GCRs with material from an asteroid while in an Earth-resonant orbit could subsequently be

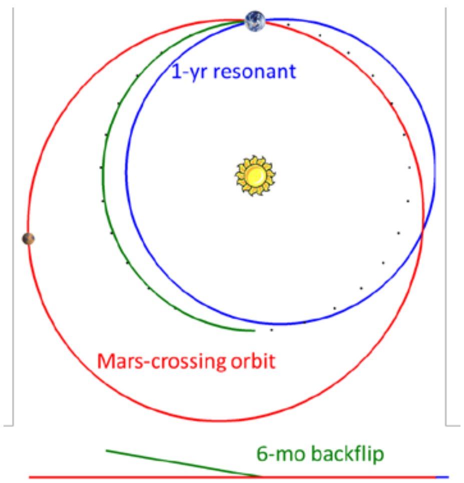

Figure 3. Redirecting small asteroids to Earth flybys could enable a wide variety of orbits where the asteroid could be "stored" including Earth-resonant orbits and Mars-crossing orbits.

transferred onto a Mars cycler trajectory, enabling crew transport to/from Mars in a multi-hundred-ton, radiation-shielded deep-space habitat. This process is illustrated in Figure 4. This is a possible basis for a robust, future Earth-Mars human transportation system, and should be studied further. It could permit astronauts to make multiple Earth-Mars-Earth trips without exceeding their allowed lifetime radiation dose.

III. ARM AND PLANETARY DEFENSE

Planetary Defense (PD), the mitigation or prevention of asteroid impacts, has been widely studied over the past decade as the hazard, real but nebulous, has slowly begun to penetrate the public consciousness. This growing awareness was punctuated on February 15, 2013 when a small asteroid (approximately 18 meters diameter) plunged through the morning sky over the Russian city of Chelyabinsk and momentarily captivated the world's attention. A successful PD effort can be parsed into three components: early warning; deflection or mitigation; and geopolitical decision. The first two components are technical in nature and both have implications for and interaction with asteroid redirection efforts.

III.A. Early Warning

Defense measures fall into two essential categories, civil defense for smaller impact threats (or "last minute" threat discoveries), and deflection for larger impact threats with greater warning time. The threshold between these two distinct responses has yet to be defined by the geopolitical community.

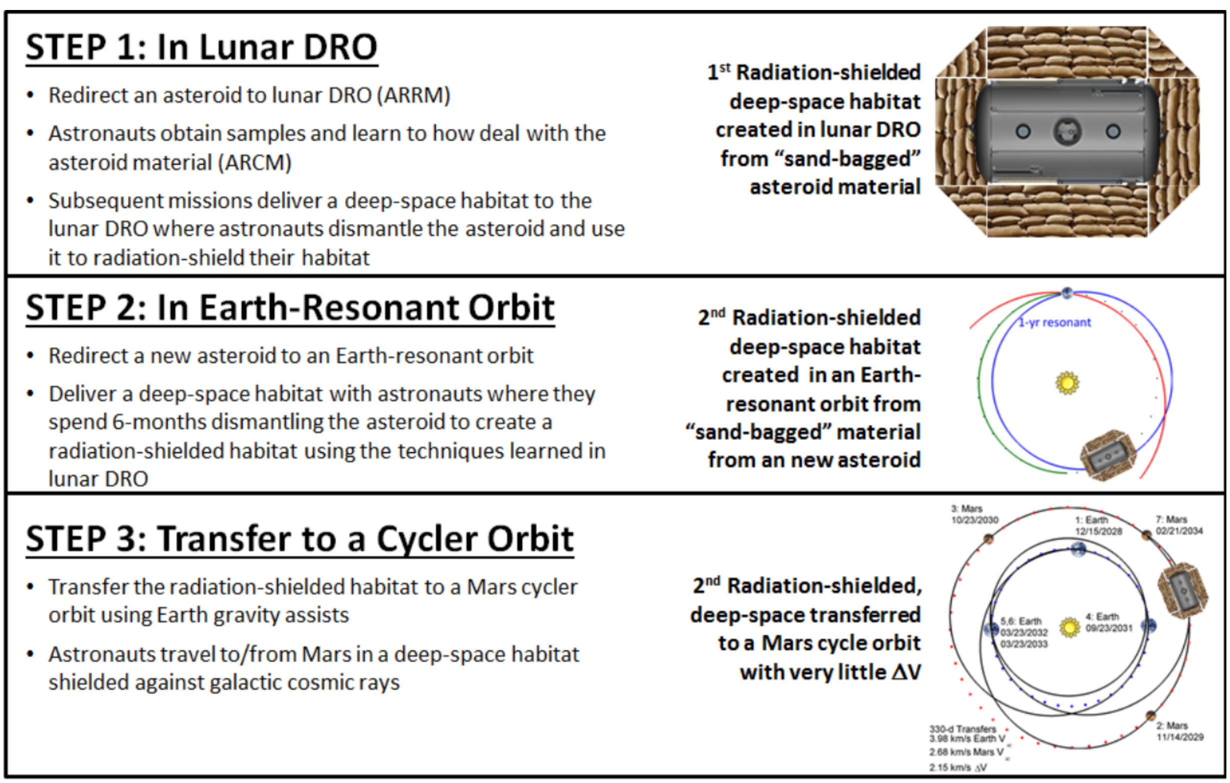

Figure 4. Illustration of a possible series of steps to create a radiation-shielded habitat on a Mars Cycler trajectory to support human exploration of Mars.

Early warning for civil defense (CD) response can vary from months or years at the upper end of the impactor size range to as little as days at the smallest threat level. The mainstream early warning efforts consist of NEO discovery, tracking and orbit determination, leading to impact prediction over extended periods of time. An emerging capability for last-minute discovery is now in development which would essentially discover objects only on "final approach" to an impact and provide, depending on the size of the impactor, days to weeks of warning. CD efforts for small imminent impacts might approximate the local evacuation response to hurricane threats.

Adequate early warning for PD deflection requires at least a decade between the initiation of a deflection campaign and the anticipated impact. The deflection option therefore depends on building a complete inventory of NEOs, projecting their orbits forward in time and identifying potential impacts out to 100 years (current practice). Impact probability becomes more precise with extended tracking and decreasing time to impact. Nevertheless in many instances the impact probability may still be significantly less than one at the latest date when a successful deflection can be initiated. Herein lies the tension between accurate early warning and geopolitical decision-making.

The asteroid impact hazard ranges widely from mass extinction at the high end to minimal surface damage at the low end. The corresponding object sizes and fluxes range from 8-12 kilometer diameter impactors impacting, on average, once per 100 million years to 15-20 meter objects impacting every 70-100 years. The respective population estimates and current inventory of these asteroids ranges from less than 10, essentially all of which we are tracking, to 10s of millions of which we have discovered and are tracking much less than one percent.

Two NEO discovery goals have been established and assigned to NASA by the US Congress. The first, to discover, track, and characterize 90% of all NEOs 1 km in diameter and greater by 2008 became law in 1998. That goal was essentially met in 2010 and approximately 96% of these objects are in the current NEO database. The second goal, written into law in 2005, was that NASA should similarly inventory 90% of objects 140 meters in diameter or greater by 2020. Approximately 10% of the estimated population of 140 meter objects are currently known and the likelihood of NASA completing this discovery goal by 2020 is essentially nil given current discovery rates and the lack of government funding for the necessary search assets. Non-government efforts to reach this goal are being undertaken which, if successful may reach the 140-meter goal by approximately 2024.

Very small NEOs, of the size of interest to the ARM community, come within the range of detection by the existing NEO discovery telescopes only on rare occasion. Nevertheless, given the large size of the population (100s of millions) they are discovered fairly frequently. Conversely those of greatest interest are restricted to the most Earth-like orbits, which results in long to very long synodic periods and substantial time between viewing apparitions. Furthermore due to their proximity at the time of observation these objects are tracked over relatively short arcs and well within the three-body gravitational domain. Filtering further yet for asteroid type (composition) reduces the inventory of suitable objects for ARM consideration to a mere handful. Hence the value to the ARM endeavor of a higher performance NEO early warning system.

III.B. Deflection

The successful deflection of a NEO headed for impact is the "holy grail" of PD. Deflection technology and techniques, while well understood and within current capability, are yet to be demonstrated and refined. Advances in the state of the art are also emerging which promise greater capability and flexibility of response. Many PD deflection concepts, both current and emerging, are potentially of interest to ARM. Conversely ARM, depending on the specific architecture, is potentially of great interest to the PD community, primarily in its potential to validate key deflection technologies. Real world validation is essential to safe PD, as the deflections must be precise in order to avoid "keyholes" as explained below.

Deflection of any NEO from an impact reduces to the task of slightly increasing or decreasing its orbital period in order to cause it to arrive late or early, respectively, for its impact rendezvous with Earth. In general the application of a small change in the NEO's velocity (typically several tenths of a cm/sec) several orbits prior to the predicted impact results in a change in arrival time at the impact intersection of 10 minutes or more, thereby resulting in avoidance of the impact. While less robust means over extended time periods are possible, the general means for generating such a NEO velocity change is kinetic impact (KI… simply colliding with the NEO) or a nuclear explosion, properly positioned (generally considered to be a "last resort" option).

This simple picture is somewhat complicated by the fact that the NEO, so deflected, would nevertheless pass nearby the Earth at the time of the predicted impact. Close gravitational encounters of this kind will further modify the NEO's orbit such that it will return to the impact intersection repeatedly with the period of return dependent on the near-miss distance resulting from the deflection. Since this near-miss distance is a continuous variable there are many resulting NEO orbital periods which are resonant with the one year Earth period. Any such whole number resonance (e.g. 3/2, 5/3, 4/7, etc.)

will result in a future impact, this impact being the result of the prior deflection. These small resonance regions, potentially encountered in a close gravitational encounter, are referred to as "keyholes" and have a small physical size due to the finite size of the Earth and the time it takes to pass through the impact intersection.

Therefore a successful NEO deflection campaign must not only cause the NEO to miss the Earth (primary deflection), but also in passing close by due to the deflection, pass between the resonant keyholes thereby avoiding a delayed impact several years later (keyhole deflection). Since keyholes are small compared with the size of the Earth (very small for those nearby the planet) and the space between them much greater than the typical keyhole dimension, it is likely that the primary deflection will not result in a resonant return and impact a few years in the future. Nevertheless the probability, while small, is not zero, and the deflection campaign cannot be declared to be successful unless passage between the keyholes is assured.

Such assurance would be provided by "trimming" the primary deflection by a small precision velocity increment if it is determined that the primary deflection has placed the NEO path unacceptably close to a resonant keyhole. The determination of whether or not a trim maneuver is required would nominally be provided by an "observer" spacecraft with precision orbit determination capability. The observer would measure the precise NEO orbit post-primary deflection thereby determining whether or not a further small adjustment to the primary deflection is required. A small but precise velocity change, if required, can be provided by several currently available means.

A gravity tractor would employ the observer spacecraft to "hover" in close proximity (2-3 NEO radii), either leading or trailing the NEO, to thereby slightly increase or decrease its orbital velocity via mutual gravitational attraction [3]. Since the observer spacecraft would have precision orbit determination capability a small but precise NEO orbit adjustment can be made as needed.

Similarly, but also not yet demonstrated, the observer spacecraft could employ opposing electric thrusters (gridded ion thrusters) to generate a small NEO acceleration by positioning the spacecraft so as to have the exhaust flow of one of the opposing pair impinge directly on the NEO [4]. Such a spacecraft could be positioned of order a kilometer away if equipped with ion engines that have an ion beam divergence half-angle of a few degrees. This approach mimics the kinetic impactor with the ion flux impinging at 60 km/s taking the place of the impacting spacecraft mass. The major difference is that with this ion beam deflector approach the impacting mass is spread out over time relative reducing its effectiveness relative to the kinetic impactor. In addition, the ion beam deflector approach does not benefit from the mass amplification factor, typically referred to as β, that can potentially increase the effectiveness of a kinetic impactor by a factor of two or more.

Potentially more powerful yet would be an observer spacecraft configured with a high power laser which could also be employed at considerable stand-off distance (a kilometer or more) to ablate a small spot on the NEO surface (or succession of such spots) thereby essentially creating a small rocket exhaust stream perpendicular to the NEO local surface, essentially using the threat object as the source of propellant to cause its deflection [5,6].

III.C. Mutual Implications between ARM and Planetary Defense

The PD search for NEOs produces discoveries of objects of all sizes that exceed the threshold radiation limits of the detectors. While PD per se is interested in those which potentially threaten life and property were they to impact, the system also discovers other objects which are potentially of interest to the ARM mission. Of concern to both PD and ARM is the very limited discovery rate of the current NEO search infrastructure. Both interests would be served by immediately upgrading the search capability to a level at least capable of meeting the assigned NASA goal of discovering 90% of 140 meter objects. While the target date of 2020 can no longer be met, 2024 is still achievable. Given that deployment of such a system would require an initial operations date of about 2018, considerable NEO discoveries of interest to ARM would begin flowing well before 2020.

Primary deflection technologies including KI and nuclear explosion (as a "last resort" option) would benefit significantly from an improved knowledge of the characteristics of potential threat objects. It is estimated that perhaps as many as 90% of the near – Earth asteroids are rubble piles. ARM, in its architectural option of capturing and redirecting an entire small NEO, uniquely provides an opportunity for detailed, up close study of a rubble-pile asteroid with the potential to significantly improve the understanding of their structure. Such an improved understanding is critical to modelling the effectiveness of primary PD deflection technologies.

Precision deflection technologies including gravity tractor, ion beam impingement, and perhaps even laser ablation, could be tested and the capability validated as an integral part of the ARM architecture. All three techniques utilize high-power SEP and would, with directed design, be of service to the mainline ARM mission. Station keeping at a NEO, maneuvering in its local proximity, as well as potentially executing a small velocity change to the object, are all of direct interest to both ARM and PD.

ARM, in its architectural option of retrieving a boulder from a large NEO, uniquely provides an opportunity to demonstrate and test a variant of the gravity tractor concept. Since the acceleration applied to the NEO by a gravity tractor is directly dependent on the mass of the spacecraft, the potential to enhance its effectiveness by first recovering a boulder from the surface of the NEO and subsequently acting as a gravity tractor is significant. For example, a 2-meter diameter boulder with a density of just over 2 gm/cc would have a mass of 10 metric tons. Depending on the specific ARM configuration, a gravity tractor so enhanced would have a "towing" capability exceeding its unenhanced performance by a factor of two. For Planetary Defense to benefit dramatically through the enhanced gravity tractor an order of magnitude more massive boulder would have to be picked up.

Alternatively, the attractiveness of demonstrating the ion beam impingement technique as a part of ARM is that this is the only technique that is completely independent of the characteristics of the threat object. (A regular gravity tractor is nearly independent of the threat object's characteristics, but must still deal with the non-uniform gravity field while attempting to hover or orbit in close proximity.) Ion beam deflection doesn't rely on the gravity of the body. It doesn't care about the details of a high-speed collision with an unknown body and how much mass might be ejected. It doesn't care about the size and brightness of the object to enable successful targeting for a high-speed collision. It doesn't care about the thermal conductivity of the surface and whether an impinging laser beam can heat it sufficiently to create the necessary rocket exhaust. Finally, it doesn't care about the technical feasibility and operational risk of picking up of order a hundred metric tons of material from a threat object with unknown surface characteristics before it can start its deflection process. The force on the threat object that the ion beam impingement technique provides is entirely within the engineering control of the spacecraft developers, with higher power systems providing greater force to the asteroid.

III.D. ARM Technology-Based Observer Spacecraft

The impact probability for most potentially hazardous objects will a have large uncertainty when a successful deflection activity must be initiated. Derivatives of the ARM SEP technology may help mitigate this problem. Small, low-cost SEP vehicles using direct-drive, ARM-derived high-voltage solar arrays and ARM-derived magnetically-shielded Hall thrusters could be configured as secondary payloads and affordably launched to any potentially hazardous object. Once at the threat object precision tracking of the spacecraft would precisely determine if it's an actual threat.

III.E. Planetary Defense Synergy with Asteroid Redirection

Although the program and mission objectives of asteroid redirection and planetary defense are totally different, the synergy between them in their development and technology is very high. As a result of ARM and the related NASA Asteroid Initiative, planetary defense has for the first time been recognized in a U.S. government program. The increased observation program supports both and is directly responsive to those in the international community calling for more attention to NEO observations for potentially hazardous asteroids. Deflection techniques may or may not end up using asteroid retrieval technology, but the analysis and consideration of them and their strategies certainly will.

IV. ARM AND RESOURCE UTILIZATION

One of the most attractive features of ARM would be the early opportunity to exploit the raw materials in the asteroid target. ARM may return tens to hundreds of tons of pristine asteroidal material to cislunar space, providing access to NASA astronauts, international partners, and commercial mining firms for demonstrations and iteration of resource extraction techniques and application.

A potential key benefit of the asteroid retrieval part of ARM is its near-term approach for dealing with the transportation challenge associated with the utilization of asteroid materials. It has long been recognized that the "best" way to return lots of material from an asteroid is to use the asteroid itself as the source of propellant for the return trip, and many schemes to do this have been proposed over the decades [7-10]. While conceptually attractive, in practice obtaining and utilizing propellant from an asteroid in order to make the return trip may initially be a difficult, expensive, and technically risky undertaking. ARM alleviates the need to do this by utilizing state-of-the-art capabilities in ground-based observation assets, low-thrust trajectory design, and solar electric propulsion to discover and characterize valuable targets that naturally return close to the Earth-Moon system and then redirect their trajectories to capture them into lunar orbits. Demonstrating the ability to affordably deliver several hundred tons of asteroid material to cislunar space, which would be many times the launch mass to LEO, could change the game for *in situ* resource utilization. Resources discussed below include: water, oxygen, metals, precious metals and silicate rock—effectively the entire asteroid could be utilized for human benefit in space.

IV.A. Radiation Shielding

Solar flares and galactic cosmic rays pose a constant and serious threat to astronauts in deep space. Massive shielding may be needed to protect deep space crews from solar protons and especially the relativistic, heavy ions that comprise cosmic rays.

Our atmosphere provides about 1 kg of air above each square centimeter of the Earth's surface, protecting us from most galactic cosmic radiation (GCR). To provide that same protection around the hull, for example, of the ISS Destiny lab module (4.3 m dia. by 8.5 m long, and 14.5 t) would require 1,440 t of mass shielding. A recent estimate states that a Mars-bound crew can avoid most of the debilitating GCR exposure during cruise behind the equivalent of 5% of Earth atmospheric protection, or 50 g/cm^3 [11]. That shielding mass applied to the Destiny module would amount to roughly 72 t.

A 2012 NASA estimate, however, states that the 5%, or RP5, level of protection may be insufficient to protect Mars-bound astronauts from excessive risk of cancer-caused death [12]. Sufficient protection may require as much as 500 g/cm^2 (the equivalent of half of Earth's atmosphere), or more than 700 t for single module [13]. Other habitable volumes in the cruise vehicle would need protection as well. Shielding mass is likely to be an important, if not the dominant, contribution to the mass budget of any crewed, Mars-bound vehicle.

Current launch costs make lifting hundreds of tons of shielding from Earth prohibitively expensive. Asteroids may serve as a source of water, metals, or regolith shielding materials, all conveniently available outside the lunar and terrestrial gravity wells.

If, using the ARM target object as a testbed, mechanical processes can be developed to gather loose asteroidal regolith or crush the weak clays comprising most carbonaceous chondrite materials, a processor could produce "sandbags" for installation around the hulls of habitable modules. Later, more sophisticated separation of asteroid material into water, metals, or organic compounds would still leave behind a substantial fraction of the processed material for use as mass shielding.

The ARM target asteroid would be an excellent candidate for testing low-g shielding production techniques. Candidate processing methods should be tested within the next five years at the International Space Station.

IV.B. Asteroidal Water

As noted in Reference 14, water is the most valuable and versatile in-space resource to be derived from asteroid materials. It is essential for life support, as a fluid and as an oxygen source, and can be separated into powerful chemical propellants.

If ARM returns a carbonaceous chondrite-type asteroid, its water of hydration (up to 20% by mass, loosely bound in the clay mineral matrix of CI chondrites) can be liberated through gentle heating. Temperatures of 250º-300º C, easily provided by solar energy, would release nearly all of the water in a typical carbonaceous chondrite meteorite. Mixed with other volatiles, the water could be preferentially condensed, filtered, and stored. Urine processors aboard the ISS already demonstrate the feasibility of extracting pure water from a contaminated water source under free-fall conditions.

An ARM target object of 500 t placed in lunar orbit may contain up to 100 tons of water, an ample amount for testing extraction, distillation, and storage technologies. NASA would be wise to choose an asteroid matching the spectra of CI or CM chondrites to maximize the probability of returning a water-rich object.

IV.C. Building materials

Metals such as nickel, iron, cobalt, and the precious platinum-group metals are found widely in meteorites. Because carbonaceous chondrites have been thoroughly oxidized at low temperatures, the dominant metal phase is magnetite (Fe_3O_4), usually around 20% by mass. Roughly 73% of that mass is iron. The iron can be extracted using hydrogen derived from asteroidal water. Magnetite reduction produces very pure iron, with additional water as a byproduct.

The majority of near-Earth asteroids characterized to date are of the S class, indicating an ordinary chondrite composition. Ordinary chondrites contain iron ranging from ~20 percent by mass among LL chondrites up to ~27 percent among the H chondrites [14]. The iron, nickel, cobalt, and traces of platinum-group metal in ordinary chondrites reside in native metal grains about the size of a pinhead.

Asteroid metal extraction would start with separation of the metal grains, using magnetic rakes swept through regolith or the crushed rocky matrix of the asteroid. Once concentrated, the metals can be separated by a commonly used industrial technique called the Mond, or carbonyl process. Carbon monoxide at a few atmospheres pressure is passed over the metal at a temperature near 100º C; the iron and nickel volatilize into gaseous carbonyl compounds, with each metal atom surrounded by four or five CO molecules. Left behind in the extraction process are cobalt and the platinum-group elements in the form of a fine magnetic dust.

By raising the temperature or lowering the pressure of the carbonyl gas, the compounds decompose separately into mirror-bright films of pure metal, leaving behind the CO for reuse. Chemical or laser vapor deposition processes can produce high-strength metal castings or thin films [14].

In replacing structural materials lifted from Earth, the most likely metal items that Lewis and Lewis propose for space production are beams, plates, fixtures, wires, cables, filament-wound containers, and thin films. The metallic potential of a 500-t ARM target of carbonaceous chondrite composition is in the neighborhood of about 70 tons of iron (in the form of magnetite).

V. OTHER APPLICATIONS OF ARM-SEP DERIVATIVES

The Asteroid Redirect Mission would drive technology developments with applicability to a number of potential different future high-power solar electric propulsion mission applications including commercial communication satellites, deep space science missions, orbital debris removal, and cargo delivery in support of human exploration missions to the Moon and beyond. The two specific solar electric propulsion technology areas that will be developed for ARM are large-area, flexible-blanket solar arrays and magnetically-shielded Hall thruster based propulsion systems. The solar array technology developments, initiated by NASA's Space Technology Mission Directorate in 2012, will result in solar array wings simultaneously proving improvements in power, mass efficiency, packaging efficiency, deployed strength, deployed frequency, and operating voltage relative to current state-of-art commercial satellite solar arrays. These properties relative to those of typical solar arrays used by high power communication satellites are shown in Table 1.

The magnetically shielded Hall thruster ion propulsion system (IPS) developments will also achieve significant advancements in relative to comparable state-of-art electric propulsion systems. These include increases in power, specific impulse, lifetime, and input voltage relative to Hall thruster ion propulsion systems currently being used by high power communication satellites (Table 2). The applicability of these technologies to the previously mentioned future high-power solar electric propulsion mission types is discussed below.

V.A. Commercial Communications Satellites

The ARM solar array and IPS developments are both likely to have broad applicability to the commercial geostationary telecommunication industry due to the economic considerations of reduced mass, improved performance, and reduced cost they promise for satellite subsystems. The modular nature of the solar array technology being developed for ARM, is anticipated to reduce solar array manufacturing costs, currently estimated at between \$0.6M and \$1M and per kilowatt by up to 30% through the application of automated assembly processes. These cost savings would enhance U.S. competitiveness in the global communication satellite market. Mass reductions achieved through the use of lower mass solar arrays or by reductions in station keeping propellant mass from operation at higher specific impulse would enable more revenue generating payload for a fixed spacecraft mass. Conversely, if the benefits of the advanced ARM SEP technology are used to reduce satellite mass, launch vehicle costs could be reduced.

Table 1: Projected ARM Solar Array Technology Characteristics

Parameter	ARM Solar Arrays	Typical Commercial GEO-comsat Solar Arrays	Improvement
Power	50 kW	<20 kW	2.5X higher power
Mass Efficiency	> 100 W/kg	60 W/kg	1.7X lighter
Packaging Efficiency	40 kW/m^3	10 kW/m^3	4X more compact
Deployed Strength	>0.1 g	0.005 g	20X stronger
Deployed Frequency	>0.1 Hz	>0.05 Hz	2X stiffer

Table 2: Projected ARM Hall Propulsion System Characteristics

Parameter	ARM Hall IPS	Typical Hall for GEO-Comstas	Improvement
Power	13 kW	5 kW	2.6X higher power
Specific Impulse	3000 s	2000 s	1.5X fuel economy
Xenon	10 t	0.4 t	25X fuel load
Lifetime	50,000 hrs	10,000 hrs	5X lifetime
Input voltage	300 V	70-100V	3X higher voltage

The economic impact of utilizing ARM technology would be the most dramatic when the geostationary transfer orbit (GTO) to geostationary orbit (GEO) insertion is performed using SEP. In this case, due to the mass reduction from removing a large chemical propulsion system, two spacecraft could be co-manifested on a single launch vehicle, effectively cutting per spacecraft launch costs in half. This approach is currently limited to only the smallest commercial spacecraft, such as the Boeing 702SP platform, because state-of-art SEP thrust limitations lead to unacceptably long GTO to GEO transfers for larger spacecraft. The high-power, high-specific-impulse SEP systems developed for ARM would enable shorter duration SEP orbit insertions for all commercial spacecraft. These benefits, already being evaluated throughout the industry, would be realized following the successful development of the ARM SEP technology. The annual cost savings from these improvements for just the domestic satellite industry could exceed $1 billion based on current satellite production/launch rates.

V.B. Deep-Space Science Missions

NASA's Dawn mission has demonstrated in dramatic fashion the benefits of solar electric propulsion for deep space science missions. Dawn's ion propulsion system enables the spacecraft to rendezvous with and orbit two high-science value targets (Vesta and Ceres) in a single mission. This two-for-the-price-of-one mission capability saves the cost of a second Discovery-class mission, currently valued at approximately $500M, for the same science.

Low-cost, light-weight, high-power solar arrays coupled with long-life, high-specific impulse Hall thrusters developed for ARM would enhance and/or enable new, high-value science missions. Concepts such as Comet Surface Sample Return (CSSR) and the Trojan Tour and Rendezvous (TTR) New Frontiers-class missions would benefit significantly from the use of ARM-developed SEP technologies. These benefits could include shorter flight times, increased payload capability, smaller, less expensive launch vehicles, and potentially lower flight system costs. Numerous Discovery-class missions contemplating the use of SEP would similarly benefit from ARM-developed SEP technologies.

ARM-derived high-power solar arrays could extend solar powered missions beyond Jupiter (the current target of the all-solar powered Juno mission). For example, a 50-kW solar array at 1 AU could provide 500 W at Saturn—enough to operate a robotic science spacecraft—assuming a low concentration ratio array to minimize low intensity, low temperature effects (LILT).

V.C. Orbital Debris Removal

The severity of the threat that orbital debris poses to the future utilization of space is such that ultimately some form of remediation will be required to avoid the "Kessler Syndrome"—a cascading of collision events rendering near-Earth space unusable. The most effective method for mitigating orbital debris is the removal of large objects from orbits with high collision probabilities because a single collision event involving even one of these object has the potential for creating tens of thousands of new lethal fragments. Analysis has shown that the most effective approach for dealing with these large objects is an orbital debris removal vehicle with sufficient propulsive capability to rendezvous and move/remove multiple large objects. The SEP technology developed for ARM could be enabling for large object orbital debris remediation because without high power and long life thrusters the number of targets that can be reached by one vehicle and the time that it takes to move between objects is prohibitive.

VI. NEW RESEARCH AREAS ENABLED BY A REDIRECTED ASTEROID

Asteroids are presently studied almost exclusively by Planetary Scientists. Their goal is to understand the formation and (often violent) history of the Solar System. An asteroid redirected by ARM, however, could become the focus of a broader scientific community. Three examples are discussed here: (1) Granular Physics, (2) Condensed Matter Physics, and (3) Materials Science.

VI.A. Granular Physics

Asteroids pose a series of problems in Granular Physics. This is the study of the physics of granular materials, which appear in such varied contexts as grain elevators, avalanches, pharmaceutical powders, and even cereal dispensers (see Fig. 5). It is a new field, about 20 years old.

Figure 5: A demonstration of the granular physics phenomenon of "jamming" in a cereal dispenser.

Rubble piles in micro-g provoke new applications of this physics. For example: (1) Attaching to and digging into rubble pile asteroids is not simple. Unless there are adequate cohesive forces holding the rubble together then applying even a weak force in tension would simply pull away the individual boulder being pulled on. Similarly, (2) attempts to harpoon the asteroid could be thwarted by "jamming", a collective effect unique to granular materials. Jamming limits the effectiveness of "bunker busting" bombs. (3) Sudden impacts can cause bulk rearrangement of the asteroid due to shock waves [15]. (4) If granular material is given sufficient energy to overcome cohesive forces, e.g. through being disturbed by a rocket exhaust or an astronaut's boot, then "Granular gases" could form with unique properties little studied in low gravity [16].

There is great interest within the granular physics community in making zero- or micro-g experiments [17,18]. Currently these experiments are limited to drop towers and "vomit comet" parabolic flights. These are necessarily short in duration. A returned asteroid would provide long durations, large samples and unanticipated novel, but naturally occurring, material arrangements. Many tests of granular physics theory can be made and would be directly applicable to working with micro-g bodies. Pilot experiments at the ISS could prepare the way for the greater range of experiments feasible with a redirected asteroid.

VI.B. Condensed Matter Physics

In condensed matter physics, even among quite simple crystals, there is a vast theoretical landscape of possible low energy, and thus stable states. This landscape is literally incalculable – it is too large to investigate numerically. Some surprisingly low energy states not realized in known materials have been found even in modeling simple Fe-Ti crystals [19].

The unusual conditions in the Solar Nebula and in the resulting asteroids allow the discovery of new minima that are realizable (K. Rabe, private communication with M. Elvis). While many of the initial materials formed in the Solar Nebula are likely to be unstable (K. Oberg, private communication with M. Elvis), there are materials found in meteorites that are otherwise unknown on Earth. Finding, cataloging and studying these crystals can guide condensed matter research into new areas.

Meteorites provide proof-of-concept samples, but the physical properties of these new materials are not theoretically predictable beyond basic quantities such as Young's modulus. To make more complex measurements requires larger samples than are typically available in meteorites. Measurements on large samples would yield otherwise unknowable behavior (K. Rabe, private communication with M. Elvis).

VI.C. Material Science

In materials science the emphasis is more on finding new materials, or even classes of materials, with interesting properties that may have technological applications. Some such materials have already been identified in meteorite minerals.

Figure 6: The Widmanstätten pattern, which is found only in meteorites – and hence in asteroids – forms over millions of years of cooling at rates of 100 – 10,000 C/million years, and experiment not reproducible on Earth. Other "meteorite materials" are known.

The condensation of the proto-solar nebula, the slow cooling of planetisimals, and asteroid collisions all produce novel conditions not reproducible in Earth laboratories. Some of these conditions simply cannot be reproduced on human timescales or in laboratory conditions. The Widmanstätten pattern (Fig. 6) is a well-known example commonly found in Nickel-Ion meteorites. The Widmanstätten pattern takes Myr to grow the alternating layers of kamacite (low Ni) and taenite (50%Ni) [19].

There are several dozen known "meteorite minerals" not found on Earth, but only in meteorites. Few have been investigated in detail so that most have very poorly characterized properties. Long formation timescales may be a common theme to these meteorite minerals as only in this way can bodies spend long enough in regions of the the complex Pressure-Temperature phase space for detectable grains of these mineral to form (e.g. Fig. 6).

One potentially technologically interesting example that has been studied in more detail is Tetrataenite [20], which is a new form of natural magnetic material [21] with high magnetic coercivity. (i.e., it resists changing its magnetic field in the presence of an external field). Once we know a material is possible and interesting, it may inspire novel means of lab-based synthesis. Attempts are now underway in Japan to synthesize Tetrataenite [22]. Alternatively, asteroids may be the only source of these materials. If they are useful enough they may justify asteroid mining.

As with condensed matter physics, a major limitation in investigating the meteor minerals is the small physical sizes of the samples that meteors generally provide. The study of the materials science properties of meteorite minerals would be

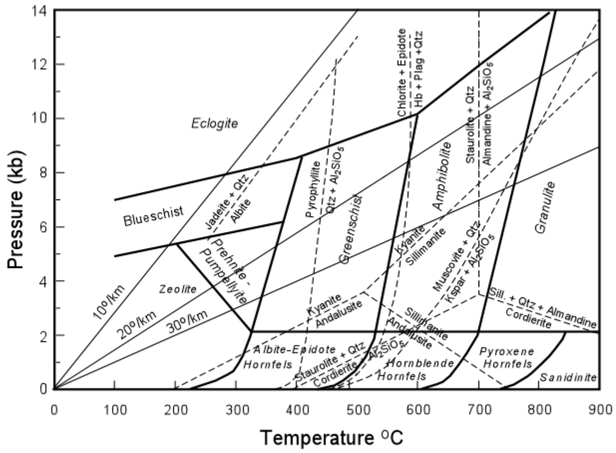

Figure 7: Pressure-Temperature phase diagram for metamorphic rocks *[TBreplaced with one for meteorites]* http://www.tulane.edu/~sanelson/ eens212/metaclassification&facies.htm

revolutionized by the bulk samples provided by a redirected asteroid.

Why not just use the meteorites we have already? The total mass of meteorites amassed in collections to date is several hundred tonnes. The bulk of this mass is made up of Nickel-Iron meteorites, and most of the rest by ordinary chondrites. (Dan Britt, Private communication with M. Elvis).

Searching for small lumps of novel materials may well involve destructive processing of tonnes of meteorites. Few curators will want to have their collections ground up in this way, so fresh supplies would need to be found. More could be collected in bulk from Antarctica or Namibia (Nancy Chabot, private communication) though the provenance of all meteorites – their original location in the Solar System – is at best sketchy.

Only a few tonnes of carbonaceous meteorites have been collected, and only a handful of these are falls into locations where their volatile content remained intact. Carbonaceous meteorites are just the sturdier remains of more delicate asteroids. These C-class asteroids are the least processed bodies in the Solar System. A native carbonaceous asteroid, little altered since its formation 4 billion years ago, may offer the best chance of finding novel materials.

All classes of asteroid material, when available in bulk and in preistine form will allow the possibility of searching for rarer new meteorite minerals and of finding larger samples that can have their physical properties characterized in detail. This will surely be an on-going research endeavor for many years.

VII. CONCLUSIONS

The Asteroid Redirect Mission (ARM) would result in a thirty-fold improvement in the state of the art of solar electric propulsion capability and would potentially return an entire small near-Earth asteroid with a mass of several hundred metric tons to a lunar distant retrograde orbit. These twin features of ARM could directly benefit a wide range of the Nation's space interests. In the two years since the original study by the Keck Institute for Space Studies (KISS), numerous concepts that expand on the capabilities that ARM would demonstrate have been identified. A follow-on KISS workshop in March 2014 collected and organized ideas from experts around the country and summarized them in this report. These concepts can be binned into two broad categories: how they facilitate the path for human spaceflight to Mars; and how they impact other important aspects of the Nation's space activities.

Fuel-efficient transportation is one of the enabling keys for improving the affordability of human missions to Mars. Solar electric propulsion (SEP) is the most advanced, fuel-efficient, in-space transportation technology available and consequently it is seeing wide-spread and expanding application to commercial communication satellites and deep space science missions. The SEP system on NASA's Dawn mission has already demonstrated record shattering ΔV of over 10 km/s. This ΔV capability would encompass what is needed to support human missions to Mars. However, to support the larger payload masses projected for human Mars missions it is necessary to scale up the size and power level of SEP systems. Such missions would require SEP system power levels of between one hundred and a few hundred kilowatts and xenon propellant loads of 14 t to 25 t. The 40-kW ARM SEP system represents a significant increase in power capability over the 2.5-kW Dawn system and the 9-kW commercial satellite systems. In addition, the ARM SEP system's ability to store and process up to 10 t of xenon also represents a significant advance relative to the 0.4 t of xenon that Dawn carries and the 0.3 t typical of commercial SEP systems. Both of these advances represent achievable, near-term improvements to the state of the art and are the appropriate sized stepping stones to the higher power, greater propellant loads needed to support human missions to Mars.

The SEP system developed for ARM would also beneficially impact a wide variety of other in-space transportation areas of interest including the LEO-to-GEO transfer of large commercial and military satellites, and high-energy deep space science missions to Mars (e.g. potential Mars Sample Return), comets (comet surface sample return) and main-belt asteroids, Jupiter, the Trojan asteroids, Saturn, and Uranus.

By capturing and returning an entire near-Earth asteroid, the asteroid redirect part of ARM would significantly impact Planetary Defense and in situ resource utilization endeavors, as well as planetary science. It is estimated that as many as 90% of the near-Earth asteroids may be rubble piles. If ARM returns an entire near-Earth asteroid, it is likely to be a rubble pile. Two of the leading target asteroids for retrieval, 2009 BD and 2011 MD, have densities consistent with rubble piles. The return and close-up investigation of a rubble-pile asteroid would provide the detailed information necessary to assess the effectiveness of the leading primary deflection techniques, kinetic impact (KI) and nuclear blast (as the deflection technique of last resort). ARM also has the potential to demonstrate a secondary asteroid deflection technique, either the gravity tractor (or the enhanced gravity tractor variant) or ion beam deflection. Demonstration of either one would inform future PD efforts and enhance confidence in the feasibility of these secondary techniques. Once returned to the lunar DRO tests of a sub-scale laser ablation technique could be performed.

The KISS study described in this report also recognized that all of the primary and secondary planetary defense techniques benefit from the advancement of SEP technology by ARM. In addition, small low-cost SEP vehicles launched as secondary payloads and using derivatives of the ARM technology (high-voltage solar arrays, direct-drive, and magnetically-shielded Hall thrusters) could be used for precision tracking of potentially hazardous objects to determine if they are actually hazardous.

Space missions currently utilize several resources available in space. They use sunlight for power, starlight for navigation, gravity for gravity assists, and atmosphere for deceleration. To date, however, no mission has made use of any of the vast material resources available in space. The asteroid retrieval part of ARM has the potential to accelerate the use of material resources in space to greatly improve the affordably of human space activities. For example the only known way to protect people from galactic cosmic rays once outside the bulk of the Earth's atmosphere and magnetic field is to provide lots of material for shielding, with shielding masses that could be of order several hundred metric tons. Such huge masses of material could be obtained from asteroids redirected to the intended point of use. In addition, the largest constituent of most asteroids is oxygen, which can be used for propellant and for life support. The right type of asteroids could possess significant fractions of water valuable for radiation shielding, propellants, and life support. Redirecting asteroids first to lunar DRO and subsequently to 6-month and 12-month Earth-resonant orbits would provide a series of useful stepping stones progressively deeper into space on the way to Mars, where at each location the asteroid material resources are harvested to provide radiation shielding and potentially other valuable materials.

Finally, the processing of asteroid material in a micro-g environment would generate the demand for improved understanding of granular flow physics and could create advances in material science.

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