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Profitable Asteroid Mining: A Pragmatic Policy Goal?

To maximize the benefits derived from off-planet resources, profitable asteroid mining may be our most pragmatic deep-space goal for the next few decades.

▪ For ecologically sustainable *terrestrial* development, what targets offer richer sources of the most critical of all industrial metals—the platinum group metals? Where else can we find these rare catalysts?

▪ For economically sustainable *extraterrestrial* development, what targets offer greater potential financial returns? The Moon is slag; it and Mars require costly rockets for landing and liftoff; neither can offer a biologically benign gravity.

This paper is part of an ongoing effort to (1) identify solar-system resources that offer humanity the greatest potential benefits, (2) describe technologies that can be used to reach and manipulate those resources, and (3) plan the demonstration missions that will bring us closer to realizing financially compelling returns. More generally, the paper aims to increase our understanding of the value of the tools—especially the robotic tools—required to reach our long-term goals in space.

Multi-generational space development programs to “sustainably send humans into the solar system” (Charles Bolden)[1] and “make our dreams in space a reality” (James Cameron)[2] need to **deliver real economic benefits.**

The following sections explore motivations, resource demand, technological demonstrations, and the alignment of agency priorities with societal needs:

1. What and Why before How
2. Economic Resources
3. Demo, Demo, Demo
4. Eventually Humans

“I agree with Mike Hawes [Associate Administrator for Program Analysis and Evaluation], your concepts are well thought out and clearly articulated.... NASA Deputy Administrator, Lori Garver [and I] ... thank you for your suggestions.”
—Dr. Robert Braun, **NASA Chief Technologist**[3]

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1. What and Why before How

"The ultimate goal [is] human expansion
into the solar system."
—The Augustine Committee (2009)[4]

Mars is *not* the ultimate goal. Offering only one-third Earth's gravity, Mars may never be healthy for Earth-evolved, cellular life. We need gravity.[5] The delicate molecular and computational apparatus within every watery cell of DNA life[6] may require gravitational conditions rather close to what they have been for 4 billon years: 980 Galileos (±0.3%). Humans may hope to *visit* Mars, but making it an "ultimate goal" is just not rational. The Moon, offering only one-sixth Earth's gravity, is even less hospitable.

On the other hand, rotating cylinders, as small as a couple hundred meters in diameter, appear quite capable of precisely simulating Earth-normal gravity.[7] Such habitats—likely built from asteroids, rather than material drawn up out of expensive gravity wells—seem to be the most plausible context for realizing our long-term goal of "humans [venturing] out into the solar system and … beyond" (Charles Bolden).[8]

To reach such ambitious goals, space agencies must be *economically* as well as politically sustainable.[9] Space agencies need to deliver substantive, tangible, **near-term benefits.** If they do not, it is unlikely that they will generate the support, the knowledge, and the technologies that are required to realize our "ultimate goals" in space.

Viable space programs must satisfy "fundamental" as well as "self-actualization" needs, as Abraham Maslow defined these in his *Hierarchy of Needs*.[10] With competing claims on increasingly limited funds, programs that argue "It's our nature to explore!"[11] may not long survive. As we emerge from the "Great Recession"[12] and enter the long "Lean Years"[13] under the darkening cloud of a growing fiscal crisis,[14] taxpayers and their representatives will make choices. When asked, voters choose to sacrifice civil space programs rather than cut funding to fundamental social programs, such as "national defense, law enforcement, environmental protection, or other more basic needs."[15] In 2010, Rasmussen found that "Fifty percent (50%) of Americans say the U.S. should cut back on space exploration given the current state of the economy."[16]

Our primate ancestors did not stand up on their hind legs in order to inspire younger generations to study the rarified art of balancing on two feet. They did it to get food and to avoid becoming food. Today we face new hungers, new dangers. It now appears likely that terrestrial sources of certain metals—which are required for ecologically sustainable technological societies—may *not* be able to satisfy 21st Century global demand.

At this historic juncture in space development, the U.S. has a terrific opportunity to re-launch its civil space agency as an economically vital, extraterrestrial branch of the USGS, creating fantastically detailed maps of—and greatly improving our access to—the **mineral wealth of the solar system.** Rather than ask, "Where should we try to send humans next?" NASA should ask, "What can we do to create *economic* value, off planet, for the taxpayers who are investing in our efforts?"

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2. Economic Resources

"If our goal is to build a permanent, expanding, self-sustaining extraterrestrial civilization, then [we need to establish a] new Solar System economy … based on resource occurrence and accessibility … and economic cost and benefit."
—Jeffrey Kargel, et al. (2008)[17]

"The mandate of government agencies that deal with mining should be proactive toward value creation."
—Juan P. Camus (2002)[18]

Economic resources in space are of three types: Location, energy, and matter. Some near-Earth locations already support profitable industrial engagements. Low-Earth and geosynchronous-Earth orbits host hundreds of revenue-generating satellites (worldwide industry revenues in 2008: >$140 billion).[19] Beyond Earth's atmosphere, solar radiation is abundant; it powers most satellites. Orbiting space-based solar power systems (SBSP) may be able to deliver huge quantities of clean, sustainable energy to Earth.[20] But to date, nothing from the vast reaches *beyond* Earth orbit has ever been involved in an economic exchange. To incrementally expand our current off-planet economy, **the next resource is clear: Near-Earth asteroids.** To take this next step, we need our space agencies to make asteroid mining a priority, and demonstrate how it can done.

Agencies should support SBSP, but it should not be a top priority for two reasons. First, SBSP already attracts interest from commercial firms and defense-related institutions.[21] Second, even if SBSP supplied 99% of the world's electricity, we're still just in Earth orbit. We haven't begun to tap the mineral wealth of the inner solar system.

We need out space agencies to reach out—with robots, certainly; *perhaps* with humans—to find, get hold of, and bring back an economically significant chunk of matter, and sell it on the open market. We need them to prime the pump for economically and ecologically sustainable, *post*-Earth-as-a-closed-system, industrial societies.

Our space agencies need to enable a revolutionary transformation in the material culture of our home planet. They need to design and launch positive economic feedback systems that utilize off-planet resources. Space agencies need to develop the skills and knowledge required to draw material resources through **extraterrestrial supply chains,** and put them to use in terrestrial systems of production. Once learned, space agencies need to transfer these skills and understandings to individuals in industry. Civil space agencies also need to help design, publish, and promote the inner-solar-system knowledgebases that will prepare today's students for *profitable* extraterrestrial careers.[22]

We need our civil space agencies to do these things, because we need the metals that are available in asteroid ore to support our technological societies on Earth, so that they may become ecologically sustainable over the decades and centuries to come.

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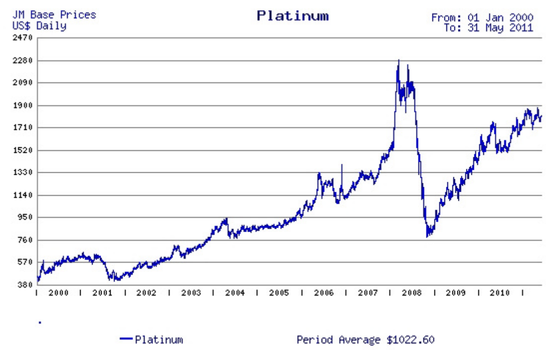
In its 1985 revision of the 1958 Space Act, Congress defined NASA's #1 Priority: "Seek and encourage, to the maximum extent possible, the fullest commercial use of space."[23] Given such direction, one might assume that today, 25 years latter, NASA's top activity would be developing economically promising space resources: energy from the sun and metals from asteroids. Instead, most funds go to programs to put humans in space.[24]

Some of these resources have *outstanding* value. Space agencies intent on addressing fundamental economic needs should focus on these materials. Platinum, for example, has sold at over $1,700/oz since January.[25]



Platinum group metals (PGMs) are great catalysts. Used in automotive catalytic converters, which are required by national governments worldwide,[26] PGM supplies are quite limited. Some models point to **terrestrial depletion within decades.**[27]

Platinum group metals are also critical as catalysts in hydrogen fuel cells, which are key to a possible post-carbon, "hydrogen economy."[28] In 2008, The National Research Council identified PGMs as the "most critical" metals for U.S. industrial development.[29]

Platinum group metals are abundant in certain types of near-Earth asteroids (NEAs). NEAs that are mineralogically similar to one of the most common types of "observed fall" meteorites (H-type, ordinary chondrites) offer PGM concentrations (4.5 ppm)[30] that are comparable to those found in profitable terrestrial mines (3-6 ppm).[31] Other meteorites suggest that some asteroids may contain much more valuable metal.[32]

The PGM value of a 200 m asteroid can exceed **$1 billion,** or possibly **$25 billion.**[33] Over 7,500 NEAs have been detected.[34] Close to a fifth of these are easier to reach than the moon; more than a fifth of those are ≥200 m in diameter: 200+ targets.[35] President Obama requested, and Congress has authorized, a four-fold increase in detection funding ($5.8 m to $20.4 m/year).[36] This could lead to ~10,000 known 200 m NEAs in a decade.[37] But detection is just a start. The costs to locate, extract, and process asteroid ore are not well understood.[38] Before significant private capital is put at risk, we need to learn more.

In cooperation with other forward looking nations,[39] the U.S. should *purchase an option* to develop asteroid resources by investing in the knowledge required to mine asteroids. We can then choose to *exercise this option* if terrestrial PGM supplies do in fact collapse. Asteroids may also be able to supply other metals that are increasingly at risk.[40] There are several candidates: In 2009, the U.S. imported 100% of 19 key industrial metals.[41]

To seek the "fullest commercial use of space," NASA should *buy down the risk* of asteroid mining ventures by investing in R&D that can give us the tools to discover, analyze, and process asteroid ore, and deliver it safely to Earth, and to Earth orbit. NASA, with other space agencies, should run demonstrations for this globally important program so that, as the GAO likes to put it, useful **"knowledge supplants risk over time."**[42]

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3. Demo, Demo, Demo

For "the nation to truly exploit deep space resources,
we need our civil space agency to develop
**the 21st Century equivalent of the
Transcontinental Railroad."**
—Bryant Cramer, Associate Director, USGS (2009)[43]

With a mission to accelerate development of valuable mineral solar system resources, space agency policies and programs regarding technology R&D come more clearly into focus. If the first asteroid mining demonstration missions are run, *from the start,* with partners in the robotics, mining, and space infrastructure industries, perhaps as few as three large-scale demonstrations can jump-start commercial asteroid mining.

NASA may initiate ***autocatalytic* asteroid mining** through a series of successes:

1. Return 1.0 tonne *pulverized*[44] but unrefined asteroid ore to Earth.
   PGM-5 concentration: ~4.5 ppm

2. Return 10 tonnes *pulverized and partially refined* asteroid ore to Earth.
   PGM-5 concentration: ~4.5% (~45,000 ppm)

3. Return 100 tonnes *more fully refined* asteroid ore to Earth.
   PGM-5 concentration: ~45%[45]

[Large satellites: ~5 t. The ISS: ~450 t.]

The value of the ore returned is on the order of $100, $10 million, and **$1 billion,** for the five most important PGMs: ruthenium, rhodium, palladium, iridium, and platinum. If the missions are successful, and if the knowledge gained by executing them is well published, industrial investors may choose to keep the ball rolling.

Asteroid mining demonstrations can evolve from past, current, and upcoming missions (e.g., Hayabusa,[46] Dawn,[47] and OSIRIS-REx[48]). The skills and tools that we require from our cooperating space agencies are drawn from many domains. We need to:

1. Detect Asteroids
2. Characterize Asteroids

3. Design, Build, and Operate Robotic Miners

4. Transport: Earth to LEO (low Earth orbit)
5. Transport: LEO to NEAs
6. Transport: NEAs to Earth

7. Manage the Space Environment

8. Evolve Knowledge and Know How

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1. Detect Asteroids

Programs intended to detect 90% of all potentially hazardous NEAs (>140 m) by 2020 are underway.[49] Today, with 2,000 such asteroids detected (~10%), it seems unlikely that the 2020 goal will be met.[50] A space-based telescope could get the job done by 2023.[51] A ground-based telescope could do it by 2030.[52] Congress just authorized an *increase* in detection funding, from $5.8 m to $20.3 m/year.[53]

The "most capable [terrestrial telescope] appears to be the Large Synoptic Survey Telescope (LSST),"[54] which plans to begin science operations in 2016. The LSST is designed to monitor the NEA population for years.[55] The 2010 Decadal Survey of Astronomy and Astrophysics ranked the LSST its highest priority terrestrial observatory. Completion costs are estimated to be around $500 million.[56]

An infrared telescope in a Venus-like orbit could detect ~90% of all NEAs larger than 140 meters in diameter in seven years, as well as "about 85% of all >100 m" NEAs, and "about 50% of all >50 m" NEAs.[57] Such a telescope, using technology from two previous successful deep-space missions—Spitzer[58] and Kepler[59]—was proposed in 2009, at a cost of $600 million.[60]

Canada and Germany plan to launch Earth-orbiting satellites intended to detect NEOs that are interior to Earth's orbit in 2011 and 2013—the Near-Earth Object Surveillance Satellite (NEOSSat)[61] and the AsteroidFinder[62]—respectively.

2. Characterize Asteroids

Asteroids offer a wealth of knowledge, as well as metal; they encode the story of the solar system. To decode this story, and to locate the most promising mining sites, we need to raise the quantity and quality of asteroid characterizations. At increasing cost levels, we need new tools to establish asteroid mineralogy using (1) telescopes on Earth, (2) telescopes in orbit, (3) spacecrafts that fly to, orbit, and "land on" asteroids, and (4) spacecrafts that return mineral samples.

Our understanding of asteroid spectra, and the association of asteroids in space with asteroids on Earth (aka: meteorites), has improved.[63] We can now discuss "asteroid and meteorite properties using a common language of mineral abundance and composition."[64] While we can do more with current terrestrial equipment,[65] what we really need is *on-site* asteroid analysis, in order to verify mineralogical inferences drawn from remote spectral analysis. This can be secured only with spacecrafts. The challenges of determining asteroid mineralogy, and the need for on-site analysis and returns, are well articulated in Burbine, et al. (2008).[66]

Japan completed the first asteroid mineral prospecting mission in June 2010. The *Hayabusa* was the first spacecraft sent to an NEA with the express goal of returning a sample to Earth.[67] To take the lead in deep-space development, the U.S. should now *send out hundreds* of relatively inexpensive, "hard-landing," mineralogical probes[68] to examine the most economically attractive NEAs, *followed by tens* of "low-cost" sample-return spacecrafts to the most attractive asteroids of the initial lot.[69] Then, with a solid grasp of asteroid "geology," we can confidently identify the most promising sites for profitable metals mining.

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3. Design, Build, and Operate Robotic Miners

Advanced robotics is the key to profitable asteroid mining.[70] Semiconductor and nanoscale hardware appears likely to sustain the exponential growth of Moore's Law for decades.[71] Robotic miners can draw on this growing power—*if* we can get new computational technology off planet and to the target asteroids.[72]

Robotic miners face many challenges. They must manage exponential complexity (a by-product of growing computational power), survive the environmental rigors of space, and execute the physically demanding work of hard-rock mining. They need to be logically robust and physically tough: able to process tonnes of rock while utilizing gigawatts of power.[73] Nontrivial engineering, to be sure.

The training required to design, build, program, and operate these robots is also far from trivial, as anyone who has assimilated an "undergraduate" robotics text can attest.[74] Governments can raise the appeal of such a challenging educational career by making a clear commitment to extraterrestrial resource development. Fundamental robotics R&D can also benefit a wide range of terrestrial industries.

4. Transport: Earth to LEO

First-generation asteroid miners may be best supported by cheaper, more reliable *heavy-lift* vehicles—such as the Ariane 5 ECA, Proton, and Delta IV Heavy—which can send 21, 22, and 23 tonnes to LEO, respectively—rather than *super-heavy-lift* vehicles—such as the retired Saturn 5 or the proposed Ares V, which are designed to send 118 and 160 tonnes to LEO, respectively.

With larger mining systems, super-heavy-lift vehicles *may* become cost effective. But before committing time and money to developing these behemoths, we need to understand the requirements of actual mining equipment. Early miners are likely to benefit more from on-orbit assembly and orbiting fuel depots. In time, "alternative" launch systems may become more attractive than our current technology, which is already very efficient (97-98%) and offers "very little room" for improvement.[75] Propellants that use *metallic hydrogen,* for example, may be able to "release 216 MJ/kg of specific energy," which greatly exceeds the specific energy of the 1972-developed, Space Shuttle Main Engine (SSME): ~10 MJ/kg.[76]

5. Transport: LEO to NEAs

In-space transport is ripe for high-risk/high-payoff "innovation tournaments."[77] New ion, plasma, Hall, VASIMR, and solar-sail propulsion technologies, as well as new software tools for finding low-cost "energy-efficient trajectories,"[78] could revolutionize our ability to ferry equipment and ore around the solar system.

6. Transport: NEAs to Earth

Only high-value metals can be delivered to Earth (due to heat dissipation during atmospheric entry). On the other hand, on-orbit manufacturing (e.g., large-scale SBSP) could utilize a wider range of asteroid materials (e.g., iron, nickel, silicon). For both destinations, we require fault-tolerant systems to safely deliver these space resources to, and into, the only self-sustaining ecosystem that we know.

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7. Manage the Space Environment

Achieving global consensus on an evolving set of regulations for adequately managing the extraterrestrial environment requires *social* technologies of institutional governance. It also requires new *mechanical* technologies.

Orbital debris, for one, has entered a crisis mode.[79] Deorbiting space trash, "an extremely difficult and likely expensive task," has been the focus of recent DOD and NASA studies.[80] No solutions are apparent. The "Kessler Syndrome"—the runaway growth of orbital debris that culminates in "cascading failures of many satellites in a period of time much shorter than years"—has already begun.[81] "As is true for many environmental problems, the control of the orbital debris environment may initially be expensive," Kessler notes, "but failure to control leads to disaster in the long-term." We must resolve this, or all bets are off.

Ground-based lasers appear to be the best technology for removing small debris, but no systems have been tested.[82] General Kevin Chilton, Commander of U.S. Strategic Command (USSTRATCOM), which is charged with space operations, has argued that we should launch a multi-national "world war on space debris."[83]

While law inevitably, and appropriately, trails industrial development, we need an evolving body of space-resource jurisprudence to maximize space benefits for current and future generations. These challenges are not primarily technological. But those working to draft as yet unwritten extraterrestrial property rights laws[84] will need new technologies to precisely define and maintain whatever off-planet property rights regime is eventually codified in national and international law.[85]

8. Evolve Knowledge and Know How

This may be the most difficult engineering task of all. Each generation of asteroid probes and sample return spacecrafts presents opportunities for competitive and evolutionary innovation. But such opportunities are also bedeviled by increasingly complex challenges of knowledge management.[86] Internal and external studies find that those who plan space programs repeatedly and regularly underestimate costs and overestimate the performance of launch systems,[87] instruments,[88] and entire missions.[89] "The most surprising result: none of these findings are new."[90]

Knowledge evolution for asteroid mining may be accelerated by publishing (on the Web) hundreds of the most important low-TRL (technology readiness level) technologies (with links to current technical documentation), along with their R&D^3 (research & development degree of difficulty)[91] cost estimate, and the prize money offered to take a technology to its next TRL. Private firms can profit (and learn) by tackling incremental challenges; and space agencies can adjust prize amounts depending on the needs of asteroid mining demonstration missions.

The success of such demonstrations should be evaluated in terms of *knowledge transfer* to industry, rather than accomplishment of one-off events in space. Civil space agencies should aim for *industry replication* of asteroid mining demonstrations. In this way, the technology can be delivered to those who drive market innovation—end users[92]—and a growing wealth of solar-system resources can be delivered to humanity.

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4. Eventually: Humans

"NASA must transition its culture from
'follow us and we will lead you to the stars'
to 'we will enable you to go to the stars.' "
—James Vedda (2009)[93]

NASA, a creation of the Cold War, demonstrated U.S. capacity to put boots on the Moon. In doing so, it fulfilled its mission (as a "non-military" branch) to help "beat the Soviets." Today we need NASA—the largest civil space agency—in cooperation with industry and other space agencies, to demonstrate the capacity to put *autocatalytic extraterrestrial resource development* into action, to achieve a more rewarding economic success and to help "contribute solutions to **[humanity's] most pressing problems.**"[94]

In 1961, it was risky for JFK to commit to putting a man on the moon. Today, with the advancing power of computational systems of all kinds, it may be *less risky* to commit to making deep space profitable. Young people are ready for highly capable robots.[95] If they can see that it offers real promise for future generations, students around the world may be willing to pay the startup costs for profitable robotic asteroid mining.

"Humans will venture out into the solar system," as Charles Bolden suggests. But anything less than an autocatalytic off-planet economy will keep us from ever becoming more than just tourists. The "game-changing" technologies that will "unlock new possibilities"[96] are those that can transform deep space from a consumer of resources into a source of value.

We should go to space, first and foremost, to get the resources we need for ecologically sustainable development on Earth, where we all live. Such an effort may, simultaneously, build an economically sustainable infrastructure for thriving extraterrestrial civilizations.

Is profitable asteroid mining a pragmatic goal?

Is any other deep-space goal more pragmatic?

Your comments and suggestions are welcome: **BC.Crandall@SpaceWealth.org**

Especially valuable would be your identification and assessment of the top two issues that need to be resolved in order to initiate a substantial, global program of asteroid mining research and development.

Through our website, ***SpaceWealth.org****, we are working to recruit and support a community of scientists, engineers, managers, scholars, and students, who share the conviction that profitable asteroid mining is a good thing. Through conversations and collaborations we aim to create an authoritative Asteroid Mining Knowledge Base.*[97]

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[1] Bolden, Charles. NASA. “Fiscal Year 2011 Budget Estimate.” p. SUM-2. <http://www.nasa.gov/pdf/428837main_NASA_FY_2011_Congressional_Justificaton_Budget_Book_Rev-01_BOOKMARKED.pdf>

[2] “I applaud President Obama’s bold decision for NASA.... This is the path that can make our dreams in space a reality.” Cameron, James. “The right way forward on space exploration.” *The Washington Post*. 5 February 2010. <http://www.washingtonpost.com/wp-dyn/content/article/2010/02/04/AR2010020402439.html>

[3] Braun, Robert. Letter to Space Wealth. 11 May 2010. Written in response to an earlier version of this paper. Dr. Braun sent that version to leaders within NASA’s Exploration Systems and Science Mission Directorates, which led to an invitation to participate in an August workshop regarding NEO Objectives, in Washington, DC. Several of the attendees clearly understood the need to focus on economically compelling objectives in space. <http://www.nasa.gov/exploration/new_space_enterprise/home/neoworkshop.html>

[4] Augustine, Norm, et al. “Review of U.S. Human Spaceflight Plans Committee Final Report: Seeking a Human Spaceflight Program Worthy of a Great Nation.” 22 October 2009. <http://www.nasa.gov/pdf/397898main_HSF_Cmte_FinalReport_High.pdf>

[5] Microgravity is radically disruptive to essential biological activity. For example, weightlessness induces expression failure in 90% of observed immune system genes. Boonyaratanakornkit J., et al. “Key gravity-sensitive signaling pathways drive T-cell activation.” *Federation of American Societies for Experimental Biology J*. 2005:2020-2. <http://dx.doi.org/10.1096/fj.05-3778fje>

[6] “The computational processes performed by a cell have features that distinguish them from any human-made machine or electronic device. The most obvious difference being that they are based on chemical reactions in aqueous solution. They require a continual supply of carbon atoms and chemical energy, considerations that do not apply to electronic circuits. Connections in a cell-based computer are made by [gravitationally influenced] physical processes of diffusion and molecular recognition.” Bray, Dennis. *Wetware: A computer in every living cell*. New Haven, CT: Yale University Press. 2009. p. 227.

[7] “The *Kalpana One* structure is a cylinder with a radius of 250 m and a length of 325 m. .... The radius is the minimum necessary to provide 1 g at the hull when rotating at no more than 2 rpm. The length is the longest possible while ensuring rotational stability.” “Long trailing vines may be cultivated on the edges of the ramps to complete a scene perhaps reminiscent of the famous hanging gardens of Babylon. This is no mere fluff. To attract suitable colonists, who will need to be technically capable and therefore fairly well off, space settlements must be attractive, wonderful places to live.” Globus, Al, Nitin Arora, Ankur Bajoria, and Joe Straut. “The Kalpana One Orbital Space Settlement Revised.” 2007. <http://alglobus.net/NASAwork/papers/2007KalpanaOne.pdf>

[8] Bolden, Charles. NASA. “Fiscal Year 2011 Budget Estimate.” p. SUM-2.

[9] One can easily imagine a space program that is *politically viable*—retaining sufficient voter support to maintain itself—*but not economically beneficial*. Such a program might show some extraterrestrial activity, but without increasing the economic wellbeing or future prospects of the community that is paying for it. Examples of maladaptive—“self-enforcing” but not “efficiency enhancing”— institutions are legion.
See: Greif, Avner. *Institutions and the Path to the Modern Economy: Lessons from Medieval Trade*. Cambridge: Cambridge University Press. 2006.

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[10] "Maslow crafted his Hierarchy of Needs, which is graphically depicted as a triangle divided into five levels, with the most mundane at the bottom [physiological and safety needs] and the most cerebral at the top [esteem and self-actualization needs]....

"The difficulty with the popular rationales for space is that *they try to appeal to self-actualization, the highest need level*. Concepts like national prestige, scientific discovery, inspiration, and destiny are worthy things to aspire to, so most people will acknowledge their support. But these things exist at a need level that most people haven't reached....

"Active members of the space community today will have a different perception than the rest of society regarding where the rationales fall in the Hierarchy. To the people who live this stuff on a daily basis, the exploration and development of space is their financial security and medical coverage at the safety-needs level, their professional and social networks at the social-needs level, and their recognition and sense of accomplishment at the esteem-needs level. Many have reached the self-actualization level where they seek the truth about life elsewhere in the universe....

"The rest of the populace outside the space community needs to see how space contributes to need fulfillment at the levels of the Hierarchy where they live and work ... economic and survival."

Vedda, James A. *Choice, Not Fate: Shaping a Sustainable Future in the Space Age*. Bloomington, IN: Xlibris. 2009. p. 161-163. Emphasis in original.

[11] "Historically commercial considerations rather than a quest for scientific knowledge has triggered much of the exploration of the Earth, and, even when the search for knowledge was a major element, much was actuated by the potential improvement of navigation so that commerce might prosper." Lyall, Francis, and Paul B. Larsen. *Space Law: A Treatise*. Surrey, England: Ashgate. 2009. p. 190.

[12] Rampell, Catherine. "'Great Recession': A Brief Etymology." *The New York Times*. <http://economix.blogs.nytimes.com/2009/03/11/great-recession-a-brief-etymology/>

[13] Brooks, David, "The Lean Years." *The New York Times*. 15 February 2009. <http://www.nytimes.com/2010/02/16/opinion/16brooks.html >
See also: *The Economist*, 18 September 2010, cover story: "Are we there yet? America's long, hard road to recovery." "For now, it is most likely that America's economy will crawl along with growth at perhaps 2.5%: above stall speed, but far too slow to make much difference to the jobless rate." <http://www.economist.com/node/17039121>

[14] "The federal government is ... spending far more than it collects in revenues, and if current policies are continued, will do so for the foreseeable future.... No reasonably foreseeable rate of economic growth would overcome this structural deficit.... If action is taken soon, the country has a wide choice of options to help achieve fiscal sustainability. All are difficult; but if action is postponed, the options will be fewer and the choices will be even more difficult. With delay, the risk of a disruptive fiscal crisis will grow, and the standard of living experienced by everyone's grandchildren is likely to be lower than it is for people today." Palmer, John L., and Rudolph G. Penner, Chairs. Committee on the Fiscal Future of the United States. "Choosing the Nation's Fiscal Future." National Research Council & National Academy of Public Administration. 2010. p. 1, 8. <http://www.nap.edu/catalog/12808.html>

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[15] Vedda, James. *Choice, Not Fate*. p. 162.

[16] Rasmussen Reports. "50% Favor Cutting Back on Space." 15 January 2010. <http://www.rasmussenreports.com/public_content/lifestyle/general_lifestyle/january_2010/50_favor_cutting_back_on_space_exploration>

[17] Kargel, Jeffery, W. Fink, R. Furfaro, H. Miyamoto. "Robotic resource exploration is a key to human expansion through the cosmos." *Proceedings SPIE,* 2008:6960. <http://dx.doi.org/10.1117/12.784643>

Kargel also authored an early paper analyzing the economic attractiveness, and technical challenges, of PGM asteroid mining:
Kargel, Jeffery. "Metalliferous asteroids as potential sources of precious metals." *Journal of Geophysical Research*. 1994;99(E10):21129-21141.
<http://www.agu.org/pubs/crossref/1994/94JE02141.shtml>

[18] Camus, Juan P. *Management of mineral resources: Creating value in the mining business*. Littleton, CO: Society for Mining, Metallurgy, and Exploration. 2002. p. 97.

[19] Futron / Satellite Industry Association (SIA). "State of the satellite industry report." June 2009. p. 5. <http://www.futron.com/upload/wysiwyg/Resources/2009SSIR.pdf>

[20] See: Nansen, R., Guest Editor. "Solar Power Satellites." *Online Journal of Space Communications*. Athens, OH: Ohio University. December 2009. <http://spacejournal.ohio.edu/issue16/main.html>

See also: Citizens for Space Based Solar Power. <http://c-sbsp.org/>

[21] Boyle, Alan. "PG&E makes deal for space solar power." *MSNBC*. 13 April 2009. <http://www.msnbc.msn.com/id/30198977/>

The U.S. Department of Defense, which spends "more than $1/kWh in forward deployed locations [tens times standard residential rates]," is also interested in developing SBPS. See: Rouge, Joseph D."Space-based solar power as an opportunity for strategic security." National Security Space Office. U.S. Department of Defense. 2007.
<http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=ADA473860>
<http://www.acq.osd.mil/nsso/solar/SBSPInterimAssesment0.1.pdf>

[22] When a child asks what they should do to become an astronaut—an off-planet worker—we should tell her or him that extraterrestrial success results from the same activities that lead to success in any field: "Make yourself valuable *in that environment*."

[23] The National Aeronautics and Space Act of 1958, As Amended, establishes the profitable utilization of space resources as its *primary* responsibility: "Section 102. (c) The Congress declares that the general welfare of the United States requires that the National Aeronautics and Space Administration ... seek and encourage, to the maximum extent possible, *the fullest commercial use of space*."
<http://history.nasa.gov/spaceact-legishistory.pdf>

[24] Top departmental budgets, FY 2010 and 2011 (enacted / requested), in billions:

1. Space Operations	$6.2 / 5.5
2. Science	$4.5 / 5.0
3. Exploration	$3.8 / 3.9

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The first and third (2010: $10 b, of a total $18.7 b) spend their money putting humans into space. These programs were never designed to reach profitability. NASA has not outlined the direct (non-spinoff) economic benefits of sending humans into space utilizing current (decades old) technology.

[25] Johnson Matthey. “Price Charts.” *Platinum Today*. <http://www.platinum.matthey.com/prices/price_charts.html>

[26] See: Medhi, Neelakshi. “Regulatory matters: Which factors matter in regulating the environment?” *Association for Public Policy Analysis and Management* (APPAM) 2009. <http://www.umdcipe.org/conferences/epckdi/26.pdf>

[27] See: [i] Gordon, R., M. Bertram, T. Graedel. “Metal stocks and sustainability.” *PNAS*. 2006;103(5):1209-1214. <www.pnas.org/cgi/doi/10.1073/pnas.0509498103>

[ii] Elshkaki, Ayman. “Systems analysis of stock buffering: Development of a dynamic substance flow-stock model for the identification and estimation of future resources, waste streams, and emissions.” See especially: Chapter 8. “The consequences of the use of platinum in new technologies on its availability and on other metals cycles.” Doctoral thesis. 2007. <https://openaccess.leidenuniv.nl/bitstream/1887/12301/14/08.pdf>

[iii] Halada, Kohmei, M. Shimada, and K. Ijima. “Forecasting the consumption of metals up to 2050.” *Journal of the Japan Institute of Metals*. 2007;71(10):831-839. <http://www.jstage.jst.go.jp/article/jinstmet/71/10/71_831/_article>

[28] Yacobucci, Brent and Aimee Curtright. “A hydrogen economy and fuel cells: An overview.” Congressional Research Service: The Library of Congress. 14 January 2004. <http://www.cnie.org/NLE/CRSreports/04Jan/RL32196.pdf>

[29] Eggert, Roderick G., Chair. Committee on Critical Mineral Impacts on the U.S. Economy. Committee on Earth Resources. National Research Council of the National Academies. *Minerals, Critical Minerals, and the U.S. Economy*. National Academies Press. 2008. <http://books.nap.edu/catalog.php?record_id=12034>

[30] Of ~50,000 meteorites, 1,233 are “falls,” observed on entry to Earth’s atmosphere. Of these, 842 (68%) are ordinary chondrites (OCs), which display elemental abundances thought to be similar to those of the proto-solar-system disk. H-type OCs constitute 28% of observed fall meteorites. Tagle and Berlin (2008) offer data on ordinary chondrite elemental abundances (ppm):

ruthenium:	1.135
rhodium:	0.230
palladium:	0.825
iridium:	0.749
platinum:	1.559

This gives a PGM-5 total of 4.498 ppm (g/t), or ~4.5 ppm. Lodders and Fegley (1998) offer similar data—ruthenium: 1.100; rhodium: 0.210; palladium: 0.845; iridium: 0.770; and platinum: 1.580—for a PGM-5 total of 4.505 ppm.

The Meteoritical Society. “The Meteoritical Bulletin Database.” 2 April 2010. <http://tin.er.usgs.gov/meteor/metbull.php>

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Tagle, Roald, and Jana Berlin. "A database of chondrite analyses including platinum group elements, Ni, Co, Au, and Cr: Implications for the identification of chondritic projectiles." *Meteoritics & Planetary Science*. 2008;43(3):541–559. <http://dx.doi.org/10.1111/j.1945-5100.2008.tb00671.x>

Lodders, Katharina, and Bruce Fegley, Jr. *The Planetary Scientist's Companion*. Oxford, UK: Oxford University Press. 1998. p. 318-319.

[31] Jones, R.T. "An overview of Southern African PGM smelting." Mintek. 2005. p. 7. <http://www.pyrometallurgy.co.za/Mintek/Files/2005JonesPGMsmelting.pdf>

[32] However, several uncertainties remain regarding the mapping between the population of observed fall meteorites and NEAs. A 2008 study of 38 NEAs found that most (~63%) are mineralogically similar to LL-type ordinary chondrites, which are less metallic than H-type OCs. "This result is surprising, because LL chondrites are the least abundant ordinary chondrites (they represent only 10% of all ordinary chondrites, and 8% of all meteorites)." Vernazza, P., R. Binzel, et al. "Compositional differences between meteorites and near-Earth asteroids." *Nature*. 2008;454:858-860. <http://dx.doi.org/10.1038/nature07154>

[33] The PGM value of a 200 m diameter asteroid mineralogically similar to one of the most common types of observed-fall meteorites (H-type ordinary chondrites, with PGM-5 abundances of ~4.5 ppm) with the density of *Itokawa* (1.95 g/cm^3), is over **$1 billion:**

Asteroid value

(H Ordinary Chodrite)

Platinum group metal (PGM) value of a near-Earth asteroid (@) mineralogically similar to an Ordinary Chondrite (H-Type) meteorite

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diameter:	**200**	**m**
radius:	10,000	cm
volume:	4,188,786,666,667	cm^3 (4/3πr^3)
Itokawa density (1.95 g/cm^3):	8,168,134,000,000	g
(rubble pile)	8,168,134,000	kg
mass:	**8,168,134**	**tonne**

Platinum Group Metal			H Ord. Chondrite (ppm)	g/asteroid	toz/ast.	$/oz	$/asteroid
44	Ru	Ruthenium	1.135	9,270,832	298,064	180	53,651,551
45	Rh	Rhodium	0.230	1,878,671	60,401	2,488	150,296,798
46	Pd	Palladium	0.825	6,738,711	216,655	832	180,239,274
77	Ir	Iridium	0.749	6,117,932	196,696	921	181,147,267
78	Pt	Platinum	1.559	12,734,121	409,411	1,838	752,629,338
				36,740,267 g			**$1,317,964,228**
				36,740 kg			
				37 tonne: return			

Market Prices - January 2011 / **Global Demand - 2009**

			$/toz (troy ounce)	,000 toz	Sales ($)
44	Ru	Ruthenium	180	583	104,940,000
45	Rh	Rhodium	2,488	548	1,363,604,840
46	Pd	Palladium	832	6,520	5,424,118,400
77	Ir	Iridium	921	79	72,755,050
78	Pt	Platinum	1,838	5,919	10,881,016,080
				13,649	
			tonne:	425	**$17,846,434,370**
					One year PGM demand

Asteroid Density
Abe, Shinsuke, Tadashi Mukai, Naru Hirata, Olivier S. Barnouin-Jha, Andrew F. Cheng, Hirohide Demura, Robert W. Gaskell, Tatsuaki Hashimoto, Kensuke Hiraoka, Takayuki Honda, Takashi Kubota, Masatoshi Matsuoka, Takahide Mizuno, Ryosuke Nakamura, Daniel J. Scheeres, and Makoto Yoshikawa. Mass and Local Topography Measurements of Itokawa by Hayabusa. Science. 2006;312(5778):1344-47. <http://dx.doi.org/10.1126/science.1126272>

Meteorite Elemental Abundance
Tagle, Roald, and Jana Berlin. "A database of chondrite analyses including platinum group elements, Ni, Co, Au, and Cr: Implications for the identification of chondritic projectiles." Meteoritics & Planetary Science. 2008;43(3):541-559. <http://dx.doi.org/10.1111/j.1945-5100.2008.tb00671.x>

PGM Market Prices and Demand
Johnson Matthey. Platinum Today: Current and Historical Prices. January 2011. <http://www.platinum.matthey.com/pgm-prices/>

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Significantly higher metal concentrations may be found, if we can identify and target an asteroid that is mineralogically similar to a group IVB iron meteorite, thought to be the “fractional crystallization of a molten, magmatic, body of metal, presumably an [ancient] asteroidal core” (Hutchison 2004). But the evolution of IVB parent-bodies remains cloudy (Walker 2008). They are recognized as some of the most anomalous meteorite samples we have “in a number of aspects,” including “the highest abundances of refractory siderophile elements such as Ir [Pt, Rh, etc.]” (Campbell 2005).

The PGM-5 value of a 200 m diameter asteroid with elemental abundances similar to an IVB iron meteorite (PGM-5: ~90 ppm) is currently (January 2011) over **$25 billion:**

Asteroid value
(IVB Iron Meteorite)

Platinum group metal (PGM) value of a near-Earth asteroid (@) mineralogically similar to an IVB iron meteorite (~"Santa Clara")

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	diameter:	**200**	m
	radius:	10,000	cm
	volume:	4,188,786,666,667	cm^3 (4/3πr^3)
Itokawa density			
(1.95 g/cm^3):		8,168,134,000,000	g
(rubble pile)		8,168,134,000	kg
	mass:	**8,168,134**	**tonne**

Platinum Group Metal			IVB Iron (ppm)	g/asteroid	toz/ast.	$/oz	$/asteroid
44	Ru	Ruthenium	25.650	209,512,637	6,735,988	180	1,212,477,786
45	Rh	Rhodium	3.860	31,528,997	1,013,681	2,488	2,522,372,345
46	Pd	Palladium	8.055	65,794,319	2,115,336	832	1,759,790,731
77	Ir	Iridium	19.790	161,647,372	5,197,084	921	4,786,254,221
78	Pt	Platinum	32.320	263,994,091	8,487,607	1,838	15,602,937,905
				732,477,416 g			**$25,883,832,987**
				732,477 kg			
				732 tonne: return			

However, even though the largest known meteorite, Hoba (60 t), is a member of the IVB group, they are rare. And, as yet, the “parent bodies of magmatic iron meteorites [such as IVB meteorites] are … not compellingly linked to any asteroid type” (Chabot 2006).

“Based on all the evidence available, [it now appears] that most Tholen M-class asteroids [thought by some to indicate “metal”] are not remnant iron cores or enstatite chondrites, but rather collisional composites of silicates and irons with compositions more analogous to stony-iron meteorites and high-iron carbonaceous chondrites” (Shepard 2010).

These two meteorite types—H-type ordinary chondrites and IVB irons—seem to bracket plausible best-case return values for asteroid mining ventures. But this, from a business perspective, is only the beginning. Any actual venture will calculate return on investment (ROI) value using net present value (NPV) calculations, as outlined in Ross (2001):

$$\mathrm{NPV} = C_{orbit}\ M_{mpe}\ f\ t\ r\ e^{-\Delta v/v_e}\ (1+i)^{-a^{3/2}} - \ (C_{manuf}\ (M_{mpe} + M_{ps} + M_{ic})\ +\ B\ n)$$

Chabot, N. L., and H. Haack. “Evolution of asteroidal cores.” In Lauretta, Dante S., and Harry Y. McSween, Jr. *Meteorites and the Early Solar System II*. Tucson, AZ: University of Arizona Press. 2006. <http://www.lpi.usra.edu/books/MESSII/9019.pdf>

Campbell, Andrew J., and Munir Humayun. “Compositions of group IVB iron meteorites and their parent melt.” *Geochimica et Cosmochimica Acta*. 2005;69(19):4733-4744. <http://dx.doi.org/10.1016/j.gca.2005.06.004>

Hutchison, Robert. *Meteorites: A Petrologic, Chemical and Isotopic Synthesis*. Cambridge, UK: Cambridge Press. 2004. <http://hdl.handle.net/10141/60376>

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Ross, Shane D. "Near-Earth asteroid mining." CalTech: Space Industry Report. 2001. <http://www.cds.caltech.edu/~shane/papers/ross-asteroid-mining-2001.pdf>

Shepard, Michael K., Beth Ellen Clark, Maureen Ockert-Bell, Michael C. Nolan, Ellen S. Howell, Christopher Magri, Jon D. Giorgini, Lance A.M. Benner, Steven J. Ostro, Alan W. Harris, Brian D. Warner, Robert D. Stephens, and Michael Mueller. "A radar survey of M- and X-class asteroids. II. Summary and synthesis." *Icarus*. 2010. <http://dx.doi.org/10.1016/j.icarus.2010.01.017>

Walker, Richard J., William F. McDonough, Jenise Honesto, Nancy L. Chabot, Timothy J. McCoy, Richard D. Ash, and Jeremy J. Bellucci. "Modeling fractional crystallization of group IVB iron meteorites." *Geochimica et Cosmochimica Acta*. 2008;72(8):2198-2216. <http://dx.doi.org/10.1016/j.gca.2008.01.021>

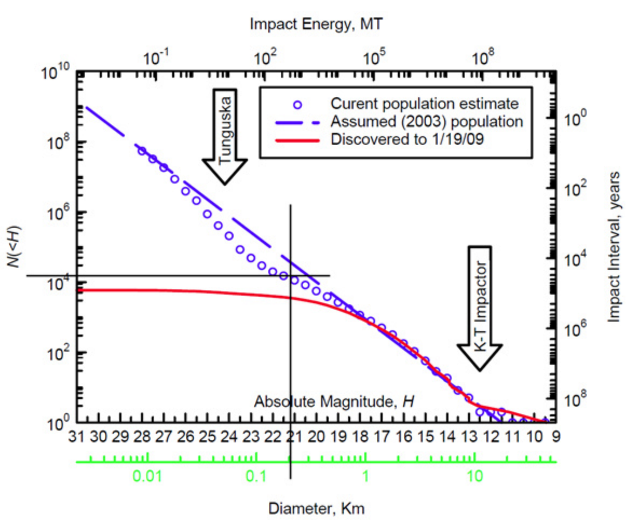
[34] NASA Near-Earth Object Program. "Known Near-Earth Asteroids per Size Bin." <http://neo.jpl.nasa.gov/stats/>

[35] See: Benner, Lance. NASA. Jet Propulsion Laboratory. Asteroids, Comets & Satellites. "Delta-v for spacecraft rendezvous with all known near-Earth asteroids (q < 1.3 AU)." <http://echo.jpl.nasa.gov/~lance/delta_v/delta_v.rendezvous.html>

These calculations assume that NEAs have "an albedo range between 0.25 to 0.05." Which means that NEAs with an absolute magnitude (H) of 21.5 are expected to be between 130 and 300 meters in diameter, or roughly 200 meters.
See: NASA Near-Earth Object Program. "Absolute Magnitude (H)." <http://neo.jpl.nasa.gov/glossary/h.html>

[36] Bolden, Charles. NASA. "Fiscal Year 2011 Budget Estimate." p. ii.
See also: "NASA Authorization Act of 2010." S.3729. Passed by the House and Senate, and signed by the president on 11 October 2010. Public Law No: 111-267. <http://thomas.loc.gov/cgi-bin/bdquery/z?d111:SN03729:@@@L&summ2=m&>
See also: "NASA Fiscal Year 2012: Budget Estimates." 14 February 2011. p. BUD-1. <http://www.nasa.gov/pdf/516675main_NASA_FY12_Budget_Estimates.pdf>

[37] "Numbers, N, of objects brighter than absolute magnitude H as a function of H":



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Shapiro, Irwin I. Chair. “Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies: Final Report.” Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies. Space Studies Board. Aeronautics and Space Engineering Board. The National Research Council. 2009. p. 17. <http://www.nap.edu/catalog.php?record_id=12842>

[38] For example, we are still discovering the fundamental physics of asteroid morphology. See: Scheeres, D.J., C.M. Hartzell, P. Sánchez. “Scaling forces to asteroid surfaces: The role of cohesion.” Cornell University: *arXiv*. 12 February 2010. <http://arxiv.org/abs/1002.2478>

[39] See, for example: The International Space Exploration Coordination Group (ISEGC), “14 space agencies [discussing] global interests in space exploration, [including] peaceful robotic and human space exploration, focusing on destinations within the Solar System where humans may one day live and work.” <http://www.globalspaceexploration.org/>

[40] Bradsher, Keith. *The New York Times*. “China tightens grip on rare minerals.” 2009. <http://www.nytimes.com/2009/09/01/business/global/01minerals.html>
See also: Nicola, Stefan. “The world’s next resource conflict.” UPI. 2010. <http://www.upi.com/Science_News/Resource-Wars/2010/02/22/The-worlds-next-resource-conflict/UPI-32341266872705/>
See also: Editorial. “Elements in short supply.” *Nature Materials* 2011;10:157. <http://dx.doi.org/10.1038/nmat2985>

[41] Including nearly all the rare earth elements, as well as indium, niobium, rubidium, strontium, tantalum, thallium, thorium, vanadium, and yttrium.
U.S. Geological Survey. “Mineral Commodity Summaries.” January 2010. p. 6. <http://minerals.usgs.gov/minerals/pubs/mcs/2010/mcs2010.pdf >

[42] “At the heart of a business case is a knowledge-based approach ... that is a best practice among leading commercial firms. Those firms have created an environment and adopted practices that put their program managers in a good position to succeed in meeting expectations. A knowledge-based approach requires that managers demonstrate high levels of knowledge as the program proceeds from technology development to system development and, finally, production. In essence, knowledge supplants risk over time.” U.S. Government Accountability Office. “NASA: Assessments of Selected Large-Scale Projects.” Report to Congressional Committees. GAO-10-227SP. February 2010. p. 8. <http://www.gao.gov/new.items/d10227sp.pdf>

[43] Cramer, Bryant. Associate Director for Geography, U.S. Geological Survey, Department of the Interior. Letter to Space Wealth. 2 September 2009. <http://spacewealth.org/letters>

[44] The grain size of the PGM material in the asteroid, and the anticipated beneficiation methodologies, will determine what “pulverized” means. Terrestrial mining operations designed to liberate PGM minerals whose average grain size is 15 and 45 µm, mill the ore so that 55% and 80% of the particles are smaller than 75 µm, respectively.
Jones, R.T. “An overview of Southern African PGM smelting.” Mintek. 2005. p. 7. <http://www.pyrometallurgy.co.za/Mintek/Files/2005JonesPGMsmelting.pdf>

[45] This level of concentration (45%) is comparable to that found in current industrial processes (30-65%) prior to the final beneficiation process of high-temperature refining,

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which results in metal concentration levels of ≥ 99.9%.
Jones, R.T. “An overview of Southern African PGM smelting.” Mintek. 2005. p. 8.

[46] JAXA. “Hayabusa.” <http://www.hayabusa.isas.jaxa.jp/e/index.html>

[47] Raymond, C.A., C.T. Russell, et al. “Exploring asteroid 4 Vesta with the Dawn Mission.” 41st Lunar and Planetary Science Conference. 2 March 2010.
<ftp://ftp.lpi.usra.edu/pub/outgoing/lpsc2010/full252.pdf>

[48] The Origins Spectral Interpretation Resource Identification Security-Regolith Explorer (OSIRIS-REx) will “rendezvous and orbit a primitive asteroid, … collect more than two ounces of material from the asteroid’s surface, [and] return to Earth.”
<http://discoverynewfrontiers.nasa.gov/news/New%20Frontiers/2009/news_123009.html>
<http://pirlwww.lpl.arizona.edu/~guym/OSIRIS-REx.pdf>
<http://gsfctechnology.gsfc.nasa.gov/ORIRIS.htm>

[49] “The [NASA] Administrator shall plan, develop, and implement a Near-Earth Object Survey program to detect, track, catalogue, and characterize the physical characteristics of near-Earth objects equal to or greater than 140 meters in diameter.... It shall be the goal of the Survey program to achieve *90 percent* completion of its near-Earth object catalogue (based on statistically predicted populations of near-Earth objects) *within 15 years* after the date of enactment of this Act [i.e., by 2020].” Emphasis added.
U.S. 109th Congress, 1st Session. S. 1281. “National Aeronautics and Space Administration Authorization Act of 2005.” Public Law No: 109-155, as of 30 December 2005.
Section 321. Subtitle C: “George E. Brown, Jr. Near-Earth Object Survey Act.” p. 28.
<http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=109_cong_bills&docid=f:s1281enr.txt.pdf>

[50] Shapiro, Irwin I, Chair, et al. Committee to review near-Earth object surveys and hazard mitigation strategies. “Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies: Final Report.” Space Studies Board. National Research Council. 2010. <http://www.nap.edu/catalog.php?record_id=12842>

[51] Hildebr, A.R., R.D. Cardinal, K.A. Carroll, D.R. Faber, E.F. Tedesco, et al. “Advantages of searching for asteroids from low Earth orbit: The NEOSSat mission.” In Hawkes, Robert, Ingrid Mann, and Peter Brown, editors. *Modern Meteor Science: An Interdisciplinary View*. The Netherlands, Dordrecht: Springer. 2005.
<http://dx.doi.org/10.1007/1-4020-5075-5_5>

[52] Shapiro, et al. “Defending Planet Earth.” 2010. p. 2.

[53] Bolden, Charles. NASA. “Fiscal Year 2011 Budget Estimate.” February 2010. p. iii.
<http://www.nasa.gov/pdf/428837main_NASA_FY_2011_Congressional_Justificaton_Budget_Book_Rev-01_BOOKMARKED.pdf>
See also, “NASA Authorization Act of 2010.” S.3729.
<http://thomas.loc.gov/cgi-bin/bdquery/z?d111:SN03729:@@@L&summ2=m&>

[54] Shapiro, et al. “Defending Planet Earth.” 2010. p. 2.

[55] “Q: Why an 8.4 meter mirror with a 3.5 degree field? Couldn’t a smaller telescope or an array of smaller telescopes do the same science in a somewhat longer time?
A: Some of the science can’t be done at all with a smaller telescope, or a group of small telescopes.... [For example, the] near-Earth object (NEO) survey is looking for things that won’t sit still for a long exposure.” LSST Science FAQ.
<http://www.lsst.org/lsst/science/science-faq#q10>

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[56] Blandford, Roger D., Chair, et al. Committee for a Decadal Survey of Astronomy and Astrophysics. "New Worlds, New Horizons in Astronomy and Astrophysics." Space Studies Board. National Research Council. 2010. p. 1-10. "The appraised construction cost is $465 million.... The annual operations costs are estimated at $42 million." <http://www.nap.edu/catalog/12951.html>

See also: Overbye, D. "Donors bring big telescope a step closer." *The New York Times*. 5 January 2008. <http://www.nytimes.com/2008/01/05/science/space/05scope.html>

[57] "Thermal infrared (~5 to ~11 microns) is the most efficient spectral regime for an efficient NEO search; ... any IR aperture from about 50 to 100 centimeters is sufficient; and ... locating a NEO-finding observatory in a Venus-like orbit (approximately a 0.7 AU semimajor axis) is ideal." Reitsema, Harold, and Robert Arentz. "NEO survey: An efficient search for near-Earth objects by an IR observatory in a Venus-like orbit." Submitted to the Primitive Bodies Subcommittee of the Decadal Survey. 16 September 2009. <http://www.psi.edu/decadal/topical/RobertFArentz.pdf>

[58] Spitzer. <http://spitzer.caltech.edu/>

[59] Kepler. <http://kepler.nasa.gov/>

[60] Reitsema and Arentz. "NEO Survey." 2009. See also: Tad Friend. "Vermin of the Sky: Who will keep the planet safe from asteroids?" *The New Yorker*. 28 February 2011. Which reports on recommendations to "place an infrared telescope into a Venus-like orbit." <http://www.newyorker.com/reporting/2011/02/28/110228fa_fact_friend>

[61] The Near Earth Object Surveillance Satellite (NEOSSat) has passed its critical design review (CDR) and is "well into Phase D" development. Launch is scheduled for mid 2011. Total mission cost, including launch: $12.5 million.
Cooper, David. CEO, Microsat Systems Canada, Inc. Email received: 29 March 2010.
<http://www.asc-csa.gc.ca/eng/sciences/neossat.asp>
<http://www.mscinc.ca/heritage/neossat.html> <http://www.neossat.ca/>

[62] Kuehrt, Ekkehard, et al. "AsteroidFinder: A German mission for the search of IEOs." American Astronomical Society. Division for Planetary Sciences. Meeting 41. 2009. <http://adsabs.harvard.edu/abs/2009DPS....41.6814K>

"The [AsteroidFinder] spacecraft bus belongs to the 'compact' class, having an overall mass of approximately 100 kg and dimensions which allow piggy-back launches. After a review process the AsteroidFinder proposal was selected in 2008 to be the first mission featuring a DLR SSB [standard satellite bus]. The launch into a Sun-synchronous low-Earth orbit is planned for 2013." German Aerospace Center (DLR). "AsteroidFinder." <http://www.dlr.de/pf/en/desktopdefault.aspx/tabid-174/319_read-18911/>

[63] Binzel, R.P., A.S. Rivkin, J.S. Stuart, A.W. Harris, S.J. Bus, and T.H. Burbine. "Observed spectral properties of near-Earth objects: results for population distribution, source regions, and space weathering processes." *Icarus* 2004;170:259-294.
<http://www.mtholyoke.edu/courses/tburbine/tomburbine/binzel.2004.pdf>
The paper "provides a summary compilation of ... 401 near-Earth and Mars-crossing objects..., the largest available uniform data set for this population."

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[64] Dunn, T.L., T.J. McCoy, J.M. Sunshine, and H.Y. McSween, Jr. “A coordinated mineralogical, spectral, and compositional study of ordinary chondrites: Implications for asteroid spectroscopic classification.” 41st Lunar and Planetary Science Conference. 2010. <http://www.lpi.usra.edu/meetings/lpsc2010/pdf/1750.pdf>

[65] “Existing programs of ground-based optical observations for characterization of NEOs are few in number, and are not coordinated among different observing teams.... Many observable NEOs are not characterized.”
Shapiro. “Defending Planet Earth.” 2010. p. 55.

[66] Burbine, Thomas H., Andrew S. Rivkin, Sarah K. Noble, Thais Mothé-Diniz, William F. Bottke, Timothy J. McCoy, M. Darby Dyar, and Cristina A. Thomas. “Oxygen and Asteroids.” *Reviews in Mineralogy and Geochemistry*. 2008;68(1):273-343. <http://dx.doi.org/10.2138/rmg.2008.68.12>

[67] JAXA. “Hayabusa.” <http://www.jaxa.jp/projects/sat/muses_c/index_e.html> <http://www.hayabusa.isas.jaxa.jp/e/index.html>

[68] The Pico Autonomous Near-Earth Asteroid In Situ Characterizer (PANIC) is “a cost-efficient, autonomous, micro-scale surface lander.... The lander has the shape of a regular tetrahedron with an edge length of 35 cm and a mass of less than 10 kg, housing three science instruments.... It was designed to achieve maximum simplicity, to limit risks and reduce cost, while still enabling fully autonomous operations [and] an uncontrolled hard landing.” Schindler, K., C.A. Thomas, and V. Reddy. “PANIC: A mission concept study for a miniaturized autonomous lander for in situ characterization of a near-Earth asteroid.” European Planetary Science Congress. 2009. <http://meetingorganizer.copernicus.org/EPSC2009/EPSC2009-758.pdf>

[69] Smith, D. B., K. Klaus, G. Caplin, M. S. Elsperman, and J. Horsewood. “Low cost multiple near-Earth object missions.” 41st Lunar and Planetary Science Conference. 2010. <http://www.lpi.usra.edu/meetings/lpsc2010/pdf/1464.pdf>

[70] Such as six-legged, asteroid lander/gripper/crawlers whose limbs are controlled by real-time Java processors:

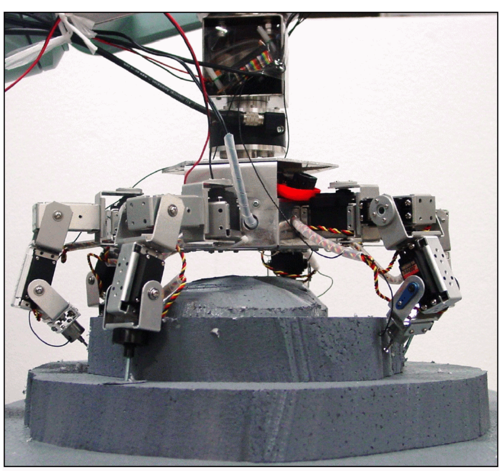

Figure 21: Picture of the successful experiment with the Hexabot Spidy performing a combination of “soft landing and grasping mode” to achieve remain attached to the surface just after touchdown.

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Valencia, Filipo. "On locomotion and grasping control of a limbed rover intended for asteroid surface exploration." International Space University, Illkirch-Graffenstaden, France / Tohoku University, Sendai, Japan. Masters of Science in Space Studies. 2006. <http://www.astro.mech.tohoku.ac.jp/~eric/files/Mendoza_Filipo_IP_Report_HR.pdf>

See also: Chacin, Marco, Andres Mora, and Kazuya Yoshida. "Multi-limbed robot control on asteroid exploration missions." Proceedings: 2009 IEEE international conference on Robotics and Automation. Kobe, Japan. 2009. <http://www.senkyo.co.jp/ists2009/papers/html/pdf/2009-k-15.pdf>

[71] Huff, Howard R. *Into The Nano Era: Moore's Law Beyond Planar Silicon CMOS (Springer Series in Materials Science: 106)*. Berlin: Springer-Verlag. 2009. <http://books.google.com/books?id=OGP-6QnHKHMC>

See also: Intel's $7 billion investment in new, 32-nanometer manufacturing facilities. "A special report on America's economy: Export or die." *The Economist*. 31 March 2010. <http://www.economist.com/specialreports/displaystory.cfm?story_id=15793128>

[72] "The net effect of designing for high [spacecraft] reliability is that spacecraft design is conservative.... Much of satellite design is thus not 'state-of -the-art' technology." Fortescue, Peter, John Stark, and Graham Swinerd, editors. *Spacecraft Systems Engineering,* 3rd Edition. Wiley. 2003. p. 8.

See also: Riedel, J. Edmund, et al. JPL. "A Survey of Technologies Necessary for the Next Decade of Small Body and Planetary Exploration." A technical supplemental to papers submitted by the Small Bodies Assessment Group to the National Academies Planetary Science Decadal Survey. "Current state of the art [for radiation hard computers is the] RAD750 ... with 10 million transistors and a clock speed of 200MHz." <http://www.lpi.usra.edu/decadal/sbag/topical_wp/JEdmundRiedel.pdf>

For comparison, the Intel Xeon processor contains up to 2.3 billion transistors running at 3.7 GHz. As the performance differential between off-the shelf and radiation hardened chips increases, it may become more cost effective to design spacecrafts that shield non-hardened chips.

[73] With a one-year mining season, complete processing of a 200 m diameter, Itokawa density asteroid (1.95 g/cm^3), robotic miners, with 95% uptime, need to process ~1,000 tonnes of ore *every hour*. Frontend mining equipment on Earth can handle an order of magnitude greater throughput. "The EX8000 will be the latest and largest in a range of shovels developed by Hitachi since 1979.... Maximum hourly production is projected to be *8,000 tonnes/hour,* with average of around 6,000 tonnes/hour."
Australian Journal of Mining. July-August 2004.
<http://hcm.vo.llnwd.net/e1/au/pdf/products/excavator/face/articles/ex8000.pdf>

If melting is used to process/refine the ore, gigawatts of power will be required.

[74] "Since [this] book is written for senior undergraduates and first-year graduate level students of engineering, the assumption is that users are familiar with matrix algebra as well as basic feedback control. Prerequisites for readers ... consist of the fundamentals of kinematics, dynamics, vector analysis, and matrix theory."
Jazar, Reza N. *Theory of Applied Robotics: Kinematics, Dynamics, and Control*. Springer. 2007.

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[75] Ketsdever, Andrew D., Marcus P. Young, Jason B. Mossman, and Anthony P. Pancotti. "An overview of advanced concepts for space access." Air Force Research Lab. Propulsion Directorate. Edwards Air Force Base, CA. 2008. <http://handle.dtic.mil/100.2/ADA484431>

[76] Ketsdever, et al. "An overview of advanced concepts for space access." p. 11.

See also: Cole, John W., Isaac F. Silvera, and John P. Foote. "Conceptual launch vehicles using metallic hydrogen propellant." Space Technology and Applications International Forum (STAIF) 2008. <http://dx.doi.org/doi:10.1063/1.2845066>

[77] Terwiesch, Christian, and Karl Ulrich. *Innovation Tournaments: Creating and Selecting Exceptional Opportunities*. Cambridge, MA: Harvard Business Press. 2009.

[78] Granvik, Mikael, Jenni Virtanen, Dagmara Oszkiewicz, Karri Muinonen. "OpenOrb: Open-source asteroid orbit computation software including statistical ranging." *Meteoritics & Planetary Science* 2009;44(12):1853-1861. <http://dx.doi.org/10.1111/j.1945-5100.2009.tb01994.x>

See also: DeBenedictis, Erika. "An optimization algorithm for space mission design: Dynamically simulating energy-efficient trajectories." Winner of the $1 million Intel Science Talent Search Award. 2010. <http://www.debenedictis.org/erika/V1v3.pdf> <http://www.intel.com/pressroom/archive/releases/20100316edu.htm>

[79] "In 2005, NASA [found] that the number of debris larger than 10 cm would continue to increase due to collisions between existing resident space objects, even if no new satellites were launched.... This result was reinforced by the first accidental collision between two large intact satellites, Iridium 33 and Cosmos 2251, in February 2009." NASA. Orbital Debris Program Office. *Orbital Debris Quarterly News*. January 2010. <http://www.orbitaldebris.jsc.nasa.gov/newsletter/pdfs/ODQNv14i1.pdf>

[80] "Tens of millions of pieces of space debris exist [within 2,000 km of Earth's surface]." Johnson, Kevin, John G. Hudson II, Jared Brower, Stehanie Cook, Edward Dae, Josh Koch, John Miller, Stephanie Silva. "Eliminating Space Debris: Applied Technology and Policy Prescriptions." U.S. STRATCOM. Global Innovation and Strategy Center. 2008. <http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA497909&Location=U2&doc=GetTRDoc.pdf>

A joint DARPA and NASA conference: "Orbital Debris Removal." December 2009. <http://www.darpa.mil/news/2009/OrbitalDebris.pdf> <http://www.space.com/news/091208-space-junk-cleanup-meeting.html>

[81] Kessler, Donald J. "The Kessler Syndrome." 8 March 2009. <http://webpages.charter.net/dkessler/files/KesSym.html>

[82] "Ground-based lasers currently offer the most efficient means for small debris remediation, but remain untested. A demonstration of ground-based laser technology under actual operating conditions is therefore of utmost priority."
Johnson, Kevin, et al. "Eliminating Space Debris." U.S. STRATCOM, GISC. 2008. p. 9.

[83] Williams, Dan. "U.S. general urges world war on space debris." *Reuters*. 27 January 2010. <http://www.reuters.com/article/idUSTRE60Q4QM20100127>

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[84] Any “exploitation of the Moon ([or] other celestial bodies) poses legal problems, and many suggestions have been made [citing ~20 such]…. That said, something will have to be done to clarify or establish appropriate rules for the exploitation of the resources of the Moon and other celestial bodies. Financiers will not risk capital if the rights to extracted materials are inadequately defined.” Lyall, Francis, and Paul B. Larsen. *Space Law: A Treatise*. Surrey, England: Ashgate. 2009. p. 190, 196.

See also: Pop, Virgiliu. *Who owns the Moon?: Extraterrestrial aspects of land and mineral resources ownership*. Springer. 2009.

Presentations at the 61st International Astronautical Congress (IAC) show that while the need for improved property rights laws are needed, the way forward is challenging. < http://rescommunis.wordpress.com/2010/09/28/iac-2010-e7-2-30-years-of-the-moon-agreement-perspectives/>

[85] “ ‘Space law’ is international law.” Hastings, Daniel E., and Jeffrey Hoffman. “Space Policy Seminar: 16.891J/ESD.129.” MIT: OpenCouseWare. 2003. <http://ocw.mit.edu/OcwWeb/Aeronautics-and-Astronautics/16-891JSpace-Policy-SeminarSpring2003/CourseHome>

[86] “It’s tempting to believe that no one else’s job could be as complex as mine. But extreme complexity is the rule for almost everyone…. What experts … have recognized is that the reason for [knowledge management failures] is not usually laziness or unwillingness. The reason is more often that the necessary knowledge has not been translated into a simple, usable, and systematic form.” Gawande, Atul. *The Checklist Manifesto: How to get things right*. New York: Henry Holt / Metropolitan Books. 2009. p. 21, 133.

[87] For example, “the initial estimated launch costs for the Space Shuttle were $200/kg, but the achieved costs are closer to $20,000/kg.” Two orders of magnitude. Ketsdever, et al. “An overview of advanced concepts for space access.” p. 5.

[88] “Finding 1. [NASA, NOAA, and DOD] instrument developments lack the resources and authority to successfully manage to cost and schedule requirements…. ~70% of the [programs that developed] instruments reported 25% or more cost overruns and ~60% … reported schedule delays of five (5) months or more.”
Leon, John. Chair. Juan C. Rivera, Co-Chair. *NASA Instrument Capability Study: Final Report*. NASA HQ. Office of the Chief Engineer. Washington, DC. 2008. p. ix. <http://oceexternal.nasa.gov/OCE_LIB/pdf/1021184main_NICS_Report_Errata.pdf>

“Planetary instruments often run into cost overruns and capability descopes due to underestimation of the technology readiness [TRL] of component subsystems.” Webster, Chris R. “Status of planetary science instrument technologies.” Presentation to the Planetary Science Decadal Survey Steering Group. National Research Council. 23 February 2010. p. 30.
<http://www.spacepolicyonline.com/pages/images/stories/PSDS%20Steering%20CMte%20Feb%202010%20Webste.pdf>

[89] “We assessed 19 large-scale NASA projects [of which] 15 had entered implementation. Nine of the 15 projects experienced significant cost and/or schedule growth from their project baselines.”
U.S. GAO. “NASA: Assessments of Selected Large-Scale Projects.” Report to Congressional Committees. GAO-10-227SP. February 2010. p. 11.
<http://www.gao.gov/new.items/d10227sp.pdf>

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90 “Despite the years of experience in executing spacecraft missions, the development of institutional standards, and the implementation of training programs, NASA projects still experience cost overruns resulting from basic project management and systems engineering issues.” Recurring problems: underestimating knowledge requirements, inadequate planning and integrated master schedules, and poor project documentation. Barley, Bryan, and Paul Gilbert. NASA Marshall Space Flight Center. Discovery and New Frontiers Program Office. And Marilyn Newhouse, Computer Sciences Corporation. “Improving the Life Cycle Cost Management of Planetary Missions: Final Report.” February 2010. p. 11, 12.
<http://discoverynewfrontiers.nasa.gov/lib/pdf/LifeCycleCostStudyReport.pdf>

91 “A measure of how much difficulty is expected to be encountered in the maturation of a particular technology is needed to complement the existing Technology Readiness Levels (TRLs) metric. TRL’s are a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology. A measure characterized as the ‘Research and Development Degree of Difficulty’ (R&D3) is proposed as an additional measure.”
Mankins, John C. “Research & Development Degree of Difficulty: R&D3.” NASA HQ. Office of Space Flight. Advanced Projects Office. 10 March 1998.
<http://www.hq.nasa.gov/office/codeq/trl/r&d3.pdf>

92 A “growing body of empirical work shows that users are the first to develop many and perhaps most new industrial and consumer products.”
von Hippel, Eric. *Democratizing Innovation*. Cambridge, MA: The MIT Press. 2005. p. 5.
<http://web.mit.edu/evhippel/www/democ1.htm>

93 Vedda, James A. *Choice, Not Fate: Shaping a Sustainable Future in the Space Age*. Bloomington, IN: Xlibris. 2009. p. 93.

94 Lyles, Lester L., Chair, et al. Committee on the Rationale and Goals of the U.S. Civil Space Program. “America’s future in space: Aligning the civil space program with national needs.” Space Studies Board and Aeronautics and Space Engineering Board. National Research Council. 2009. p. 16. <http://www.nap.edu/catalog/12701.html>

95 *Wall-E,* the film of a space-robot love story/hero’s quest, topped the charts for G-rated releases in 2008, and came in 5th for gross domestic proceeds of all 2008 releases. World gross to date: $520 million. <http://www.boxofficemojo.com/movies/?id=wall-e.htm>

96 “The newly established Office of the Chief Technologist ... will fund advancements in next-generation technologies, to help improve the Nation’s leadership in key research areas, enable far-term capabilities, and spawn game-changing innovations that can unlock new possibilities.”
Bolden, Charles F., Jr. “NASA Administrator Statement before the Subcommittee on Commerce, Justice, Science, and Related Agencies. Committee on Appropriations. U.S. House of Representatives. 23 March 2010. p. 3.
<http://appropriations.house.gov/Witness_testimony/CJS/Charles_Bolden.3.23.10.pdf>

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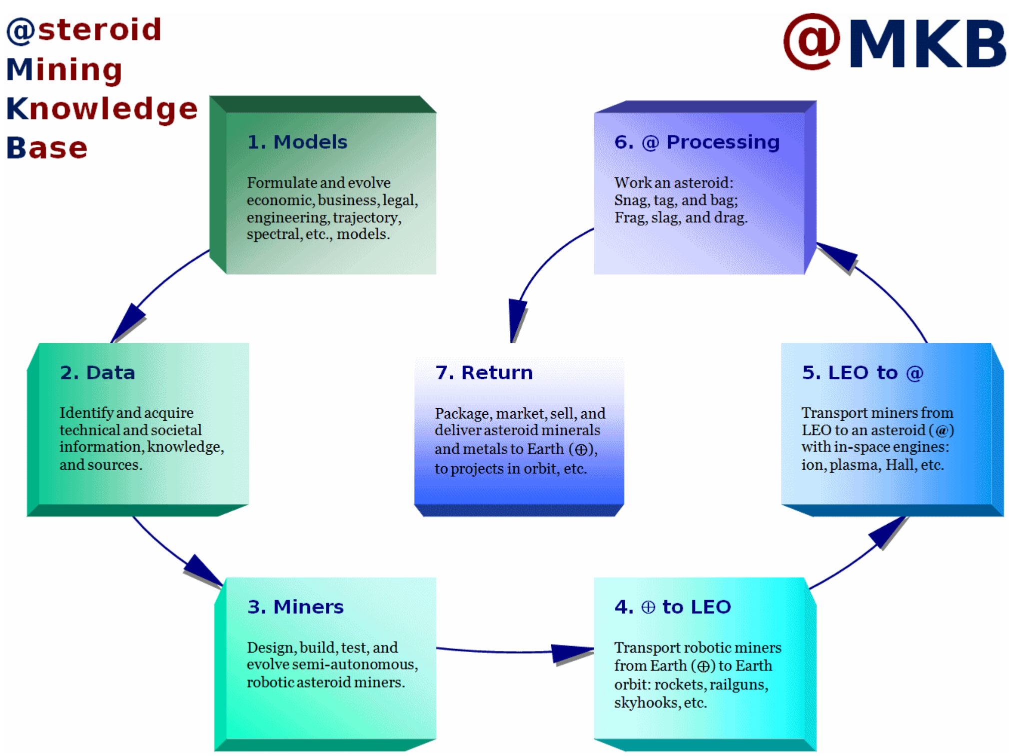
97 Space Wealth: An *Asteroid Mining Knowledge Base* (@MKB): <http://spacewealth.org/AMKB>



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