Asteroids
Working Group Report

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Asteroids Working Group

Part of the Next Generation Exploration Conference

Declaration

The economic potential of thousands of near-earth asteroids (NEAs) will help to support future exploration endeavors and human presence in space. Strong evidence suggests that NEAs are rich in metals, water, and/or organic materials, and reaching them will require relatively low fuel costs. Extracted materials from the NEAs can be used to manufacture structures, fuel, and other resources for mankind's exploration of the solar system. In addition, NEAs have a large range of orbits, allowing some to be utilized as traveling resource platforms that may also be used for low-energy transportation and scientific study of our solar system. Finally, as history has proven, NEAs can collide with Earth and have potentially catastrophic consequences to life and infrastructure. Exploration and understanding of asteroids is essential to humanity's future, both on Earth and in space.

5.0 Action Items:
- 5.1 Asteroid Science and Technology Recommendations / Notional Asteroid Missions
- 5.2 Education and Public Outreach

1.0 Introduction

The study and utilization of asteroids will be an economical way to enable exploration of the solar system and extend human presence in space. There are thousands of near-earth objects (NEOs) that we will be able to reach. They offer resources, transportation, and exploration platforms, but also present a potential threat to civilization.

Asteroids play a catastrophic role in the history of the Earth. Geological records indicate a regular history of massive impacts, which astronomical observations confirm is likely to continue with potentially devastating consequences. However, study and exploration of near earth asteroids can significantly increase advanced warning of an Earth impact, and potentially lead to the technology necessary to avert such a collision. Efforts to detect and prevent cataclysmic events would tend to foster and likely require international cooperation toward a unified goal of self-preservation. Exploration of asteroids will help us to understand our history and perhaps save our future.

Besides the obvious and compelling scientific and security drivers for asteroid research and exploration, there are numerous engineering and industrial applications for near-term asteroid exploration.

We have strong evidence that some asteroids are metal rich. Some are water and organic rich. They can be reached with a very low fuel cost compared to other solar system destinations. Once we reach them, there are efficient, simple extraction technologies available that would facilitate utilization. In addition, the costs of returning extracted resources from asteroids will be a fraction of the cost to return similar resources from the moon to Low Earth Orbit (LEO). These raw materials, extracted and shipped at relatively low cost, can be used to manufacture structures, fuel, and products which could be used to foster mankind's further exploration of the solar system.

Asteroids also have the potential to offer transport to several destinations in the solar system. In addition to Mars and the Asteroid belt, it is possible to nudge the orbits of NEOs to provide convenient transport to other destinations. Resources to support life on these long voyages may be gathered from the host asteroid itself. As asteroids travel over a wide range of inclinations and ranges, they offer possible platforms to perform scientific investigations. These include unique vantage point observations of the sun and planets. These observations can help us to understand solar activity and space weather. They also afford us an opportunity to see how the earth looks from afar with different perspectives. When we look for planets outside of our solar system, these observations will help us to calibrate our data. Asteroids may also be used as platforms to support very long baseline interferometry with unprecedented angular resolutions.

2.0 Themes

2.1 Utilize the unique attributes of Near-Earth Objects (NEOs) to enable and enhance sustainable robotic and human space exploration into the solar system.

Develop the technologies and operations necessary to make effective use of the resources NEOs provide, including:

- Extraction of abundant natural resources and raw materials necessary for exploration (water, regolith, metals)

- Use of NEOs as a low-energy "transit" system between the orbits of Earth, Mars, and the asteroid belt.

2.2 Pursue scientific activities to address fundamental questions about Asteroids, the solar system, the universe, and our place in them

Engage in scientific investigations:

- Of the Asteroids: Study the history of the Asteroids, their composition, and structure to learn about the evolution of our solar system;

- From the Asteroids: Use Asteroids as a traveling platform for performing scientific investigations.

2.3 To characterize and mitigate the risk Asteroids pose to life and infrastructure.

Study and catalog Asteroids and develop procedures to avert undesirable asteroid collisions with Earth, spacecraft, habitations beyond Earth, and infrastructure throughout the solar system.

2.4 Supported Themes for Categories

For the purposes of comparing and contrasting Asteroid objectives (below), we have defined six supporting themes:

- Science
- Exploration
- Impact Prevention
- Commerce / Earth Benefit
- Global Partnership
- Public Engagement

3.0 Objectives

3.1 Astronomy and Astrophysics

3.1.1 Observe Earth and other planets as a Calibrator for extra solar planets detection

Summary: The search for extra-solar planets will yield photometric and spectroscopic light curves. To determine if these extra solar planets have life or could support life, we need a calibrator such as the earth.
Value: Asteroids can carry instruments to locations offering different vantage points of the earth and other planets. These instruments can be revisited when the asteroid returns closer to earth.

3.1.2 Use as a platform for VLBI Astrophysics

Summary: The highest angular resolution for astrophysics is afforded by interferometry.
Value: Asteroids can provide rides for radio telescopes that can work in conjunction with those on other asteroids as well as on the earth and moon to provide very long baselines and unrivaled angular resolution making possible great advances in astrophysics and cosmology.

3.1.3 Study Zodiacal Dust

Summary: Study the zodiacal dust to determine its effect on extra solar planet detection. Dust within our solar system may affect these measurements. Also, dust in extrasolar systems can affect the detection of earth like planets.
Value: Asteroids can be chosen that sample various regions of the solar system and provide distribution information. For example, samples taken from above or below the ecliptic plane can potentially yield valuable information.

3.2 Heliophysics

3.2.1 Observe the Sun

Summary: Learn about global solar phenomena with multiwavelength observations. Understand space weather.
Value: Asteroids can offer different perspectives (including solar poles and far side of the sun) on the sun than those measurements just from the earth. In particular, we can choose asteroids that can give us far-side views of the sun simultaneous to earth observations and therefore get a more global view of solar phenomena.

3.2.2 Observe and Characterize the Solar Wind

Summary: Learn about the solar wind and space weather.
Value: Asteroids can offer different perspectives on the sun than those measurements just from the earth. In particular, we can choose asteroids that can give us farside views of the sun simultaneous to earth observations and therefore get a more global view of solar phenomena.

3.3 Geology

3.3.1 Understand the origin, composition, and structure of Asteroids

Summary: Determine the internal structure, mineral composition, and dynamics of Asteroids using a long-lived and extensive network of seismometers and/or penetrators and/or in situ and sample return analysis.
Value: The study of asteroids will help establish connections with existing meteorite collections. Asteroids may provide information about the state of the solar system from

formation to the present time. Knowledge of the composition is important for resource exploitation.

3.3.2 Gain a better understanding of the history of the moon by studying impact craters on asteroids

Summary: Make crater size and number distribution measurements. Correlate these with independent measurements of age.

Value: This will give collision rates that can be applied to lunar history models.

3.3.3 Study water and other volatiles on asteroids

Summary: Identify and quantify water and other volatiles and measure the distribution within the asteroid.

Value: Asteroids and comets are believed to be the source of any water and organics to the early earth and that we may find on the moon and other planets. Also, they may be the best source of these useful resources for exploration.

3.3.4 Characterize potential resources

Summary: Locate and quantify (develop planetary-scale maps) surface/near-surface deposits of potentially valuable resources, including both minerals and water.

Value: Future exploitation of asteroid resources is facilitated if a global surface map of these resources exists. Such a resource map is also of scientific value in helping to define variations in surface compositions.

3.3.5 Characterize the impact process

Summary: Study the physical and compositional effects of hypervelocity impact using lunar craters, from micron-sized zap pits to multi-ring basins. Study excavation and modification stages of impact process and their physical and compositional effects. Study the transport and mixing of materials as a result of impacts. Study the morphology of freshly formed craters and of their ejecta distribution.

Value: Use record of impacts preserved on the Asteroids to unravel complex processes, operative on all the planets. Will help characterize the recent impact rate and gardening rate.

3.4 Life Support and Habitat

3.4.1 Provide safe and enduring habitation systems to protect individuals, equipment, and associated infrastructure

Summary: During short and long-duration stays on an asteroid, individuals will need a habitat that will protect them from the environment. A number of implementation strategies are possible for this habitat, including using regolith as protection from radiation, and meteorite impact. In addition protection must be afforded to individuals and equipment traveling to/from the asteroid. Inside the habitats, basic life support and recreational activities should be provided to the crew. Over time, the life support systems should move from open to closed systems, with food production, water and air regeneration, and waste management systems.

3.4.2 Improve upon existing biologically based life support system components to support long duration human exploration missions

Summary: A number of plant and bacterial species have been identified for studying fundamental and applied topics related to the long term effects of the environment on processes associated with bioregenerative life support systems. These studies will determine the feasibility of integrating plants and microbes into the life-support systems for food production and treatment of water, air, and solid wastes.

3.4.3 Provide agriculture services to support life support systems
Summary: Agricultural services include the use of regolith as the growing medium for plants and crops, or the operation of a green-house or farm using imported (e.g. Earth soil or hydroponic) medium.

3.4.4 Provide health care services to aid life support operations
Summary: "In-Situ" medical care will be an important facet of working and living. Common ailments (e.g., colds, flu) can be treated medically without major impact to the mission execution. More serious problems (e.g., muscle strains, broken bones) may require stabilization of the patient and immediate (or near-immediate) return to Earth.

3.5 Materials Processing

3.5.1 Beneficiation
Summary: The process of enriching or separating minerals.

3.5.2 Regolith Digging
Summary: Designing the processes and developing the equipment necessary to dig regolith.

3.5.3 Environment Sealing
Summary: Sealing processing chambers in the presence of Asteroid regolith and dust.

3.5.4 Processing Techniques
Summary: Utilizing the environment and minimizing the equipment necessary for chemically and mechanically processing material/minerals into useful products.

3.5.5 Mineral Sieving
Summary: Separating differences in size and shape of minerals and materials.

3.5.6 Material Collection
Summary: Designing the processes and developing the equipment necessary to collect minerals, ores, and materials.

3.5.7 Material Storage
Summary: Refrigeration and Liquefaction of processed materials and minerals.

3.6 Communication and Navigation

3.6.1 Interplanetary Internet
Summary: Ubiquitous communication and navigation that is secure, reliable with high-bandwidth.

3.6.2 Autonomous systems and expert systems
Summary: Allowing reduced communications requirements

3.7 Power

3.7.1 Solar Energy

Summary: Utilize direct solar power as primary energy source for processing needs.

3.7.2 Requirement Definition and Characterization

Summary: Identify and define power and energy requirements for Asteroid activities (science, resource utilization, habitation, and threat mitigation).

3.8 Surface Mobility

3.8.1 Implement surface mobility systems to support both crew and cargo traverses in reduced gravity

3.8.2 Provide surface mobility capabilities for the purpose of constructing and operating an outpost

3.9 Operational Environmental Monitoring

3.9.1 Monitor space weather to protect inhabitants and gather data about our solar system

3.9.2 Monitor real-time environmental variables affecting safe operations

3.10 Crew Activity

3.10.1 Develop teleoperation capabilities to support human operation of equipment on the asteroid's surface. Implement human interaction systems (telepresence) to support automation technologies required for lunar operations.

3.10.2 Provide arts, entertainment, recreation, and leisure activities because for the well-being of the crew

3.11 Asteroid Resource Utilization

3.11.1 Characterization

Summary: Determine minerals present and the chemical and physical distribution of these minerals. Characterize the surface and subsurface mechanical properties of Asteroids.

3.11.2 Sample Return

Summary: Collect representative samples and return them to a laboratory.

3.11.3 Fabrication

Summary: Building of structural elements on the surface of Asteroids.

3.11.4 Resource- and Environment- Appropriate Refining Technologies

Summary: Turning beneficiated minerals into useful raw materials.

3.12 Commercial Opportunity

3.12.1 Business Plan

Summary: Establish viable business models and productive companies performing asteroid resource extraction and processing.

3.12.2 Tourism
Summary: Development of an Asteroid tourism industry.

3.12.3 Insurance
Summary: Establish a reasonable insurance environment that encourages Asteroid commerce.

3.12.4 Legal
Summary: Establish a reasonable legal regime encouraging Asteroid commerce and investment, including property rights protection.

3.12.5 Environmental Issues
Summary: Establish favorable environmental assessment and protection requirements.

3.12.6 Energy
Summary: Develop technologies for fabricating solar generation facilities from asteroid products

3.13 Public Engagement and Inspiration

3.13.1 Extend awareness of space activities to diverse, non-traditional communities, utilizing non-traditional means, to enhance public engagement.
Summary: Non-traditional methods of public engagement are rarely used for the space program. The proposal would to involve musicians, artists, poets, story tellers, etc. in public outreach about space to try and reach the general public in a new way. Non-traditional methods have proved effective in formal and informal education settings as well.
Value: The value of these diverse methods is that they may reach a set of the population not touched by traditional education and public outreach activities. These education activities could expand the workforce by demonstrating the excitement of and reasons for space exploration to diverse communities

3.14 Transportation

3.14.1 Provide redundant transportation services to and from the asteroid

3.14.2 Develop reliable methods of transporting materials to and from an asteroid

3.14.3 Develop methods of using an asteroid as a spacecraft to more distant exploration objectives

3.14.4 Optimize transportation methods to minimize thrust and delta v requirements

3.15 Global Partnership

3.15.1 Establish a global partnership framework to enable all interested parties (including non-space faring nations and private companies) to participate in asteroid exploration and resource utilization.
Summary: A global framework, able to encompass both commercial and governmental involvement, should be established to coordinate the asteroid-related activities of all interested parties. This framework should allow for (but may not require) coordination of roadmaps and missions, sharing of infrastructure and facilities, while maintaining autonomy (if desired) of participants.

Value: International collaboration, including government-government, government-commercial, and commercial-commercial, (where government involvement can be at the state or province level) can be efficient, cost effective, enable the long-term stability of the program, and promote international peace. Fostering collaboration has the potential to increase the amount of asteroid activity by increasing the total amount of financial and human resources available to the endeavor and increasing the level of public support. Finally, by allowing participants to maintain their autonomy within the overall program, each participant can establish their own goals, as best suit the needs of their stakeholders.

3.15.2 Establish standards and common interface designs to enable interoperability of systems developed by a global community.
Summary: Use existing standards and establish new standards for data, communication, and equipment. Standards should enable systems produced by different parties to be interoperable.
Value: Standard interfaces will enable exploration stakeholders to share infrastructure and consumables, thereby enhancing the affordability, sustainability, and safety of asteroid-based activities. Standardization will also allow suppliers to compete across emerging space commerce markets. One of the potential impacts to establishing standards is that it increases the barriers to entry for some participants.

3.16 General Infrastructure

3.16.1 Provide finance and insurance services to support businesses operating on NEOs.
Summary: Earth-based banking industry especially for the financing of NEO-related industries.
Value: Financing of NEO-related industries will be an important fundamental step toward self-sufficient and sustainable lunar commerce.

3.16.2 Provide warehousing services on NEOs.
Summary: Warehousing is the storage capability for goods in transit between their points of origin and destination.
Value: Inexpensive storage of goods between their points of origin and destination will be very important to the development of a sustainable and self-sufficient NEO business.

3.16.3 Develop infrastructure and utilities systems on NEOs to aid NEO operations.
Summary: Utilities can include power generation. Infrastructure can include anchor points or transportation systems. These are capabilities required by virtually all activities that will be conducted on NEO surfaces.
Value: Many basic needs for living and working on NEO surfaces must be met for efficient use of the in-situ resources (including humans working on the surface). Commercially developed infrastructure and utilities would enable government and commercial entities t

3.17 Operations Test and Verification

3.17.1 Engage in operations testing to understand the effect of the NEO environment on basic working tasks (with timescales applicable to early crewed Moon and Mars missions)
Summary: Test and refine techniques for living and working in the NEO environment. Individuals living on NEOs should learn how to do everyday things, such as cook, clean, and live their daily lives in a NEO habitat. Techniques must also be refined for basic work

Value: Systematic, comprehensive characterization of how fundamental living and working tasks are best accomplished in the lunar environment. This will speed the acclimatization to living on NEOs.

3.18 Guidance, Navigation and Control

3.18.1 Establish beacons for interplanetary navigation, communication, and threat assessment

Summary: Put transponders on selections of NEOs ranging between Earth and Mars for use in navigation between planets and NEOs.

Value: Provides interplanetary navigation network. Can provide information on undiscovered NEOs from orbital tracking. Also can be used to understand non-Newtonian dynamics.

3.18.2 Investigate and develop methods for orbit modification

Summary: It can become necessary to change the orbits of NEOs. As such, developing methods that work are needed.

Value: Provides the capability to change the positions of NEOs for a variety of purposes.

4.0 Issues and Enablers:

1. Interpretations of current international treaties prohibit commercial ownership of resources and should be revised.

2. Establish an international organization with jurisdiction to allocate usage and access rights for asteroids and provide a forum for dispute resolution (modeled after International Telecommunications Union).

3. Establish minimal environmental requirements and abolish biological contamination requirements for asteroids (with appropriate sunset clauses).

4. Develop technological capabilities to operate in the asteroid environments (e.g. In situ operations, materials processing, ubiquitous communications, life support/habitation, autonomous robotic capability, etc).

5. Develop technologies and procedures to detect and deflect asteroids with natural or human altered trajectories that pose a threat.

6. Promote governmental or commercial programs and economic activities that provide an anchor tenant for asteroid derived products.

5.0 Action Items:

5.1 Asteroid Science and Technology Recommendations / Notional Asteroid Missions

Asteroid mission to test strategies for (1) mitigating the risk associated with Earth impact hazard and (2) in situ analysis in preparation for resource utilization. This would include NASA, other space agencies, and non-governmental organizations (NGOs) to ensure that there is a mission to an asteroid in the next decade. We envision a mission that will rendezvous with a carbonaceous asteroid, analyze its composition, extract volatile materials, and use them to change the orbit of the asteroid.

We recommend that an element for asteroid research for both science and technology be added to future calls for NASA Research Opportunities in Space and Earth Sciences (ROSES). Currently NASA includes asteroid research as a component of Planetary Geology and Geophysics--elevating this to a top level of ROSES will help immediately align the focus of the scientific and engineering community to asteroid research.

We propose a sample return mission from a carbonaceous NEO, which implants a radio transponder for Yarkovsky Effect measurements to better predict asteroid trajectories and assess terrestrial impact hazards. This should be done on as many different spectral classes of NEO to construct taxonomy of these objects. This would get at the heart of understanding the dynamical evolution of these objects as well as gaining a detailed understanding of the chemical composition. This would provide unparalleled information about solar system history and resources in near Earth space.

To demonstrate the transport capability of NEOs, we propose to launch a spacecraft to an NEO, ride it out, and then leave the asteroid on a trajectory to Mars, the asteroid belt or another target. Ideally resources would be extracted from the carbonaceous asteroid during transport and utilized by the spacecraft as propellant.

Finally, we encourage continued and expanded observations of NEO's to assess potential impact threats. This will guide the prioritization of targets for future asteroid missions.

5.2 Education and Public Outreach

Due to the potentially valuable uses of asteroids for exploration, we recommend the inherent beneficial characteristics of Near-Earth Asteroids which enable early, sustainable exploration of the inner solar system be promoted to various stakeholders (policy-makers, public, engineers, and scientists). Examples of these characteristics include abundant water and mineral resources and low energy orbital transits between NEOs and LEO/HEEO.

To engage universities, we recommend a student designed and built asteroid probe. A competition focused on an asteroid rendezvous, answering meaningful scientific questions and addressing exploration objectives would also engage the current student populations and increase public awareness of the benefits of asteroids.

We recommend that there should be a Centennial Challenge for non-government entities to demonstrate resource extraction from an asteroid.

Finally we recommend space agencies to formalize a sustainable Young Professional's Advisory Body. An advisory body, consisting largely of young professionals, encompassing multiple nationalities and multiple disciplines should be established to provide semi-annual or annual briefs and updates to higher ranking officials that are currently driving the exploration goals. The proposed body should have the support of the main space agencies and current commercial players, and should be empowered to provide recommendations.

Asteroids
Working Group

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Introduction

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Team Members

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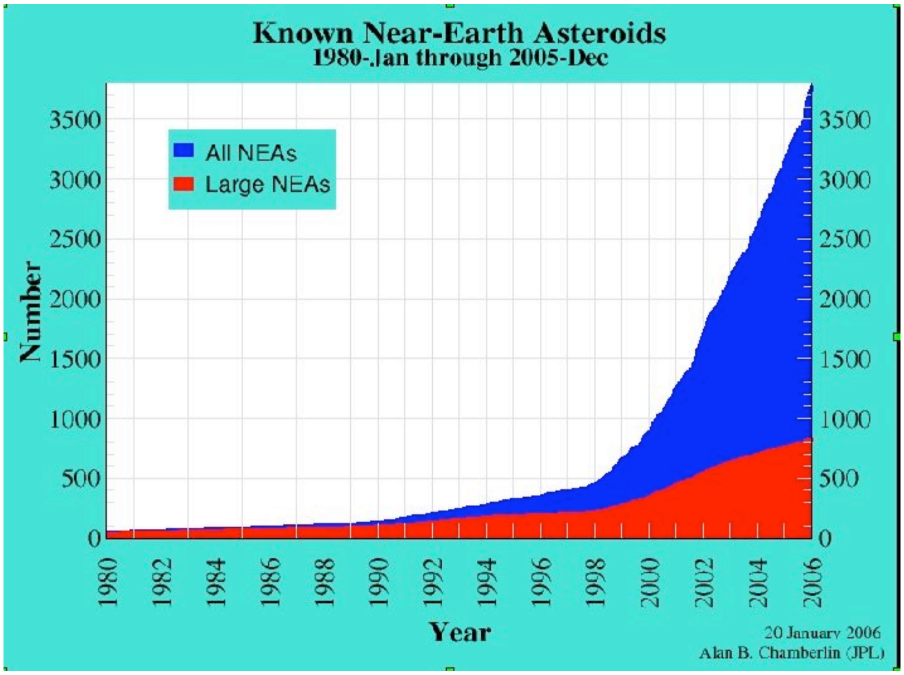
Background



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Background

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Asteroid Themes

1. **Enhance space exploration**
    - Resource utilization
    - Platform for transportation
2. **Pursue scientific activities**
    - In situ or sample return missions
    - Investigate solar system origins
3. **Understand and mitigate risk asteroids pose to Earth**
    - Detection and inventory
    - Impact prevention technologies
4. **Cross-cutting themes consistent with lunar exploration**
    - Expand Earth's economic sphere
    - Strengthen and build global partnerships
    - Engage, inspire, and educate public

Asteroid Objectives

- Material Processing (Beneficiation)
- Asteroid Resource Utilization
- Commercial Opportunities
- Power
- Communication
- Global Partnership
- Public Engagement and Inspiration
- General Infrastructure
- Program Execution
- Operations Test & Verification
- Astronomy and Astrophysics
- Heliophysics
- Geology
- Life Support and Habitat
- Environmental Hazard Mitigation
- Surface Mobility
- Operational Environ Monitor
- Crew Activity
- Transportation

Issues & Enablers

- **Legal**
  - International treaties
  - Jurisdiction to allocate usage and access rights
- **Environmental**
  - Minimal environmental requirements
  - Abolish biological contamination requirements
- **Technological**
  - operate in the asteroid environment
- **Security**
  - Detect and deflect asteroids
  - Natural or human-altered trajectories
- **Economic**
  - Anchor tenant for asteroid derived products.

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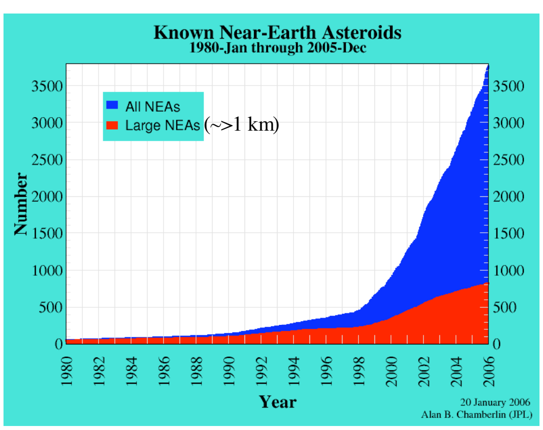
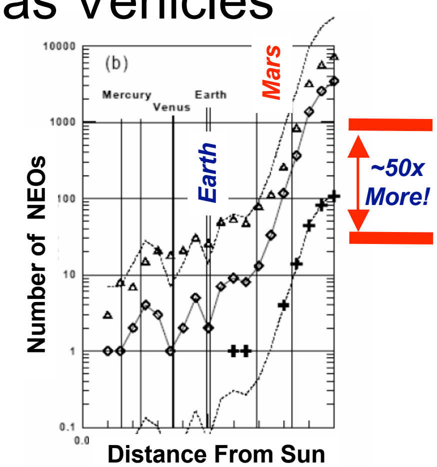
Action Items

- **Science and Technology**
  - Impact Hazard and Response Analysis
  - Resource Utilization Proof of Concept
  - Demonstrate Asteroids as Vehicles



The more we look, the more we will find....



And it gets more intense at Mars

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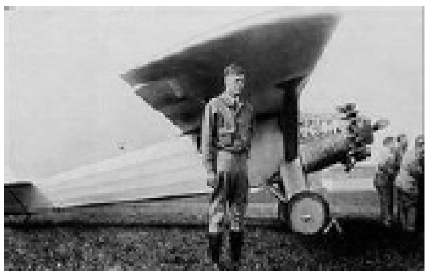
Action Items

- **Education and Public Outreach**
  - Student Lead Asteroid Mission
  - Centennial Challenge Category
  - Young Professional Advisory Panel



Charles Lindberg/Spirit of St. Louis: $25,000 for first non-stop flight between Paris and New York.

Burt Rutan/SpaceShipOne: Winner of the $10M, suborbital space flight X PRIZE.

Asteroids are a logical next challenge!

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Asteroids as Transport

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