John Lewis
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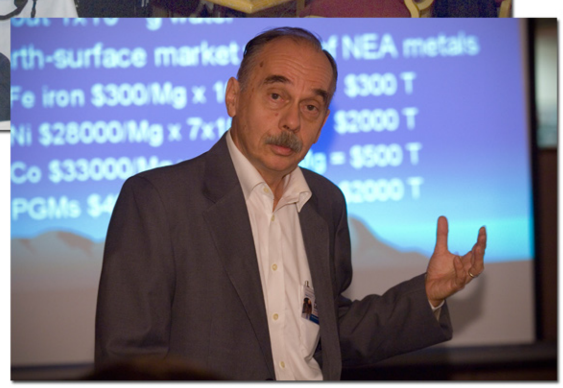
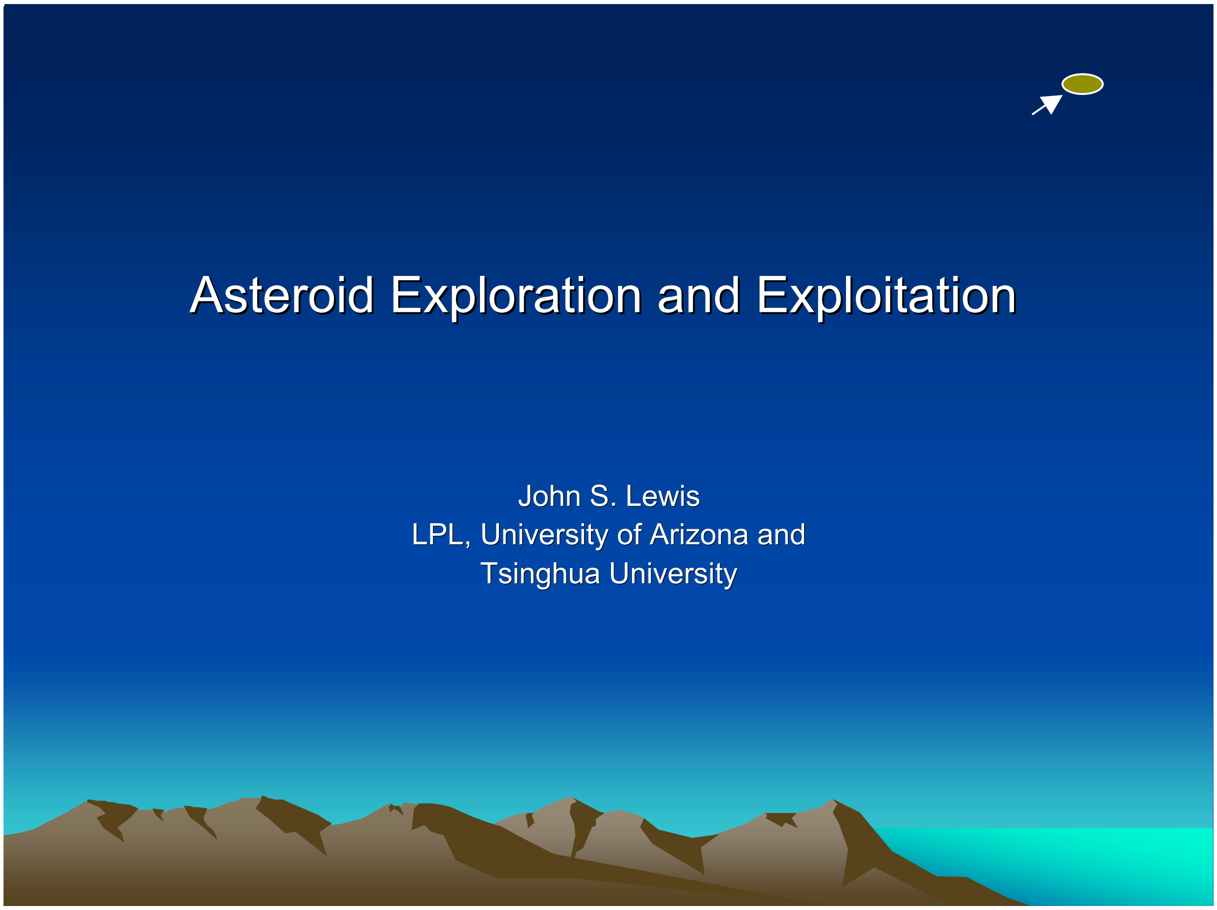
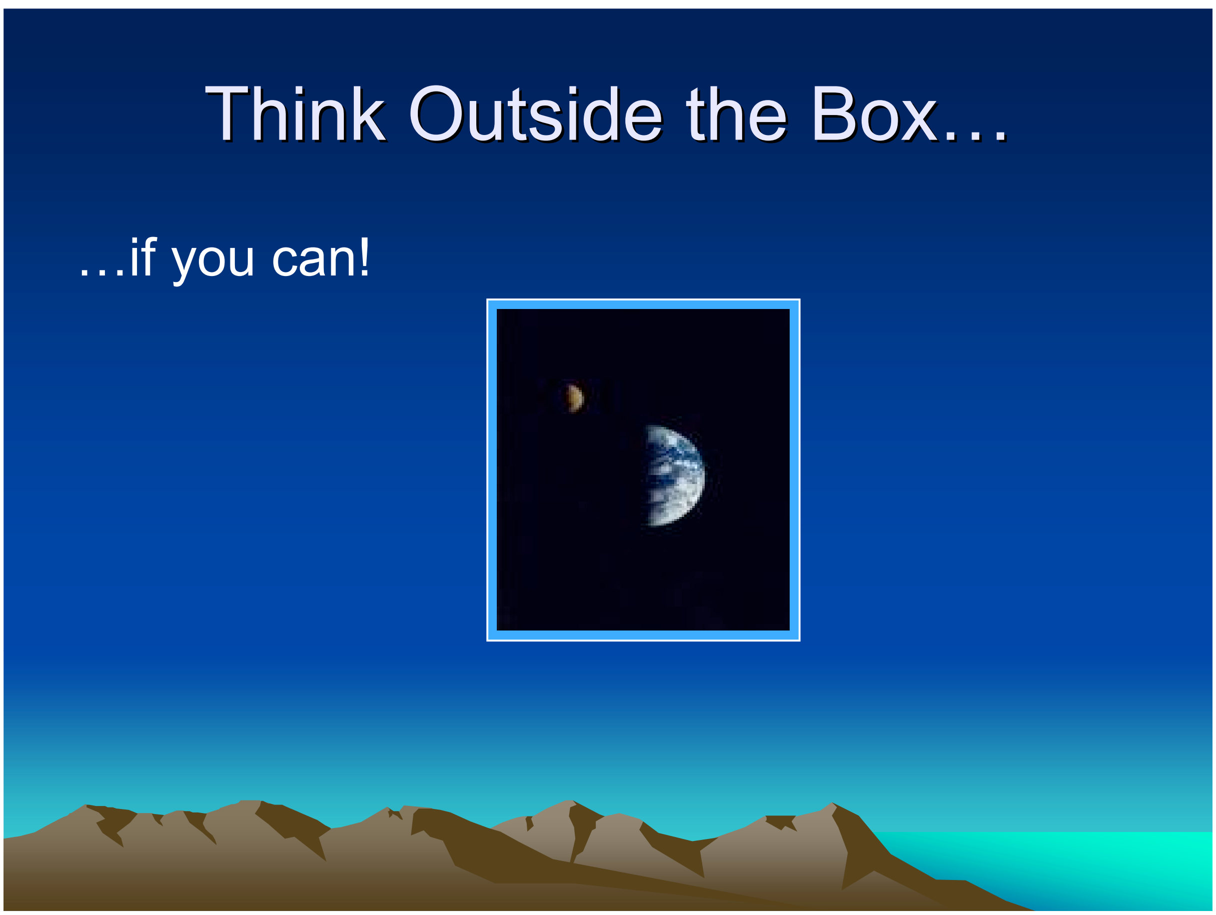
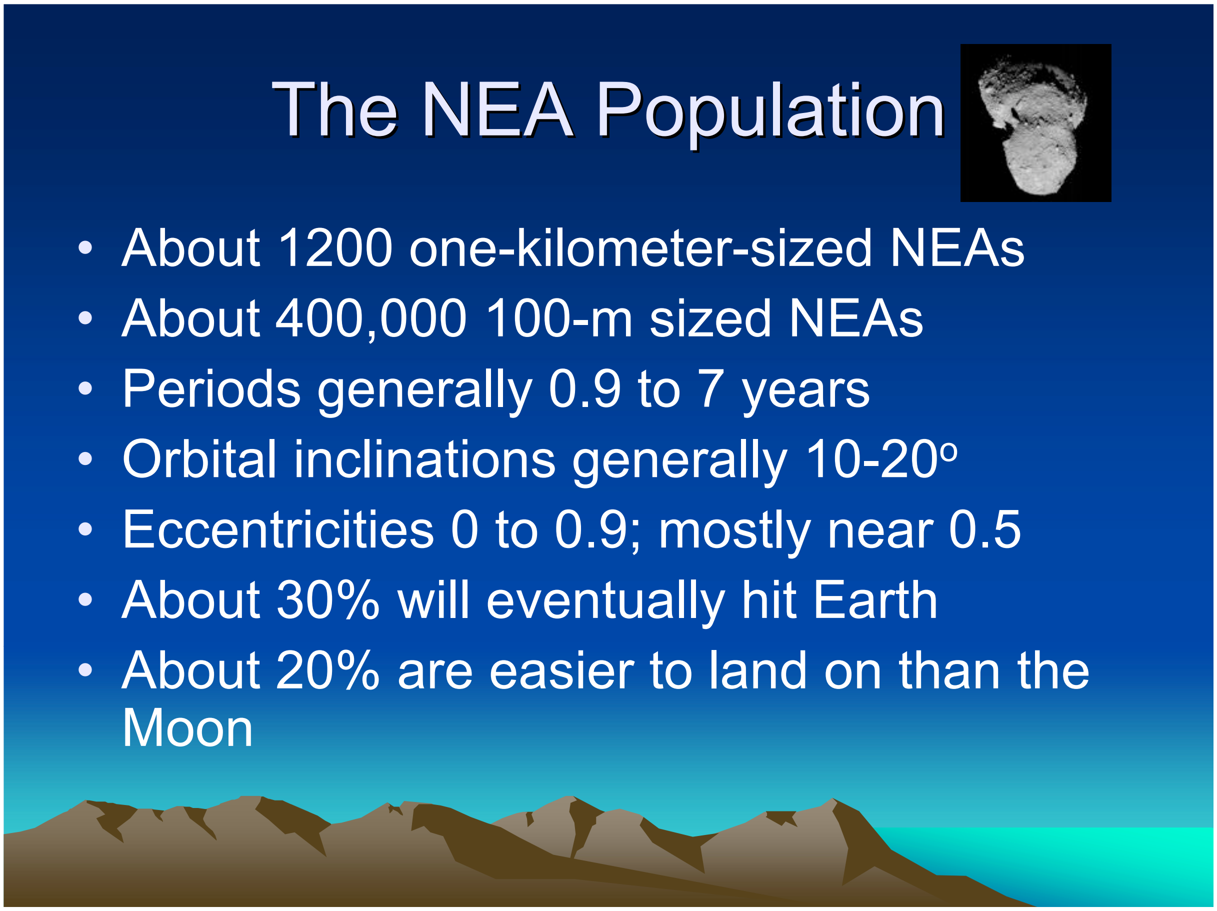
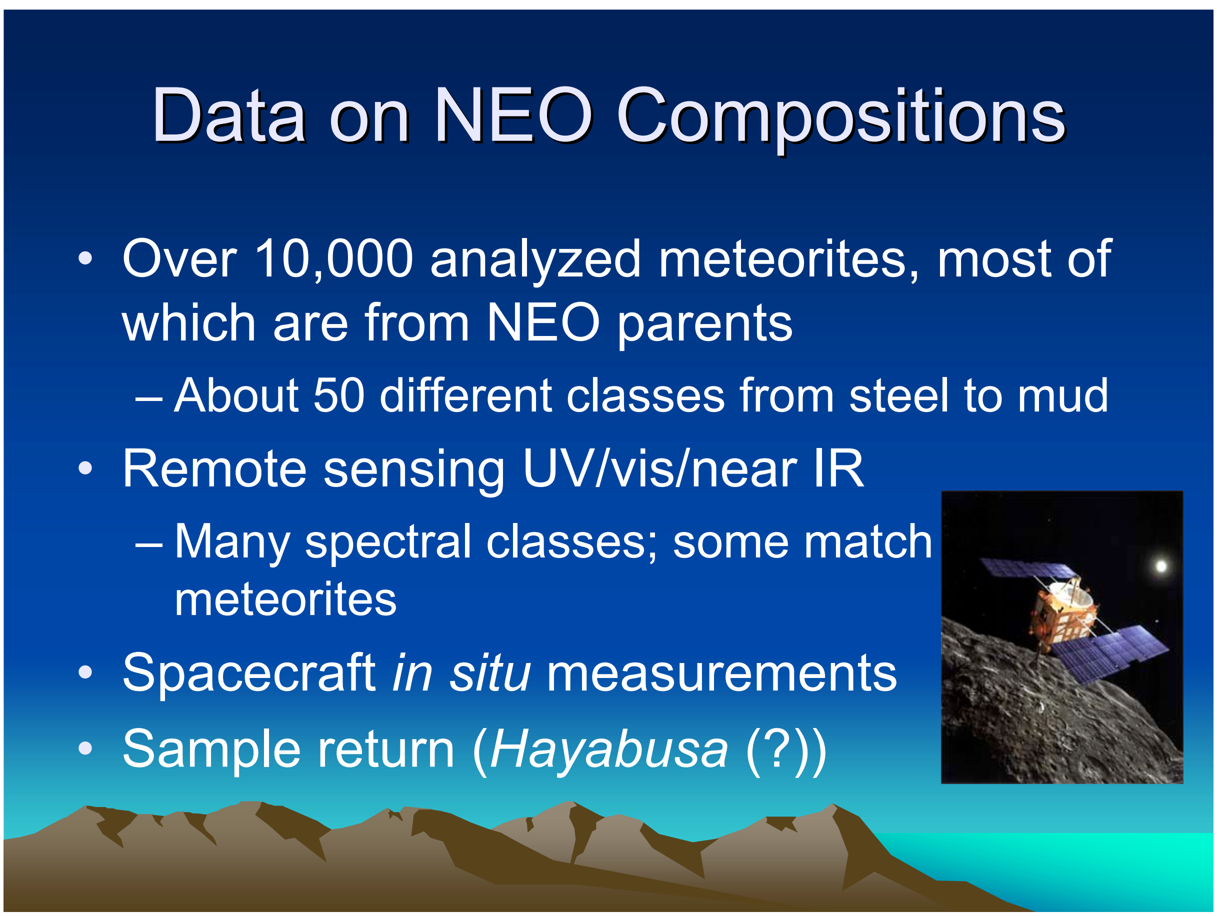
John S. Lewis is Professor of Planetary Sciences and Co-Director of the Space Engineering Research Center at the University of Arizona. He was previously a Professor of Planetary Sciences at MIT and Visiting Professor at the California Institute of Technology. Most recently, he was a Visiting Professor at Tsinghua University in Beijing for the 2005-2006 academic year. His research interests are related to the application of chemistry to astronomical problems, including the origin of the Solar System, the evolution of planetary atmospheres, the origin of organic matter in planetary environments, the chemical structure and history of icy satellites, the hazards of comet and asteroid bombardment of Earth, and the extraction, processing, and use of the energy and material resources of nearby space. He has served as member or Chairman of a wide variety of NASA and NAS advisory committees and review panels. He has written 17 books, including undergraduate and graduate level texts and popular science books, and has authored over 150 scientific publications.




Asteroid Exploration and Exploitation
John S. Lewis
LPL, University of Arizona and
Tsinghua University


Think Outside the Box…
…if you can!

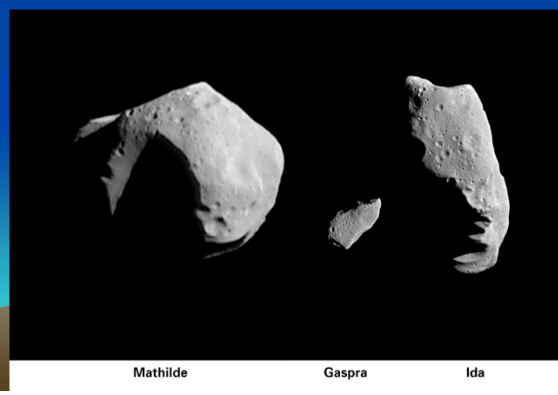

The NEA Population
• About 1200 one-kilometer-sized NEAs
• About 400,000 100-m sized NEAs
• Periods generally 0.9 to 7 years
• Orbital inclinations generally 10-20°
• Eccentricities 0 to 0.9; mostly near 0.5
• About 30% will eventually hit Earth
• About 20% are easier to land on than the Moon


Data on NEO Compositions
• Over 10,000 analyzed meteorites, most of which are from NEO parents
– About 50 different classes from steel to mud
• Remote sensing UV/vis/near IR
– Many spectral classes; some match meteorites
• Spacecraft *in situ* measurements
• Sample return (*Hayabusa* (?))

Traits of Economically Desirable NEAs

Easy access from LEO/HEEO

- Easy return to LEO/HEEO
- Abundance of useful materials
- Simple, efficient processing schemes

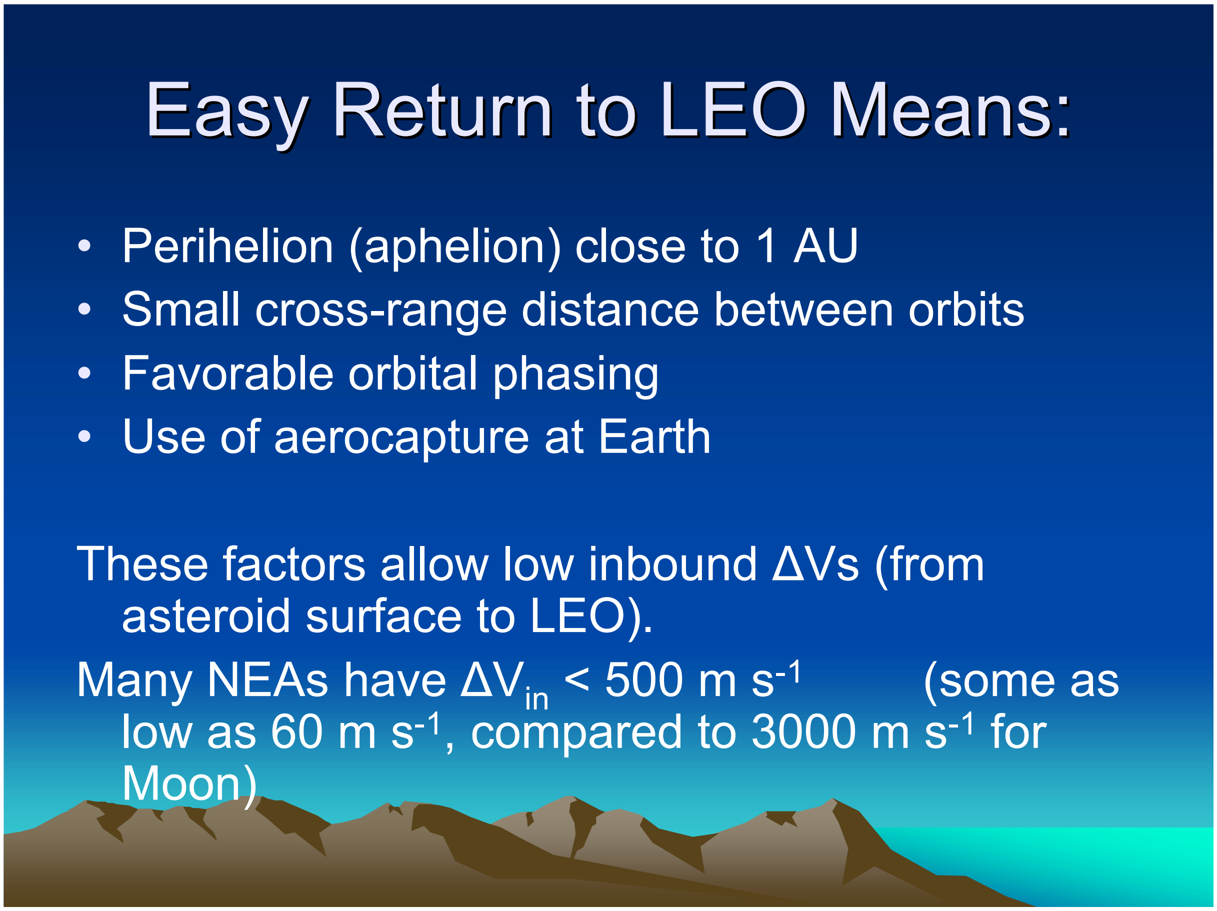


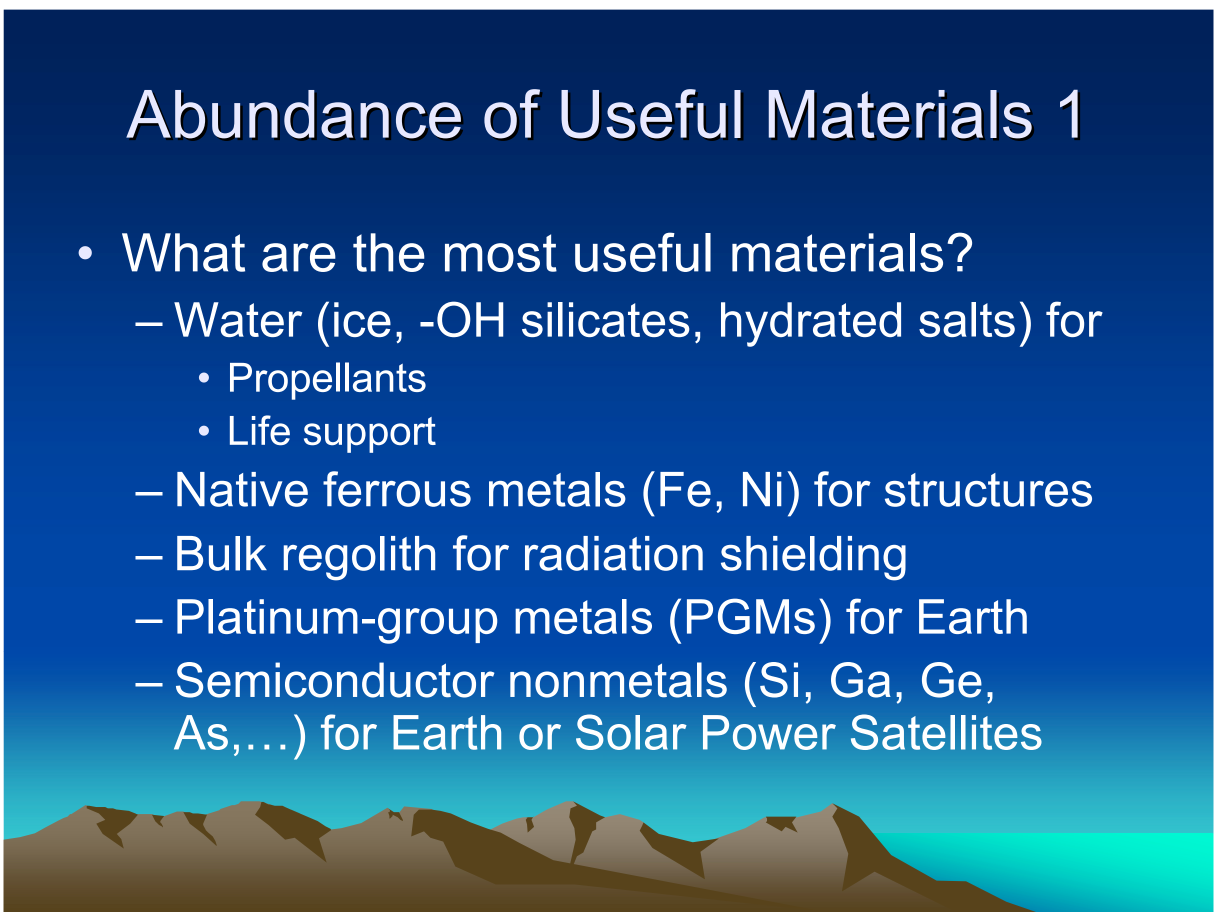
Easy Access from LEO Means:

- Perihelion (or aphelion) close to 1 AU
- Small eccentricity
- Low inclination

These factors combined allow low outbound ΔVs (from LEO to soft landing)

About 240 km-sized NEAs have $\Delta V_{out} < 6$ km s^{-1} (vs. 6.1 for the Moon)


Easy Return to LEO Means:
• Perihelion (aphelion) close to 1 AU
• Small cross-range distance between orbits
• Favorable orbital phasing
• Use of aerocapture at Earth
These factors allow low inbound ΔVs (from asteroid surface to LEO).
Many NEAs have $\Delta V_{in} < 500$ m s^{-1} (some as low as 60 m s^{-1}, compared to 3000 m s^{-1} for Moon)


Abundance of Useful Materials 1
• What are the most useful materials?
– Water (ice, -OH silicates, hydrated salts) for
• Propellants
• Life support
– Native ferrous metals (Fe, Ni) for structures
– Bulk regolith for radiation shielding
– Platinum-group metals (PGMs) for Earth
– Semiconductor nonmetals (Si, Ga, Ge, As,…) for Earth or Solar Power Satellites

Abundance of Useful Materials 2

- Comparative abundances
  - Water
    - C, D, P chondrites have 1 to >20% H_2O; extinct NEO comet cores may be 60% water ice
    - Mature regolith SW hydrogen reaches maximum of about 100 ppm in ilmenite-rich mare basins (water equivalent 0.1% assuming perfect recovery)
  - Metals
    - To 99% in M asteroids; 5-30% in chondrites
    - Lunar regolith contains 0.1 to 0.5 % asteroidal metals

Simple, Efficient Processing Schemes

- "Simple and Efficient"
  - Low energy consumption per kg of product
  - Processes require little or no consumables
  - Few **mechanical** parts
  - Modular design for ease of repair
  - Highly autonomous operation
  - On-board AI/expert systems for process control
  - Self-diagnosis and self-repair capabilities
  - Maximal use of low-grade (solar thermal) energy
  - Regenerative heat capture wherever possible

Examples of Processing Schemes

"Industrial Cosmochemistry"

- Ice extraction by melting and sublimation of native ice using solar or nuclear power
- Water extraction from –OH silicates or hydrated salts by solar or nuclear heating
- Electrolysis of water and liquefaction of H/O
- Ferrous metal volatilization, separation, purification, and deposition by the gaseous Mond process
  - $Fe^{o}(s) + 5CO \leftarrow\rightarrow Fe(CO)_5(g)$
  - $Ni^{o}(s) + 4CO \leftarrow\rightarrow Ni(CO)_4(g)$

Magnitude of NEA Resources

- Total NEA mass about 4×10^{18} g
- About 1×10^{18} g ferrous metals
- About 1×10^{18} g water
- Earth-surface market value of NEA metals
  - Fe iron \$300/Mg x 10^{12} Mg = \$300 T
  - Ni \$28000/Mg x 7×10^{10} Mg = \$2000 T
  - Co \$33000/Mg x 1.5×10^{10} Mg = \$500 T
  - PGMs \$40/g x 5 x 10^{7} Mg = \$2000 T

High-value Imports for Earth

- PGM prices (\$US/troy ounce)

– Pt	\$1032
– Pd	276
– Os	380
– Ir	380
– Rh	4650
– Ru	165

- Nonmetals for semiconductors
  - In(\$27/toz), Ga (\$16/toz), Ge, As, Sb, Se…

High-Utility Materials for Use in Space

- Structural metals
  - High-purity iron from Mond process
    - 99.9999% Fe: strength and corrosion resistance of stainless steel
  - High-precision chemical vapor deposition (CVD) of Ni in molds
    - Custom CVD of Fe/Ni alloys
- Bulk radiation shielding
  - Regolith, metals, water (best)

One Small Metallic NEA: Amun

- 3554 Amun: smallest known M-type NEA
- Amun is 2000 m in diameter
- Contains about 30x the total amount of metals mined over human history
- Contains 3×10^{16} g of iron
- Contains over 10^{12} g of PGMs with Earth-surface market value of about $40 T

Propellants from Water

- Direct use of water as propellant
  - Solar Thermal Propulsion-- STP ("Steam rocket")
  - Nuclear Thermal Propulsion– NTP
- Electrolysis of water to H/O
  - H_2 STP
  - H_2 NTP
  - H_2/O_2 chemical propulsion →

NEAs as Traveling Hotels

- Typical NEAs have perihelia near Earth and aphelia in the heart of the asteroid belt
- NEA regolith provides radiation shielding
- Asteroid materials provide propellants
- Earth-Mars transfer orbits possible
- Traveling hotels/gas stations/factories… colonies?

The Martian Connection

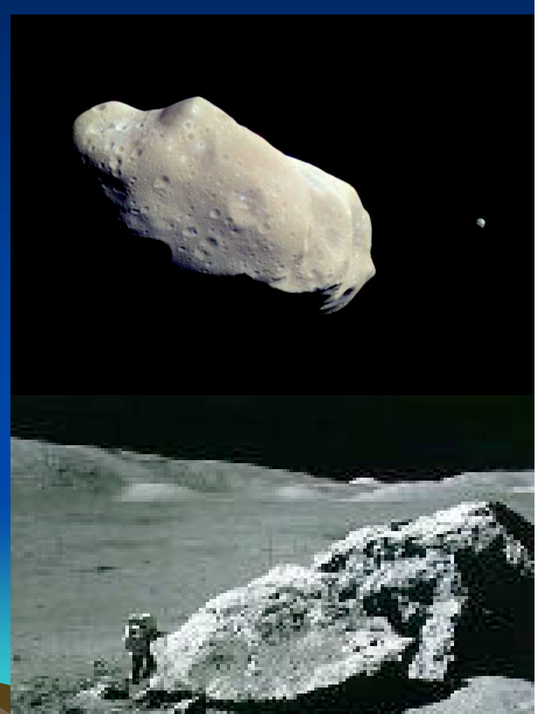
- NEAs as transportation aids
  - Traveling gas stations
  - Traveling hotels
- Manned Mars mission rehearsals
- Phobos and Deimos as former NEAs parked in areocentric orbit

Space Colonization

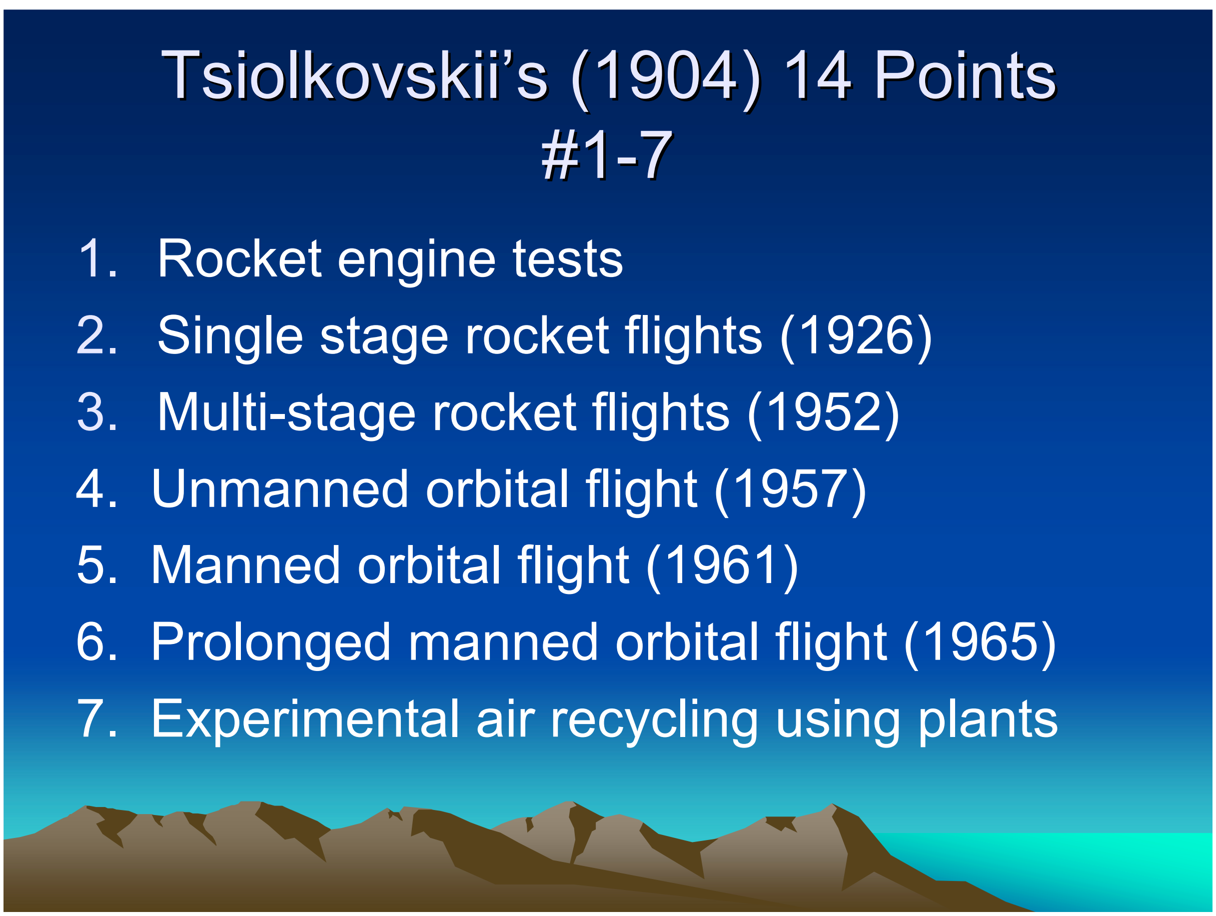
- Asteroids are primarily mine sites, not resorts or suburbs
- Early exploitation should be simple, energy-efficient, and unmanned
- People will arrive as needed
- This vision dates back to Tsiolkovskii (1903) and Goddard (1908)
- Space colonization is not a goal; if it happens it will be as a response to compelling opportunities

Asteroids Over the Moon?

- Asteroid strong points:
  - Low ΔV_{out}
  - Very low ΔV_{in}
  - Resource richness and diversity
- Lunar strong points:
  - Short trip times
  - Helium-3 recovery?




Rôles of Private Enterprise
• Low-cost competitive access to space
• Large-scale competitive mineral exploration
• Efficient, competitive resource exploitation
• Construction and operation of communication and transportation hubs (LEO, GEO, HEEO, lunar L1, etc.)
We CANNOT AFFORD a centrally-controlled, duplication-free, government-dominated effort

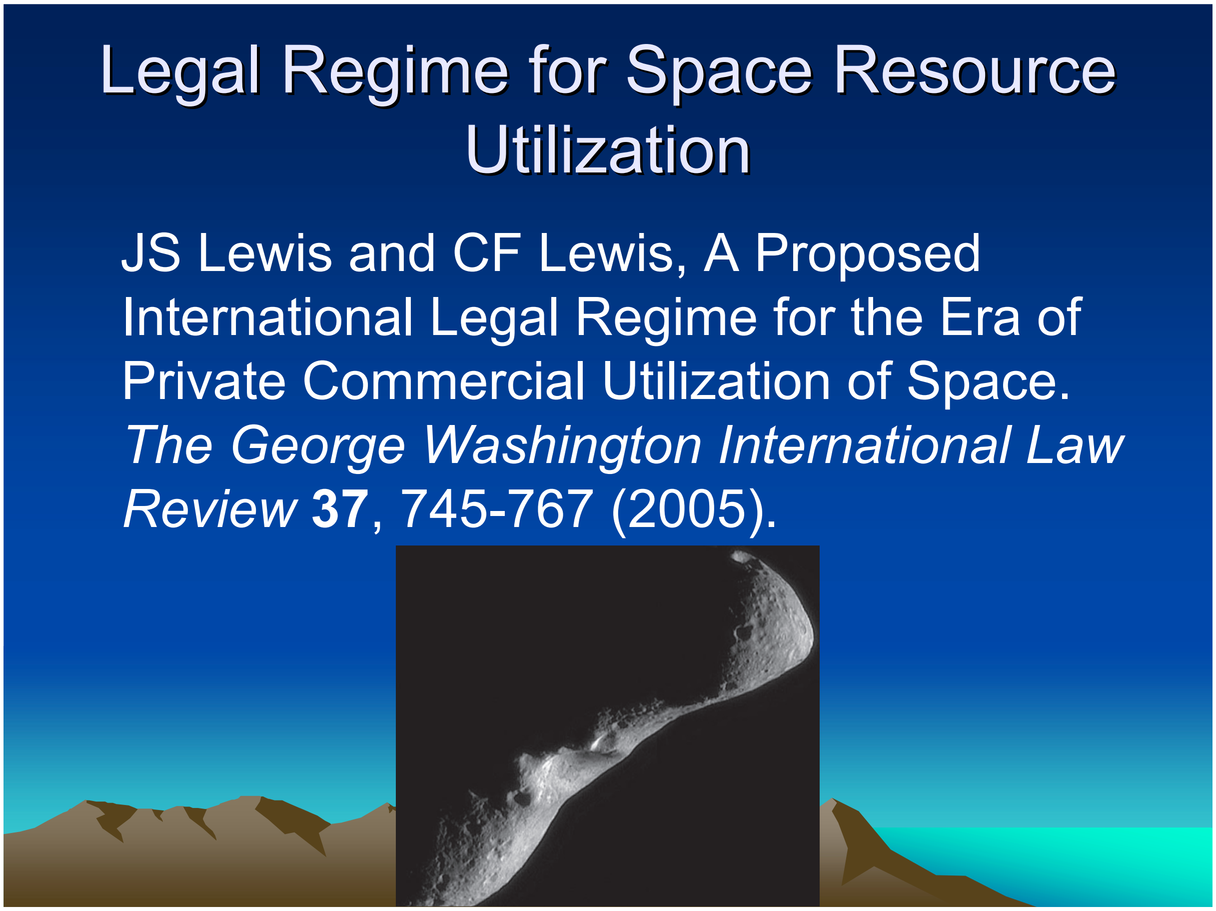

Tsiolkovskii's (1904) 14 Points #1-7
1. Rocket engine tests
2. Single stage rocket flights (1926)
3. Multi-stage rocket flights (1952)
4. Unmanned orbital flight (1957)
5. Manned orbital flight (1961)
6. Prolonged manned orbital flight (1965)
7. Experimental air recycling using plants

Tsiolkovskii's points 8-14

8. Spacesuits for use outside spacecraft (1965)
9. Space agriculture as a source of food
10. Earth-orbiting space colonies
11. Use of solar energy for transportation and power in space
12. Exploitation of asteroid resources
13. Space industrialization
14. Perfection of mankind and society

Suggested Reading

- JS Lewis and RA Lewis, *Space Resources: Breaking the Bonds of Earth, 407 pp.* Columbia Univ. Press, (1987)
- MF McKay, DS McKay and MB Duke, eds., *Space Resources*, 942 pp. NASA SP-509 (1992)
- JS Lewis, MS Matthews and M Guerrieri, eds., *Resources of Near-Earth Space,* Univ. of Arizona Press, Tucson. 977 pp. (1993)
- JS Lewis, *Mining the Sky: Untold Riches from the Asteroids, Comets, and Planets,* Addison-Wesley, Reading, MA. 274 pp. (1996)


Legal Regime for Space Resource Utilization
JS Lewis and CF Lewis, A Proposed International Legal Regime for the Era of Private Commercial Utilization of Space. *The George Washington International Law Review* **37**, 745-767 (2005).


A New, Broader Perspective
(Back to the Future of Tsiolkovskii and Goddard)