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Asteroid Exploration and Exploitation

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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
ΔV_{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 $\Delta V$s (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% H₂O; 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
  - \( \text{Fe}^0(s) + 5\text{CO} \leftrightarrow \text{Fe(CO)}_5(g) \)
  - \( \text{Ni}^0(s) + 4\text{CO} \leftrightarrow \text{Ni(CO)}_4(g) \)

Magnitude of NEA Resources

- Total NEA mass about \(4 \times 10^{18} \text{ g}\)
- About \(1 \times 10^{18} \text{ g}\) ferrous metals
- About \(1 \times 10^{18} \text{ g}\) water
- Earth-surface market value of NEA metals
  - \( \text{Fe iron} \text{ $300/Mg} \times 10^{12} \text{ Mg} = \$300 \text{ T} \)
  - \( \text{Ni} \text{ $28000/Mg} \times 7 \times 10^{10} \text{ Mg} = \$2000 \text{ T} \)
  - \( \text{Co} \text{ $33000/Mg} \times 1.5 \times 10^{10} \text{ Mg} = \$500 \text{ T} \)
  - \( \text{PGMs} \text{ $40/g} \times 5 \times 10^7 \text{ Mg} = \$2000 \text{ T} \)
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 $3 \times 10^{16}$ 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
  - H₂ STP
  - H₂ NTP
  - H₂/O₂ 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 $\Delta V_{out}$
  - Very low $\Delta V_{in}$
  - 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

Legal Regime for Space Resource Utilization


A New, Broader Perspective

(Back to the Future of Tsiolkovskii and Goddard)