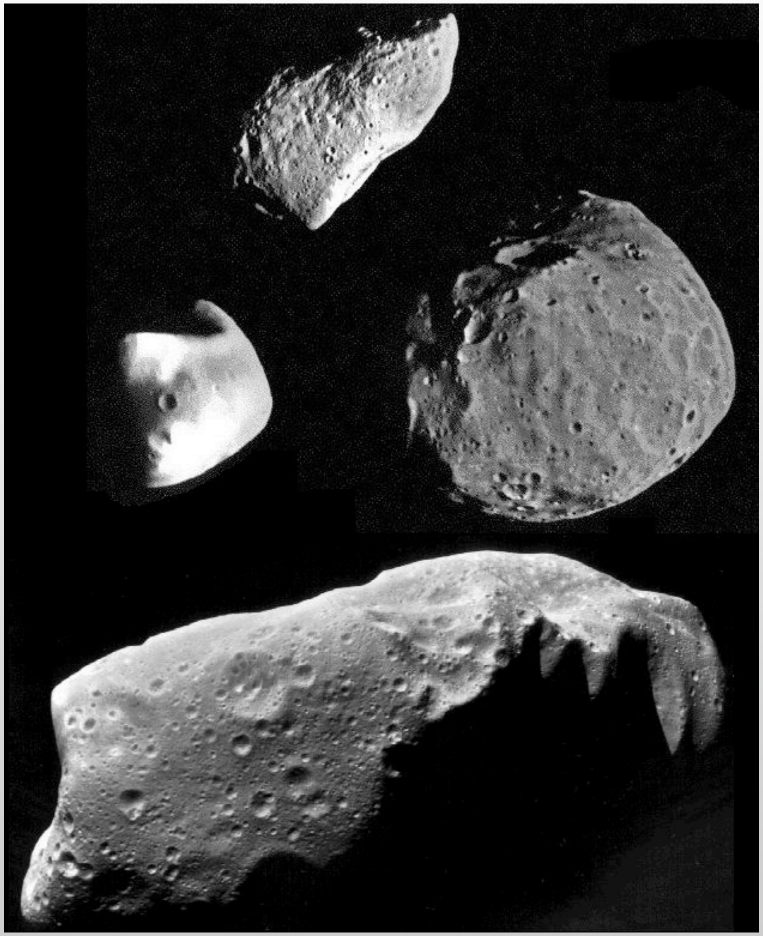
Asteroid Mining Project



Deliver Metals to Earth

Large or Small Asteroids?

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Original Task

- *Define a system to mine a large metal asteroid for metals and bring them to the Earth's surface.*
- *Define a system to return small metal asteroids whole.*
- *Perform a trade study comparing these options.*
- *Define a development path that can be financed by borrowing against the value of the materials.*
- *Define a business plan that avoids flooding the market and depressing prices.*
- *Make a legal argument that consuming NEOs does not violate existing space law.*

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M-Class Asteroids

- Determine by spectroscopy from the ground
- Probably the source of iron meteorites
  - 95% Fe, Ni, and Co
  - 0-350 ppm precious metals [1]
- Possibly 6-7% of NEOs (Near Earth Objects)
- Kargel: 1 km diameter worth $323 billion
- Lewis: 3554 Amun (2km) worth $20 trillion

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Metallic Near Earth Objects

- 900 NEOs diameter > 1 km (60 M-class [1])
- 200,000 diameter > 100 m (10,000 M-class)
- 1 billion diameter ~ 10 m [3] (70,000,000 M-class)
- Far more diameter ~ 1m

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Mine Large Asteroid

- Target
  - Only one needed
  - Most diameter > 1 km known
  - Precious metal content difficult to predict.
  - Robust to rotation rate, within reason.
- Difficult to automate mining as composition uncertain
- Many NEOs are ruble piles and easy to mine
  - Possibly not metallic NEOs

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Return Small Asteroids

- Very large number of potential targets
  - There should be one wherever you want one :-)
- Many nearly-identical missions
  - Inherently redundant
  - Inherently small
  - Robust to composition
  - Economies of scale
- Not necessarily robust to high rotation rate.
- Detection difficult.

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Detection of Small Asteroids

- Current Earth-based optical asteroid telescopes
  - Smallest found ~ 5m diameter
  - Maximum 1m detection distance ~ 10^6 km
  - 2,000 to 200,000 1m diameter within range at any given time
  - 5-7 hit the Earth each day
- To find them in time, may need appropriately placed space telescope(s)
  - Where do we want small asteroids to be? Look there.

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Additional Consideration

- Carbonaceous chondrites (C-Type) may be good targets [1,9]
  - LL up to 5% metal, of which 50-220 ppm is precious
  - Other chondrites up to 20% metal
  - May be rubble piles
    - Separation by magnetic raking may be possible
  - Non-metallic content can be used for reaction mass on return flight or volatiles for in-space activities
- Problems
  - Probably require local processing

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Other Products [10]

- Large scale space development requires volatiles: water, C, N, etc.
  - May be current market for ComSat propellant, ISS water, etc.
- Many NEOs have ample quantities of volatiles
  - Extinct comets, ~8% of NEOs [11], are largely water with dry exterior.
  - Carbonaceous condrites have ample volatiles
- Kluck suggests drilling through dry exterior and injecting fluid [10].
- Others have proposed baking volatiles out with a solar oven.

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Regolith and Rotation

- Large NEOs are expected to have a thick layer of impact-generated regolith similar to the Moon.
- Small NEOs may not, because
  - Impact velocities are the same, but gravitation attraction is much less so most of impact fragments will escape.
  - Photo-thermal (YORP) effects can induce rapid rotation which can throw loose material off the main body
    - The same effects can cause also slow rotation rates
  - Note that rotational dynamics are such that NEO rotation rate changes. Thus, for small NEOs and some propulsion methods, one might want to choose those with low rotation rates.

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Return Transportation [7]

- Delta-v to LEO (Low Earth Orbit)
  - Some NEOs
    - < 5 km/s outbound delta-v
    - ~ 2 km/s inbound to LEO, can be lower
  - For comparison: 6.3 km/s to lunar surface [6]
- Use asteroid material for return reaction mass
  - Mass drivers, rotary launchers
  - Thermal concentrators
    - May not work well with metallic asteroids
- Use materials from one NEO to propel another
- Solar sails

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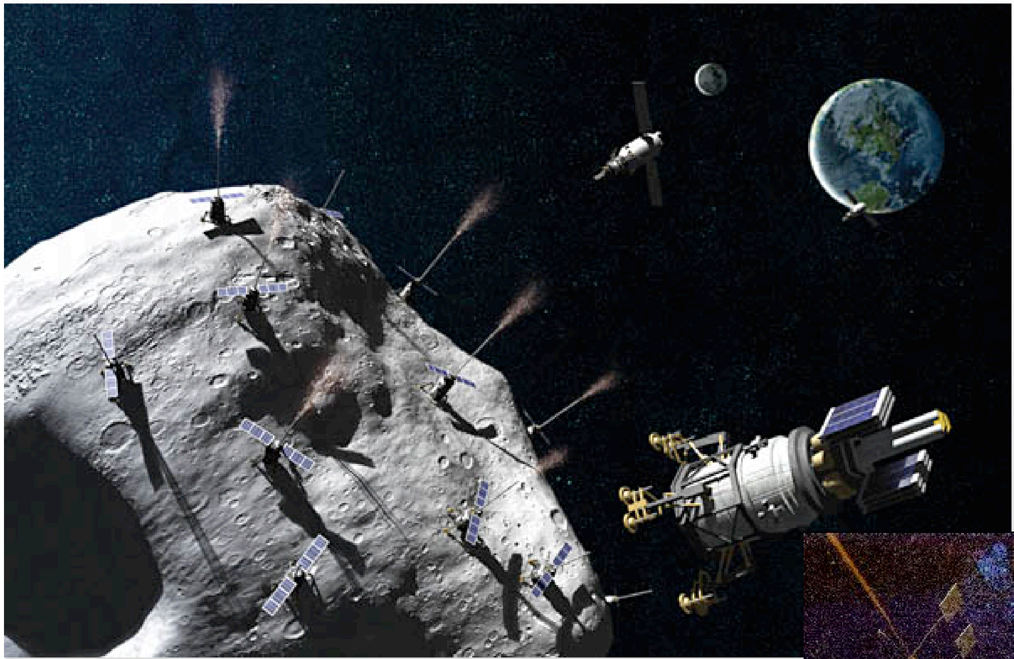
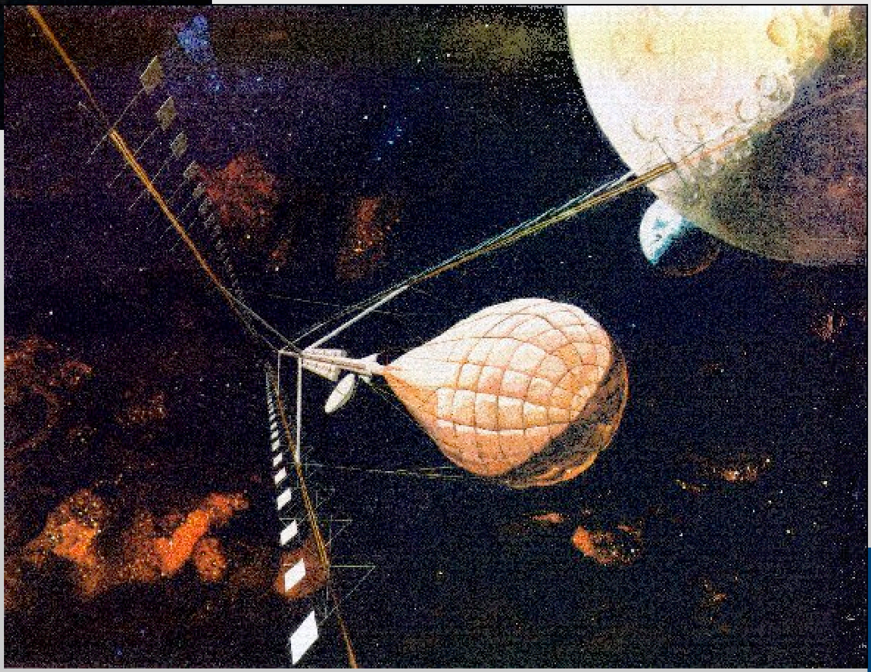
Mass Driver [8]



- Electromagnetic buckets throw regolith
- Tech similar to maglev trains

- A few hundred m/s demonstrated
- Km/s achievable



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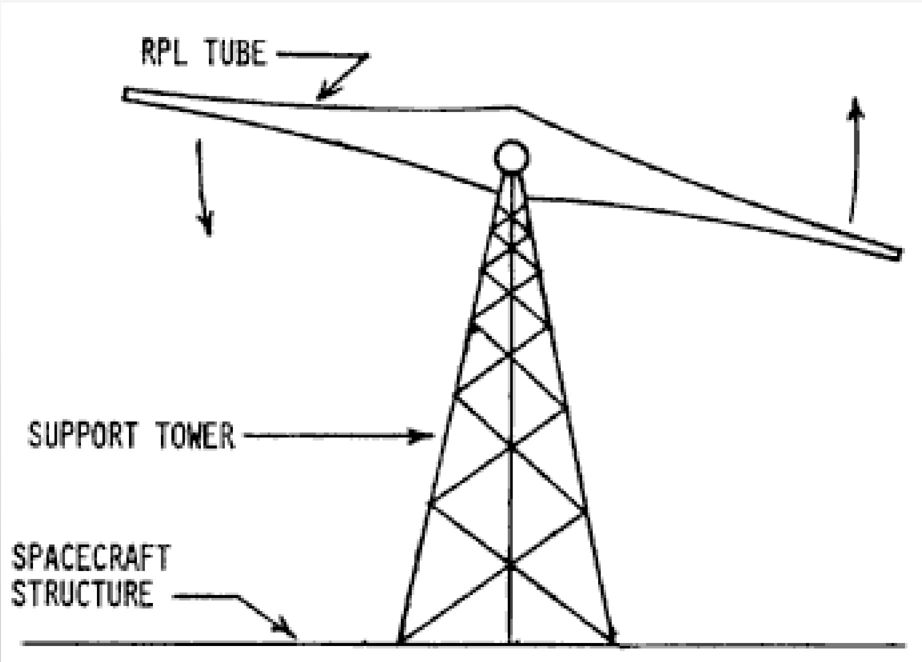
Rotary Launcher



- Feed material into tube
- Unprocessed regolith would be ideal
  - May degrade tube quickly

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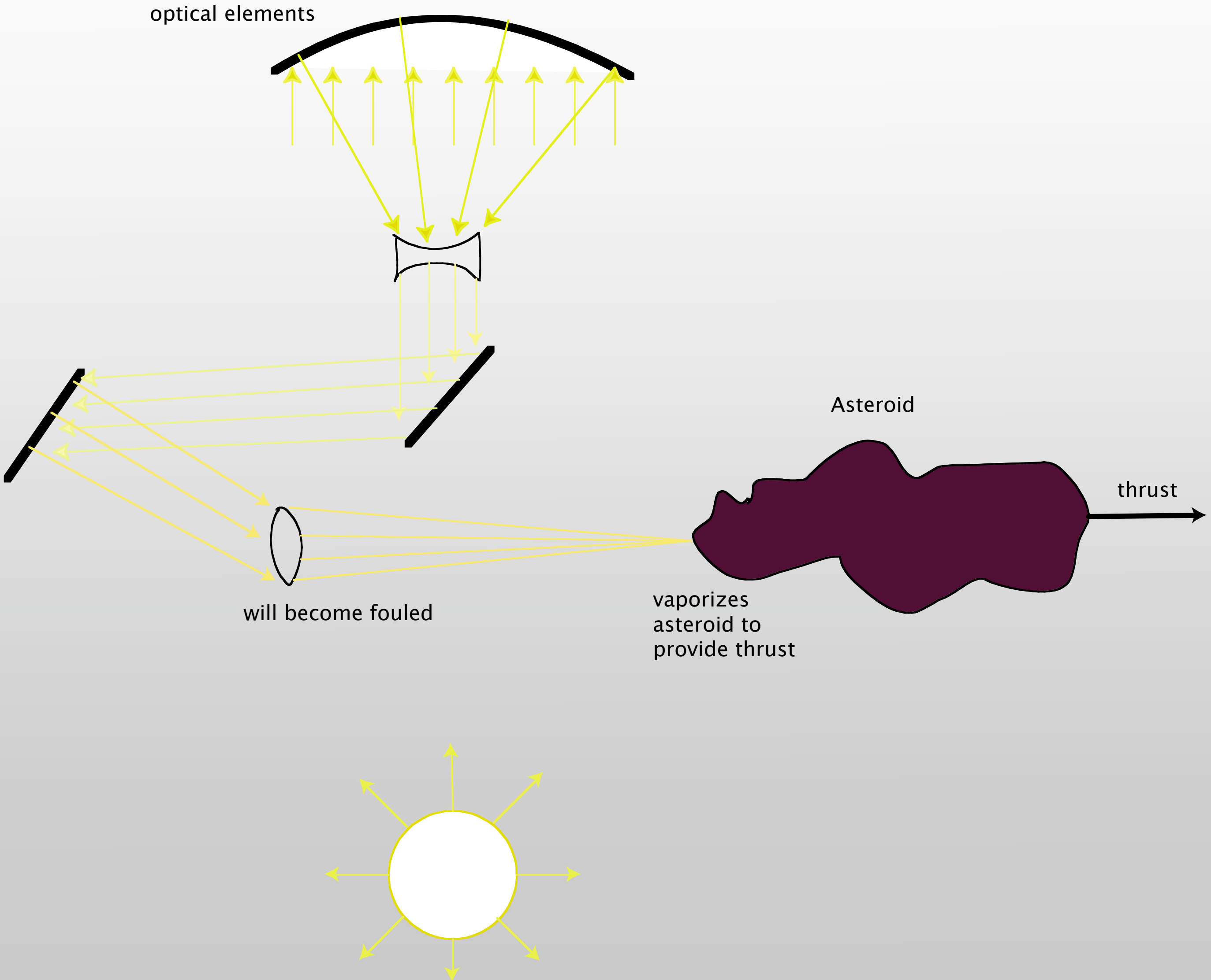
Free Flying Thermal Concentrator



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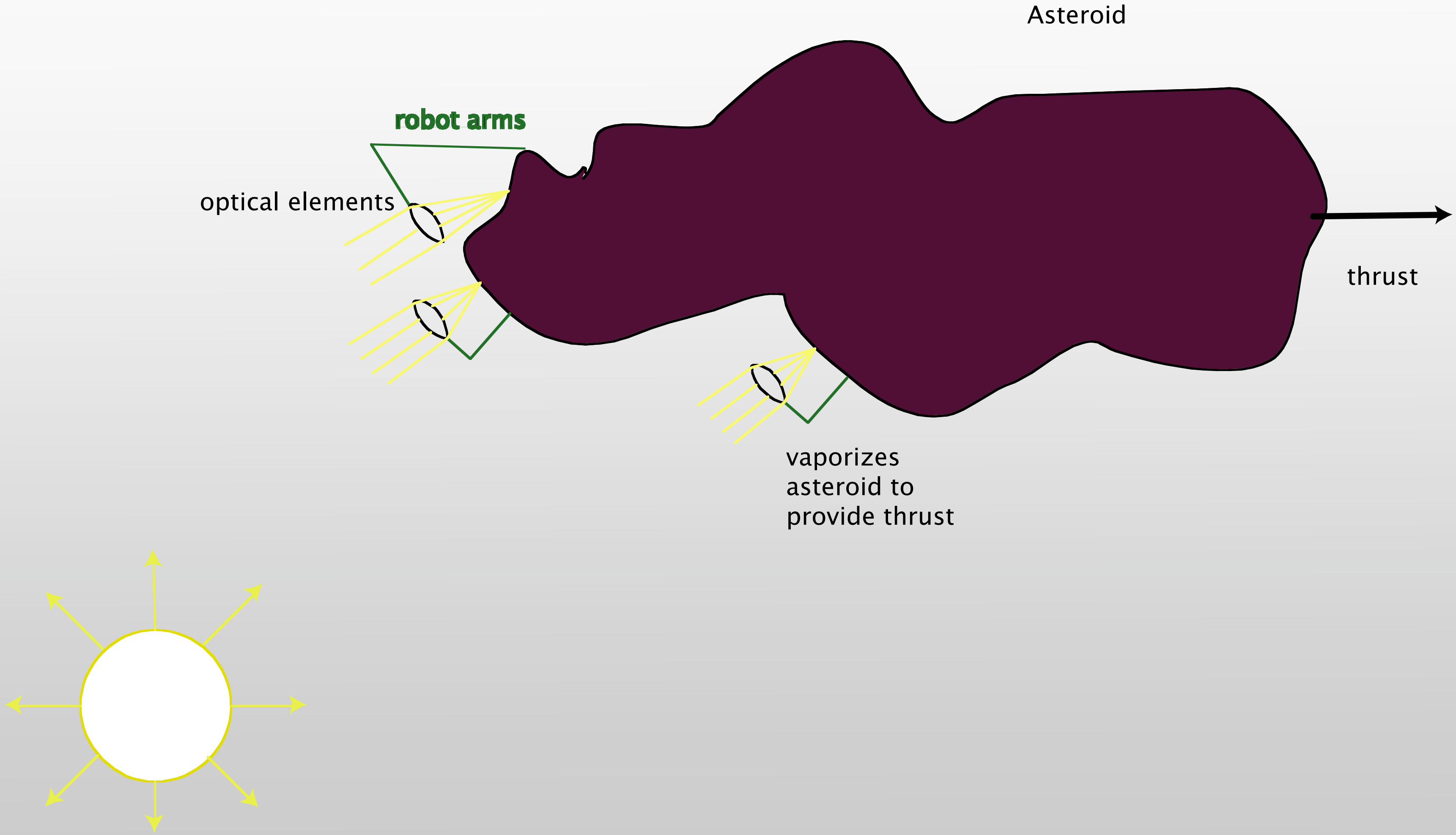
Attached Thermal Concentrator



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Use Another NEO's Materials

- Problems with using NEO's own material
  - Use up what we want
  - Thermal vaporization may not work well on metallic asteroids as metals conduct heat well.
  - Metallic asteroids may have little regolith due to ductility.
  - Small asteroids may have little regolith due to low gravity and rotation.
- So use another NEO's materials [4]
  - Use mass driver or rotary launcher to send a stream of small particles to impact the target asteroid
  - Need NEO with suitable orbital elements and ample regolith to provide a source of the particles
    - Smaller NEOs more likely to have suitable orbital elements
    - Large NEOs more likely to have ample regolith
  - Insensitive to target asteroid materials, rotation rate
  - Very poorly explored, but promising

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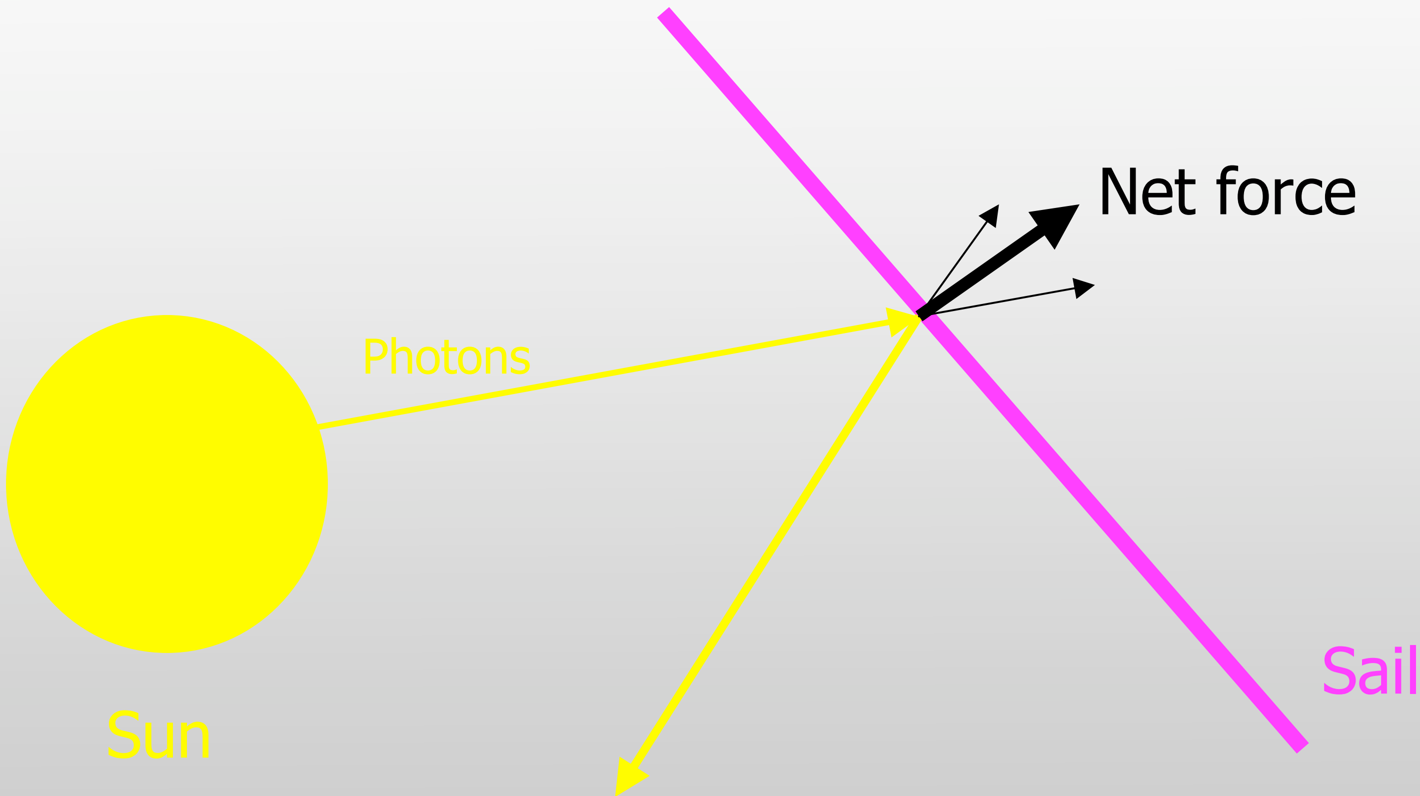
Solar Sailing 1



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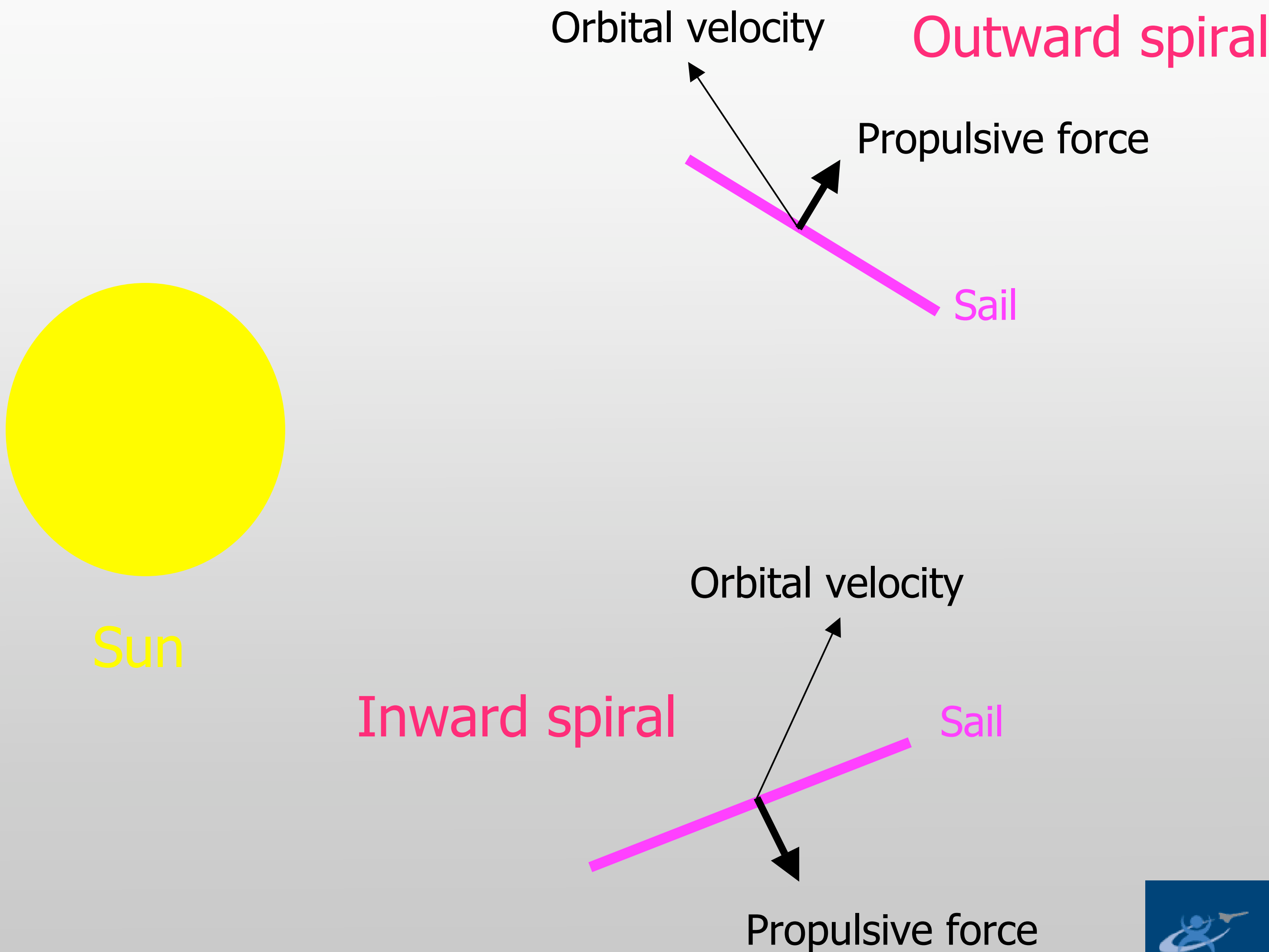
Solar Sailing 2



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Solar Sail 3 [5]

- Characteristic acceleration of 0.25 mm/s^2 produces up to ~0.5 km/s delta-v per month
- To return a 0.4m diameter metallic asteroid (500kg) sail-material-only mass is:
  - Ground manufacture 174kg (5.27g/m^2, 182m side)
  - Space manufacture 33kg (1.17 g/m^2, 170m side)
- How attach to spinning/tumbling asteroid?
  - Find slow rotators?

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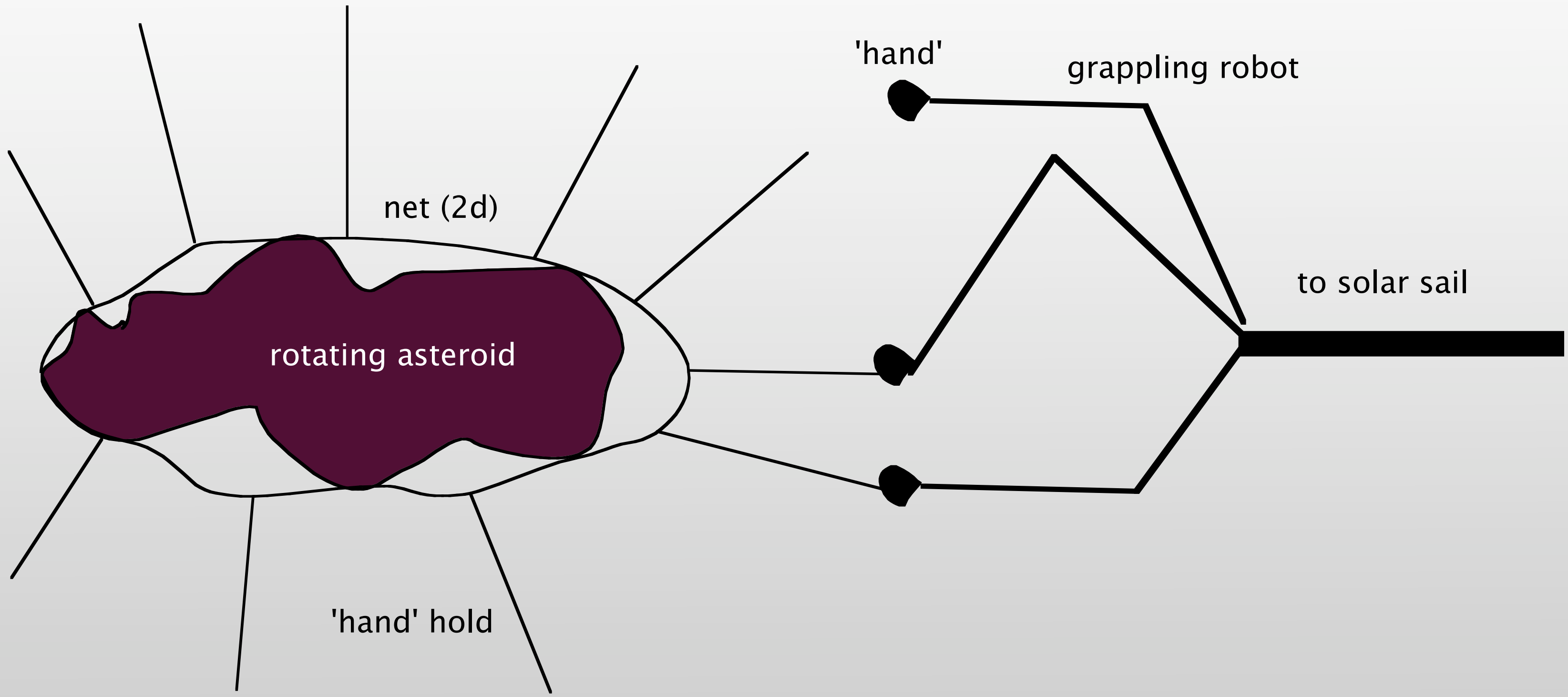
Solar Sail 4



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LEO-Earth

- Aerobrake
  - Ok for small quantities (precious metals)
  - Atmospheric chemistry limits use for bulk materials (iron, steel, etc.)
    - Unless airships work [12]
- Vehicle
  - Reusuable -- must relaunch
  - Fabricated in space from extra-terrestrial materials to be delivered

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Floating to Orbit [12]

- Airships (JP Aerospace)
  - Experimentalists
  - Vehicles
    - Ground to 40 km
    - Floating base at 40 km
    - Orbital airship constructed at base
      - Km scale
      - Floats to 60 km
      - Low thrust engines
      - 1-5 days to get to orbit
      - High drag return
  - Materials delivery easier

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Human Systems Integration Division

Business Issues

- *Financing and business plan*
  - *It may not make sense to try to develop dollar/euro quantities, too many unknowns*
  - *A parameterized mathematical model of the business system might be a real contribution*
    - *Costs of development, operations*
    - *Include all the components, mining, transportation to/from LEO*
    - *Price of metals as a function of asteroidal supply*
    - *Effect of an in-space market for volatiles*
- *Make a legal argument that consuming NEOs does not violate existing space law.*
  - *If this is impossible, perhaps suggest an appropriate legal regime for UN adoption*

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Summary

- Asteroid metals may have high value on Earth
  - NEO water, nitrogen, carbon may be valuable in space
- Large vs Small asteroid has no killer trade
  - This project: do the detailed trade study
- Transportation to LEO is major problem
  - In some ways easier than from the Moon
  - Multiple potential solutions
- LEO->Earth transport challenging

http://www.nss.org/settlement/asteroids/

References (abbreviated)

- [1] Jeffrey Kargel, "Asteroid: Sources of Precious Metals," http://www.outofthecradel.net/WordPress/wp-content/uploads/srn_v3n12.pdf
- [2] John Lewis , Mining the Sky
- [3] David L. Rabinowitz, "Are Main-Belt Asteroids a Sufficient Source for the Earth-Approaching Asteroids? Part II." Icarus, V127 N1:33-54, May 1997.
- [4] C. E. Singer, "Collisional Orbital Change of Asteroidal Materials," Space Manufacturing 3, 1979.
- [5] Al Globus, "AsterAnts," http://alglobus.net/NASAwork/papers/AsterAnts/paper.html
- [6] M. J. Sonter, "The Technical and Economic Feasibility of Mining the Near-Earth Asteroids" http://www.nss.org/settlement/asteroids/sonter.html

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- [7] Alan J. Willoughby, "Adroitly Avoiding Asteroids-Clobber Coax or Consume" http://www.nss.org/resources/library/planetarydefense/1995-AdroitlyAvoidingAsteroids-ClobberCoaxOrConsume.pdf
- [8] Brian O'Leary "Mass Driver Retrievals of Earth-Approaching Asteroids," Space Manufacturing Facilities 2: Space Colonies, pp. 157-168
- [9] David Kluck "Near-Earth Extraterrestrial Resources," Space Manufacturing Facilities 3, pp. 97-108
- [10] David Kluck "Exploitatin of Space Oases," Space Manufacturing Facilities 10, pp. 136-156
- [11] DeMeo and Binzel "Comets in the near-Earth object population," Icarus, V 194, issue 2, April 2008, pp436-449
- [12] John Powell, <u>Floating to Space: The Airship to Orbit Program</u>