Asteroid Retrieval and Mining

with High Power Electric Propulsion

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The ***BIG*** questions about Asteroid Mining are:

Why?

Why now?

and…**How?**

Why? Three Major Reasons:

1. Investigating Near Earth Asteroids (NEA) is the next step in the manned exploration program
    - NASA has a goal to visit an asteroid by 2025
    - It's easier to bring one here than to send astronauts out to one

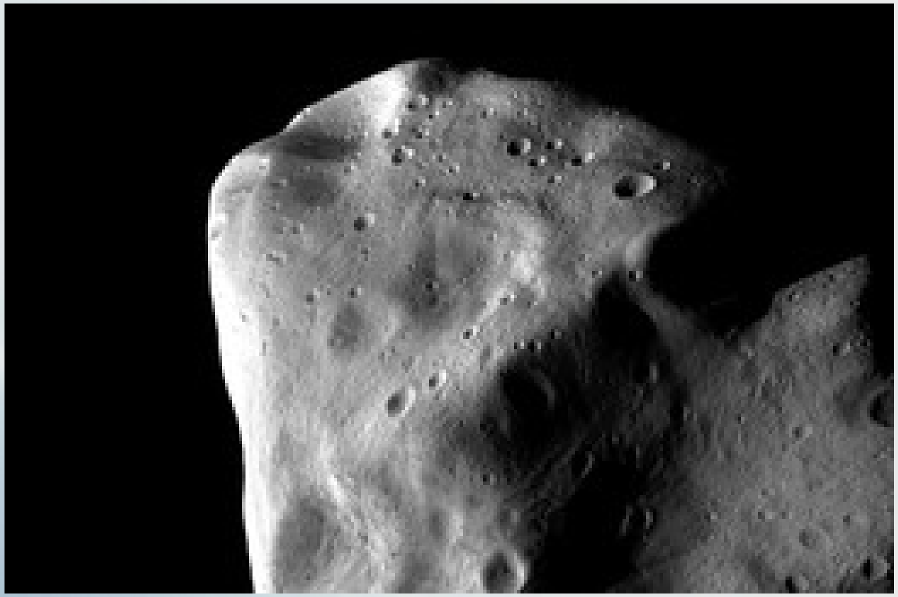
2. Synergy with Planetary Defense
    - Learning to change asteroid orbits and understanding their properties will help in defending Earth from potential asteroid impacts

3. Exploitation of Asteroid Resources
    - Obtaining materials in space is useful for exploration mission to avoid the extremely high cost of launching material into space (≈\$30,000/kg to GEO and \$100,000/kg to high lunar orbit using conventional chemical propulsion)
    - Potential for return of precious materials to Earth
      Gold=\$56k/kg, Platinum=\$52k/kg, Rhodium=\$49.3k/kg, etc.

Asteroid Mining for Resources

A 500-metric ton carbonaceous C-type asteroid likely contains:

- 100 tons of water
- 100 tons of carbon-rich compounds
- 83 tons of iron
- 6 tons of nickel
- 1 ton of cobalt
- 200 tons of silicate residue (similar to lunar material)



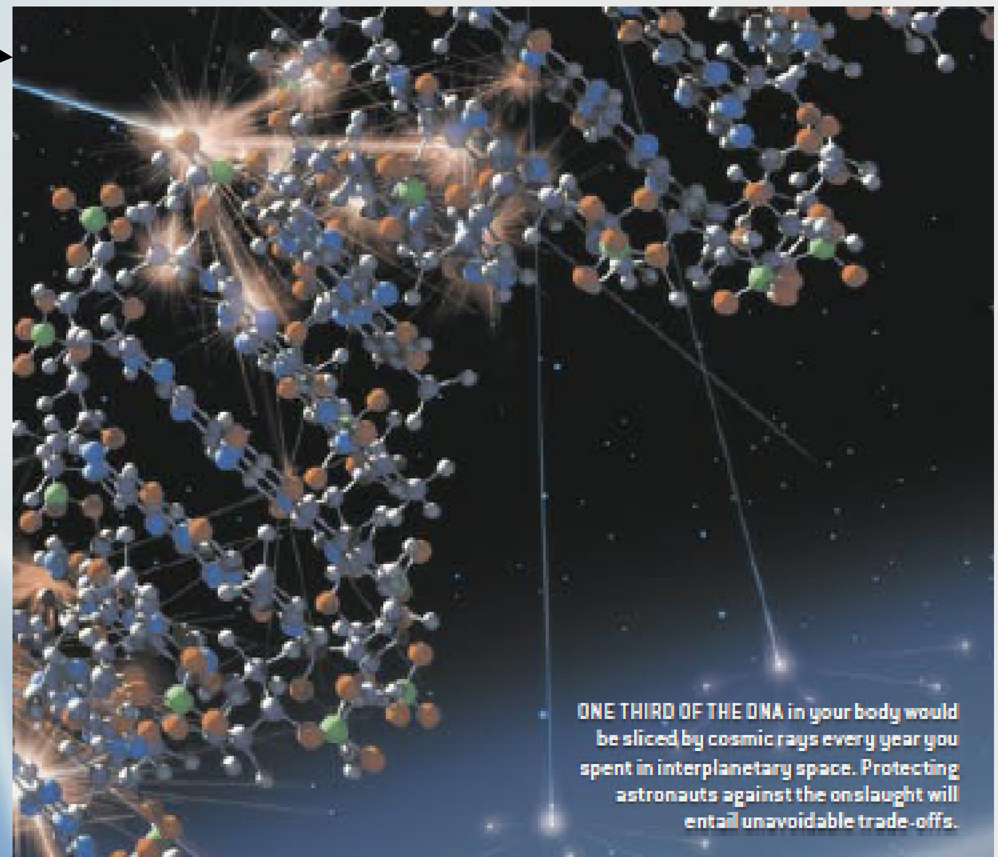
This material is useful for

- human life support
- propellant
- construction materials
- ***Shielding materials***

The Need for Shielding in Space

Shielding is ***critically*** needed for human space flight outside LEO

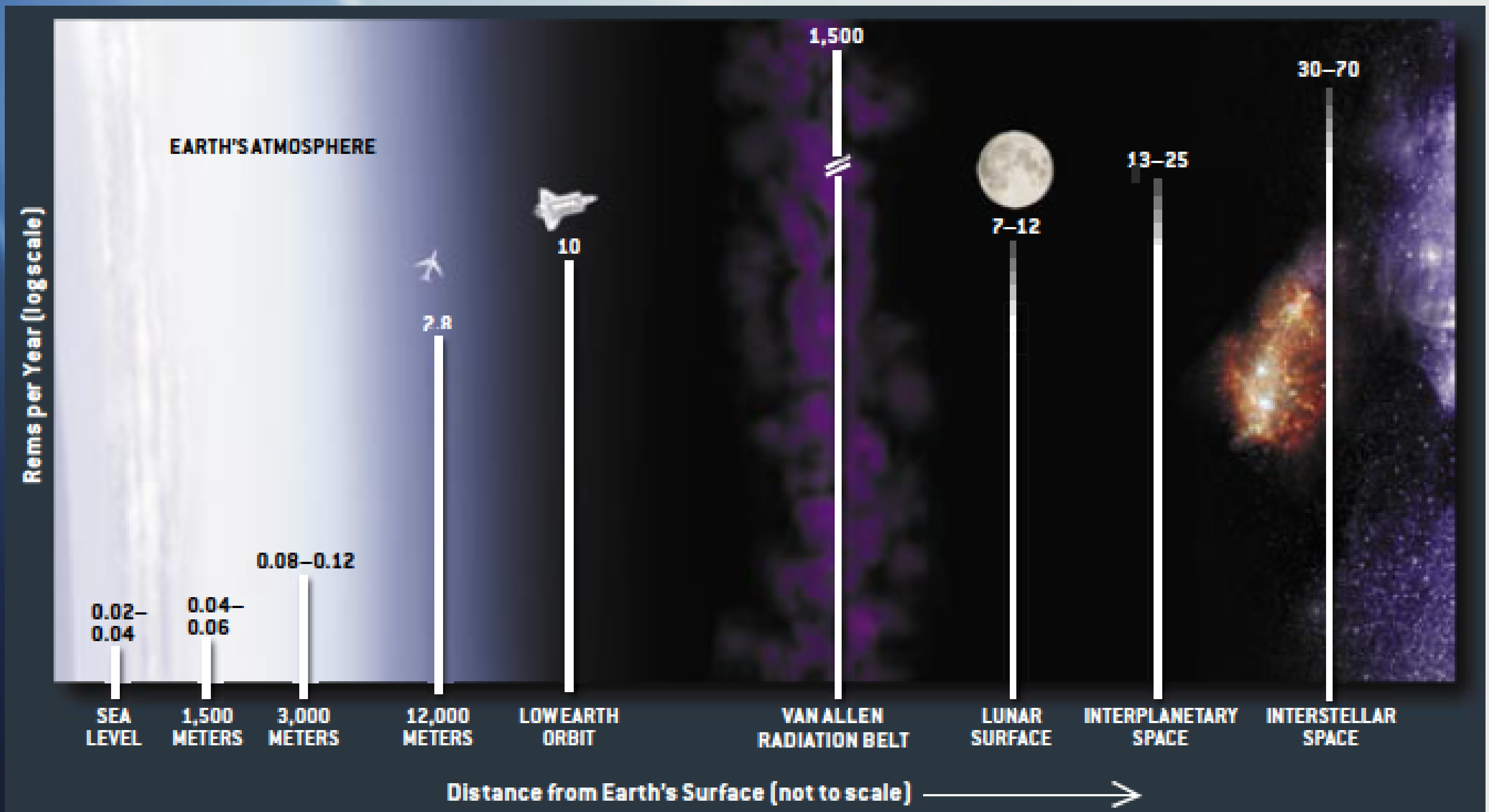
Exposure to Galactic Cosmic Rays is likely ***THE*** show-stopper for human deep-space exploration
- causes cancer
- known cause of blindness due to cataract formation



E. Parker, Scientific American, Feb. 2006

The only known solution is to provide sufficient radiation shielding mass

Radiation Doses facing Astronauts



E. Parker, Scientific American, Feb. 2006

- Maximum dose allowed by the government is ***5 Rems per year***
- The Earth's atmosphere shields us from cancer-causing doses of cosmic rays ***(>10 Rems/yr outside LEO)***
- Solar Flares are another large source or radiation in space

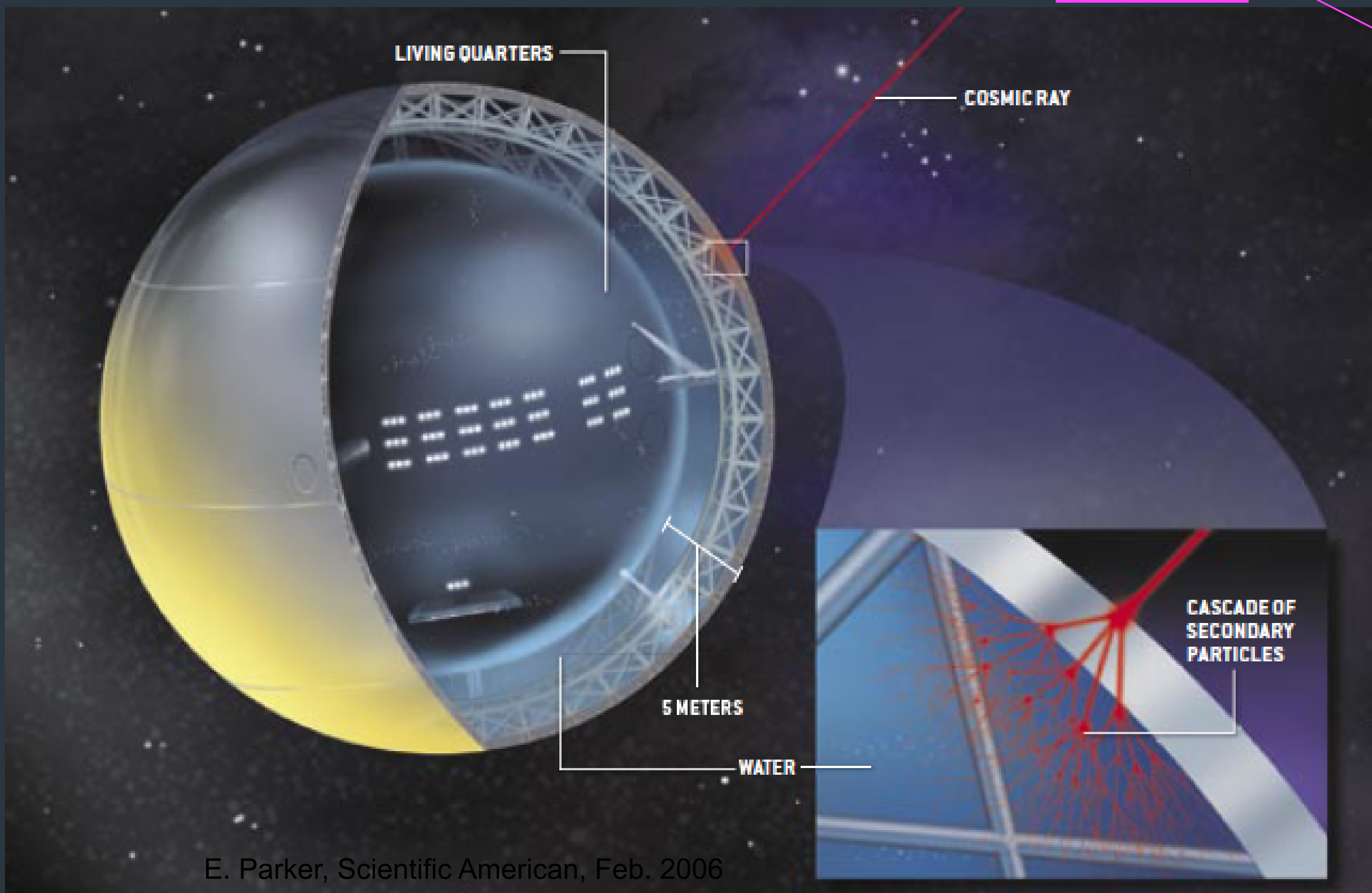
Shielding Requires Mass in Space

A large mass around the astronauts absorbs incoming radiation and the secondary particles it produces. A spherical shell of water five meters thick provides the same protection that Earth's atmosphere offers at an altitude of 5,500 meters (18,000 feet).

PROS:
Simple
Guaranteed to work

CONS:
Way too heavy

Use H_20 from space!



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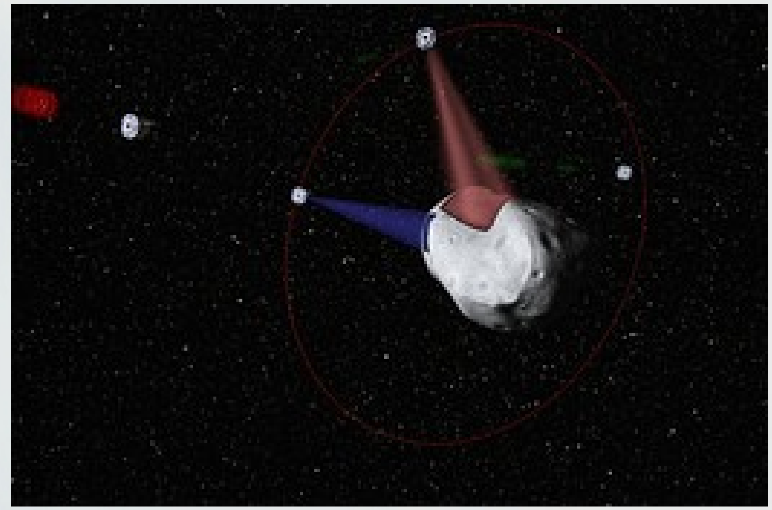
Asteroid Mining

How? (we'll come back to "Why Now?" later)

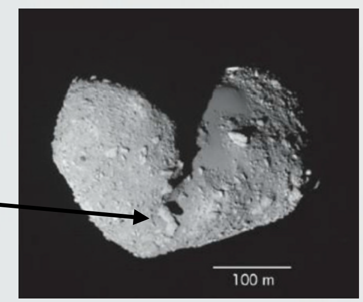


1. Find candidate NEOs
   - more Earth observation
   - LEO observation
   - robotic precursor space-craft to characterize surface

2. Exploit asteroid resources

   Two Options:

   1. Send astronauts to NEOS
      - grab boulders and material
      - probable 2+ year trip (*radiation issues*)
      - expensive multiple-launches needed



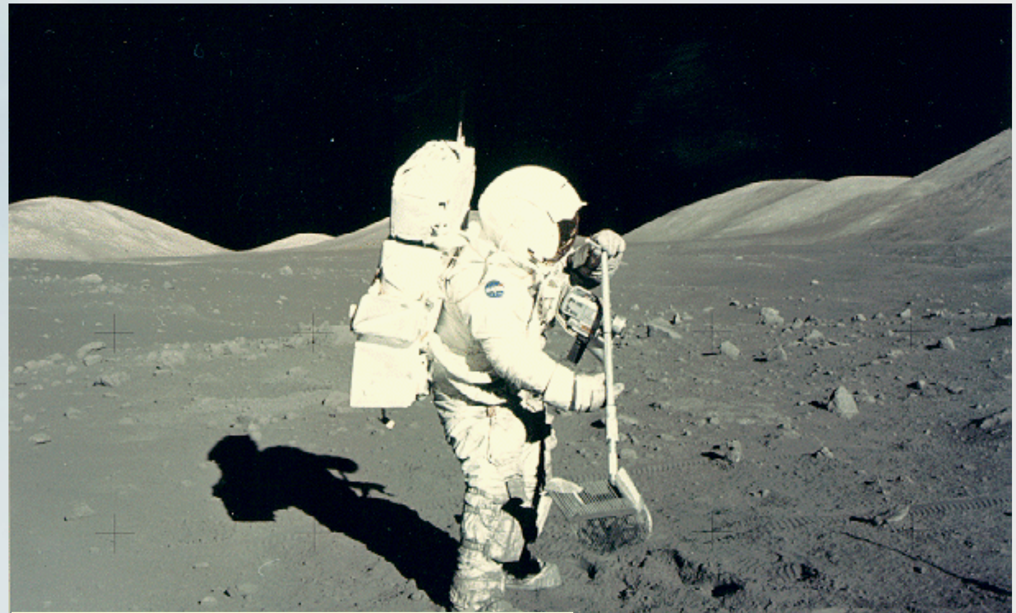
3. Retrieve an asteroid and bring it to back to the Earth

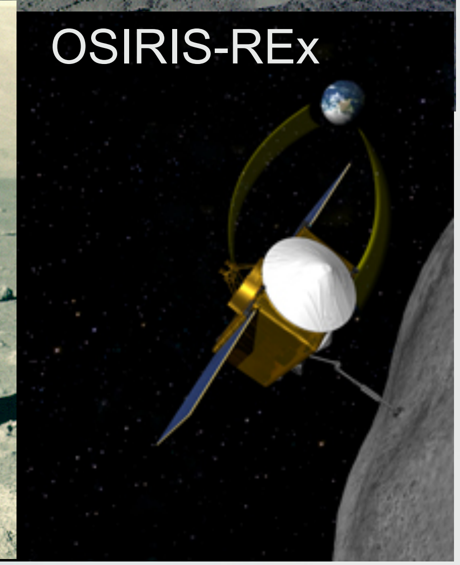
Sample Returns in Perspective

The Apollo program returned 382 kg of moon rocks in six missions.

The OSIRIS-REx mission will return at least 60 grams of surface material from a NEA by 2023.

John Brophy of JPL proposes returning an entire ~7-m dia. near-Earth asteroid, with a mass of order 500,000 kg, to a high lunar orbit, by 2026.





'Levitated Mass.' at the LA County Museum of Art

Why Return an Entire Asteroid?

- Create a near-term mission target in cislunar space that requires the presence of a human crew
  - First step on flexible path into the solar system
  - Test bed for human exploration operations
- Enable Asteroid Exploitation/ Resource Utilization
  - Water
  - Propellants
  - **Materials for radiation shielding**
- Scientific investigation

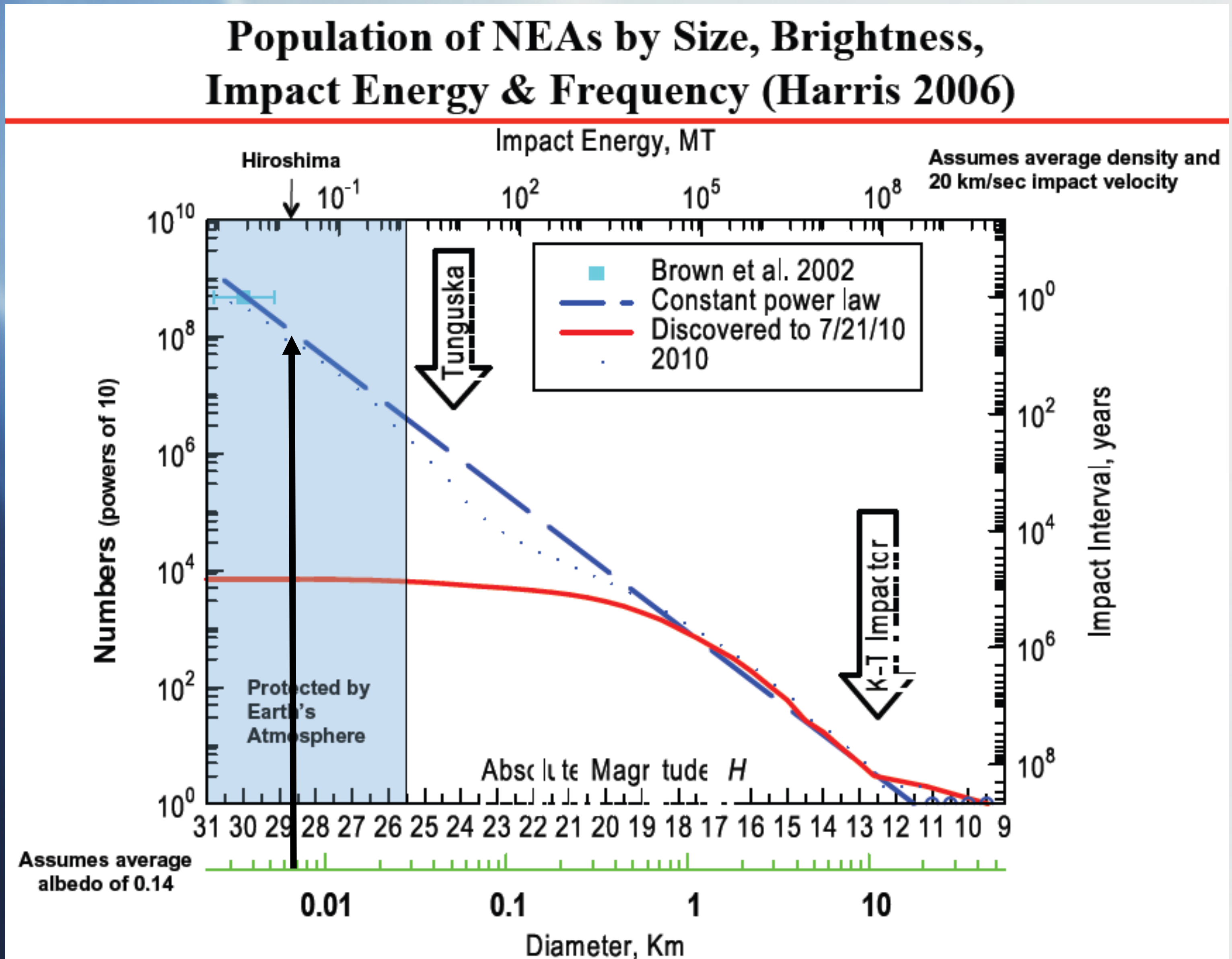
Asteroid Mass vs Diameter

Diameter (m)	Asteroid Mass (kg)		
	1.9 g/cm^3	2.8 g/cm^3	3.8 g/cm^3
2.0	7,959	11,729	15,917
2.5	15,544	22,907	31,089
3.0	26,861	39,584	53,721
3.5	42,654	62,858	85,307
4.0	63,670	93,829	127,339
4.5	90,655	133,596	181,309
5.0	124,355	183,260	248,709
5.5	165,516	243,918	331,032
6.0	214,885	316,673	429,770
6.5	273,207	402,621	546,415
7.0	341,229	502,864	682,459
7.5	419,697	618,501	839,394
8.0	509,357	750,631	1,018,714
8.5	610,955	900,354	1,221,909
9.0	725,237	1,068,770	1,450,473
9.5	852,949	1,256,977	1,705,898
10.0	994,838	1,466,077	1,989,675

The International Space Station has a mass of about 450,000 kg

Most NEAs have densities between 1.9 and 3.8 g/cm^3

~100 Million 7-m NEAs

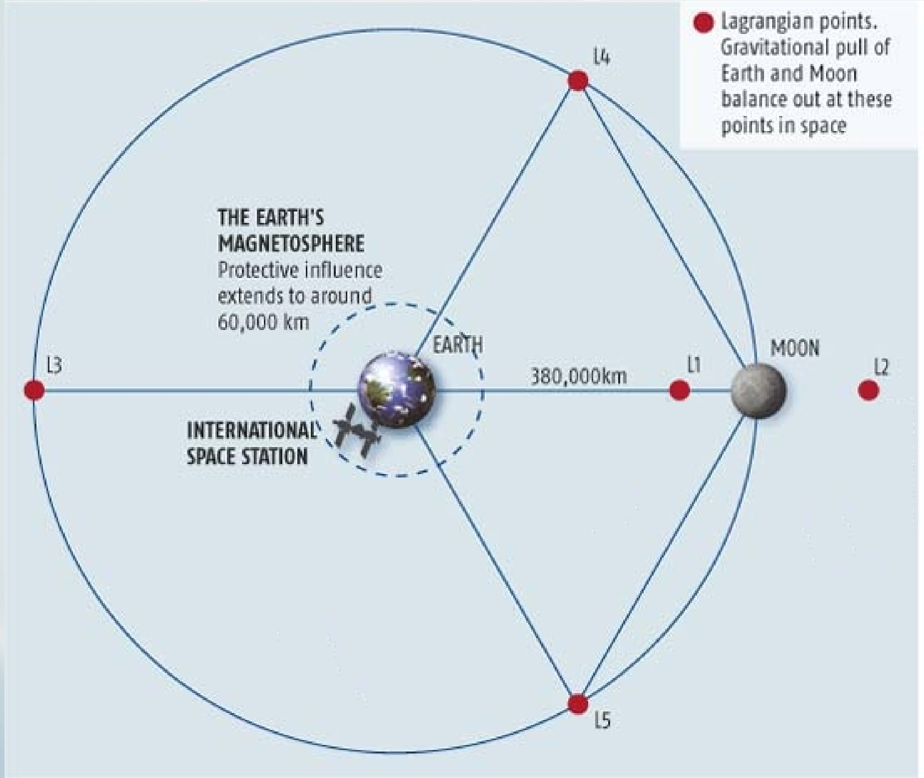


Where Bring It?

- We want to bring it to a near-Earth orbit so the in-space trip time by astronauts is minimized
- This has to not only ***be*** safe, but be ***perceived*** to be safe by the general public

Bring It to an Orbit by the Moon

- Desire a near-moon location so trip time by astronauts is only a few days
- The Earth-moon L1 and L2 Lagrangian points (2-body stable orbits), or a Distant Retrograde Orbit (DRO - 3-body stable orbit) are good

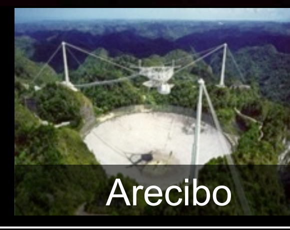


- Select orbit so asteroid can only fall into the moon if anything goes wrong

Asteroid Redirect Mission: Three Main Segments

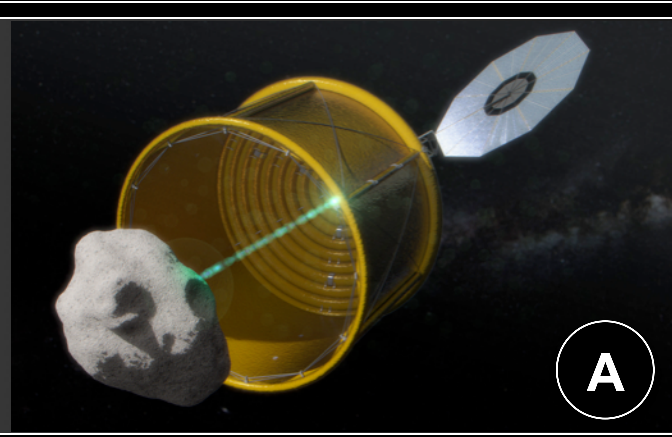
IDENTIFY

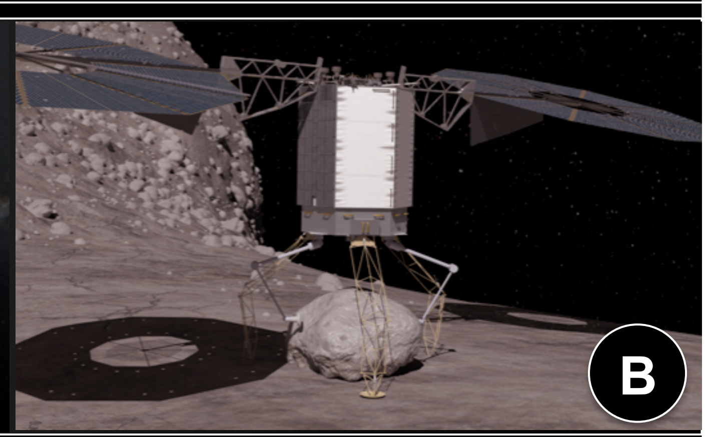
Ground and space based assets detect and characterize potential target asteroids



REDIRECT

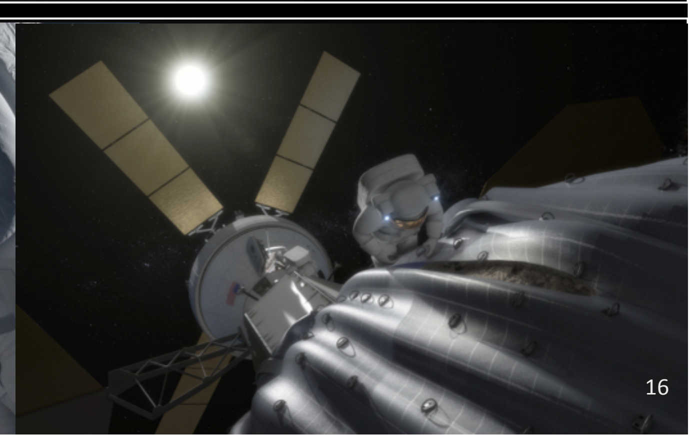
Solar electric propulsion (SEP) based system redirects asteroid to cis-lunar space (two capture options)





EXPLORE

Crews launches aboard SLS rocket, travels to redirected asteroid in Orion spacecraft to rendezvous with redirected asteroid, studies and returns samples to Earth

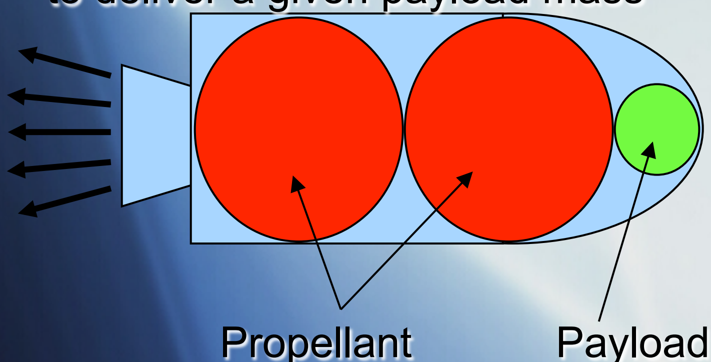


How? .....The Spacecraft

- A mission that uses only chemical propulsion would likely require ≥100 metric tons of chemical propellant
  - Space shuttle can deliver "only" 30 metric tons to LEO
  - Delta-IV Heavy can deliver ≈20 metric tons to LEO
  - Will need multiple launches….$$$

Chemical Propulsion

A **large** amount of propellant is needed to deliver a given payload mass

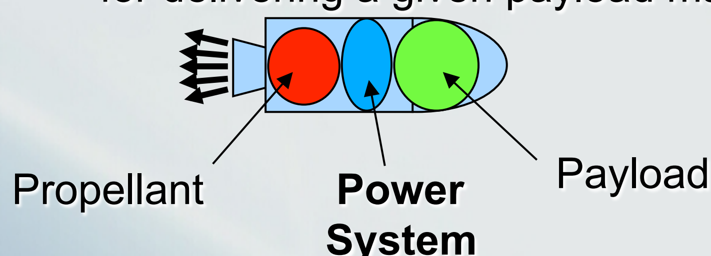


Like a Hummer

Like a Prius

Electric Propulsion

Higher Isp, less propellant needed for delivering a given payload mass

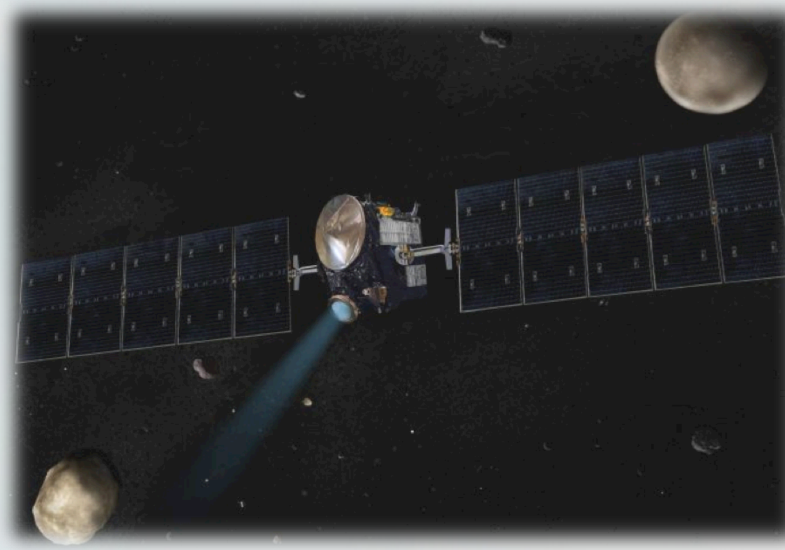


This mission is enabled by electric propulsion!

Mass delivered = initial mass at earth times $e^{-\Delta v/Isp*g}$

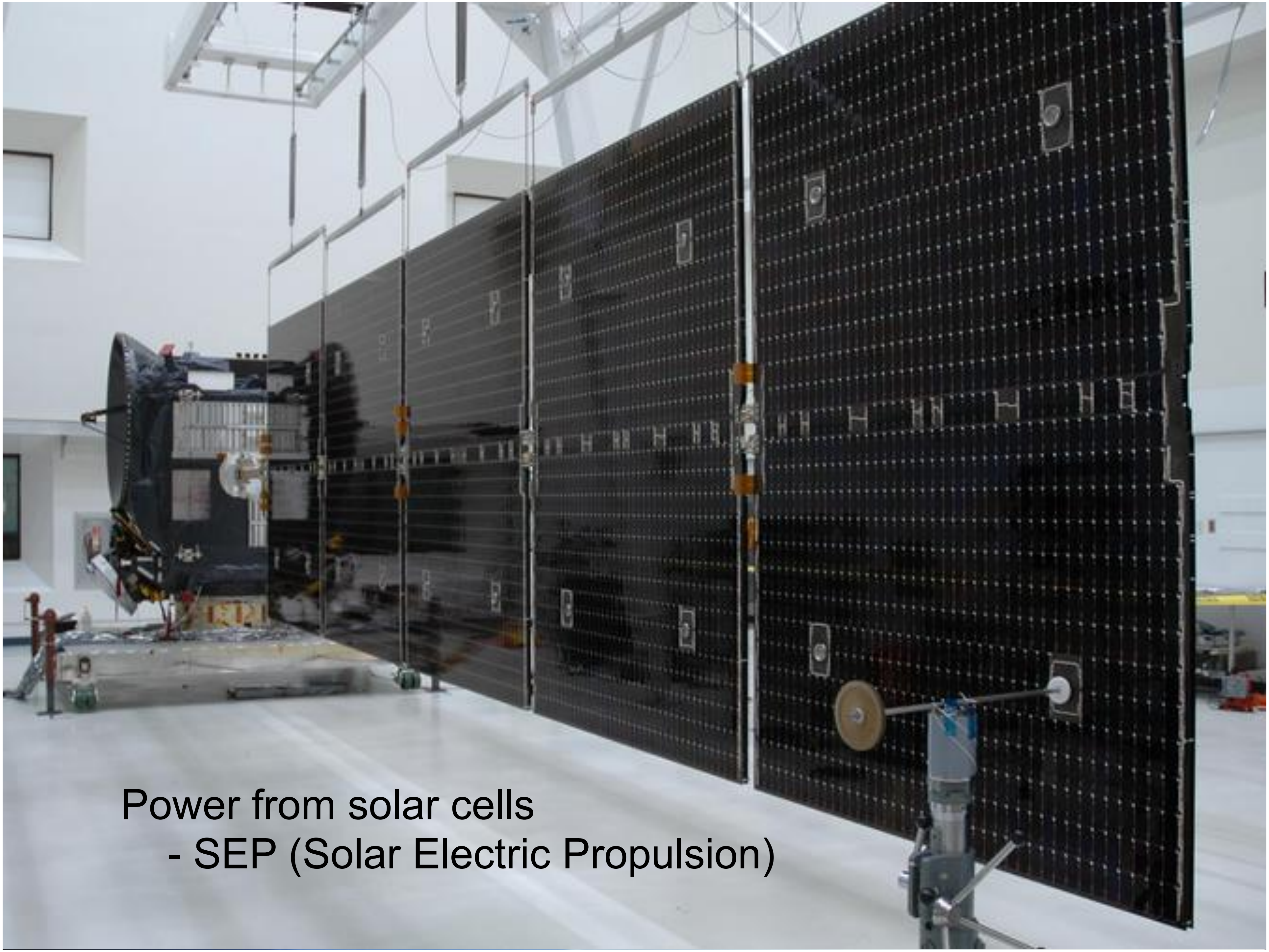
Example: Solar Electric Propulsion on DAWN

- DAWN is presently flying to two main-belt asteroids
- A chemical propulsion system would have had a 7500 kg launch mass
- DAWN used a 2.3 kW solar-electric ion propulsion system to reduce the launch mass to 1200 kg and save $200M



NSTAR
ion thruster

DAWN stowed before launch

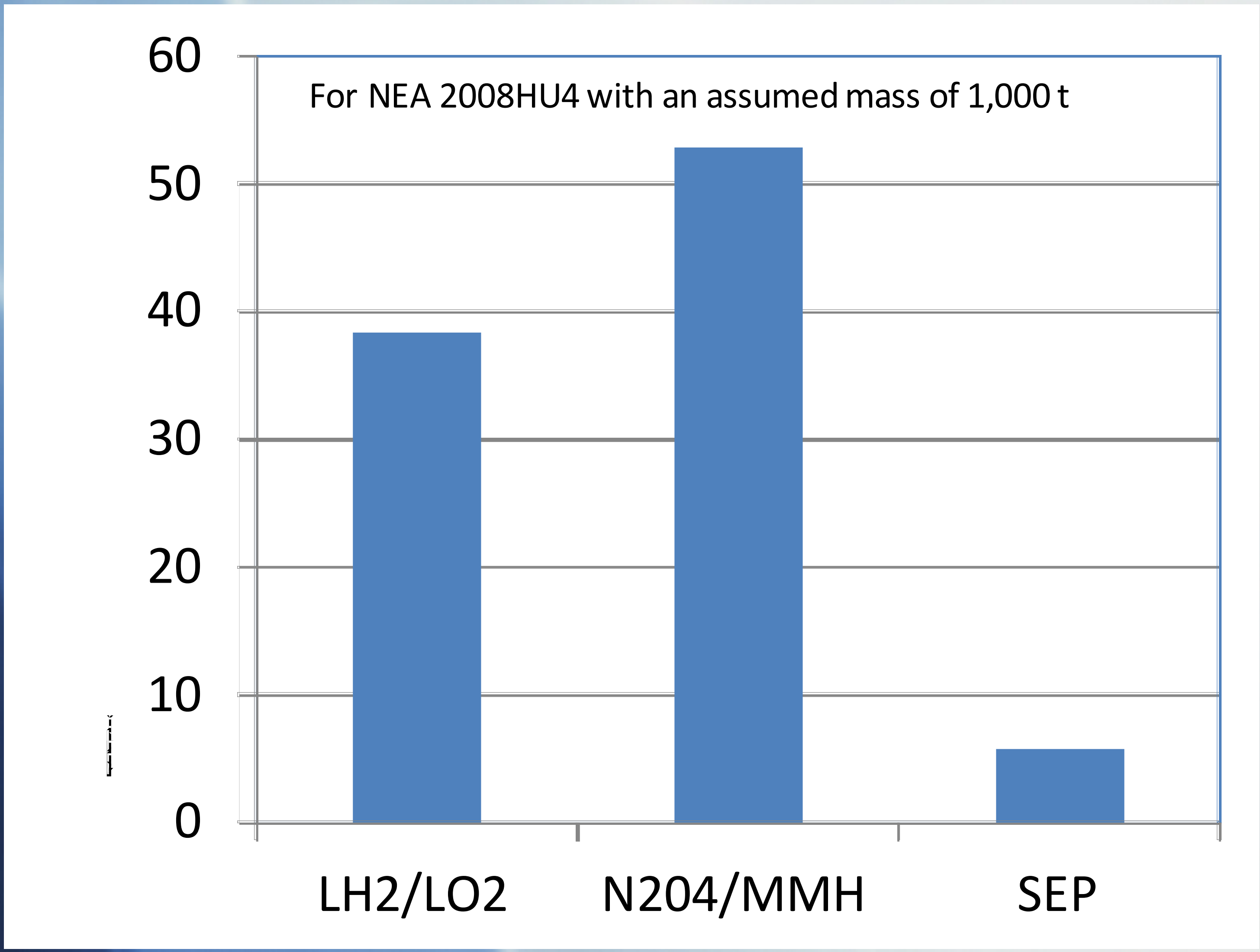


Power from solar cells

- SEP (Solar Electric Propulsion)

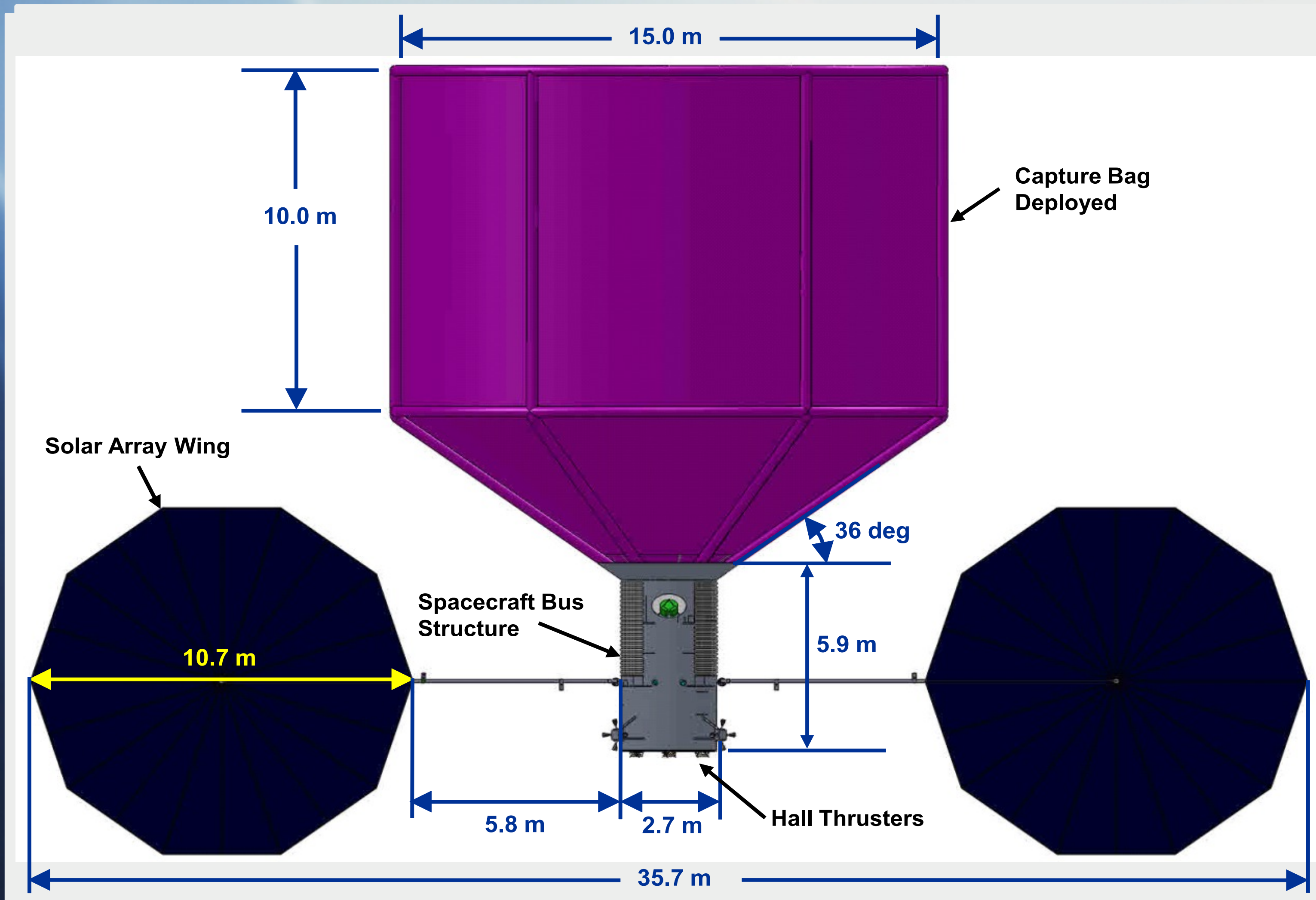
High-Power SEP is Enabling

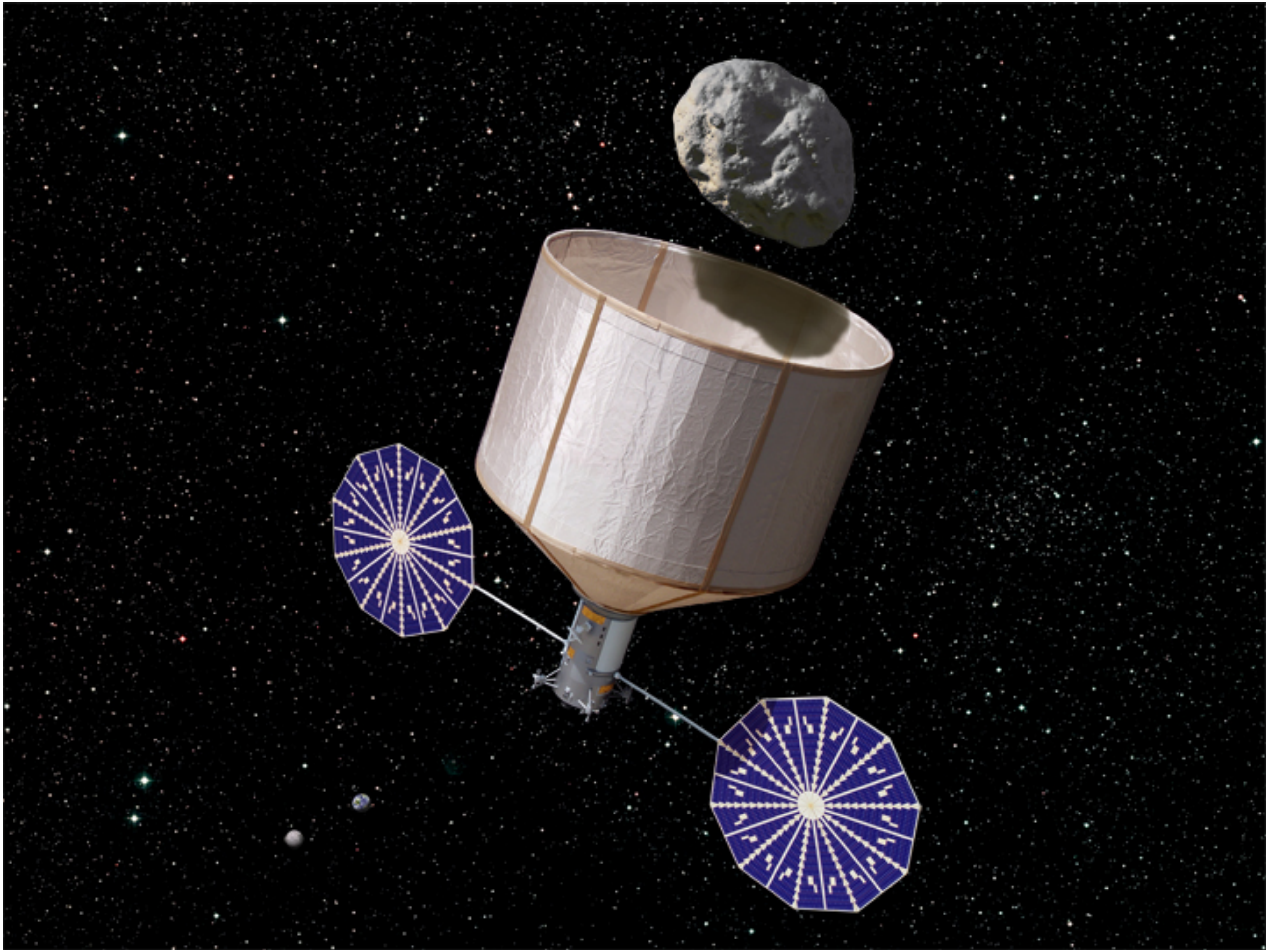
Example: Required Propellant Mass at the NEA

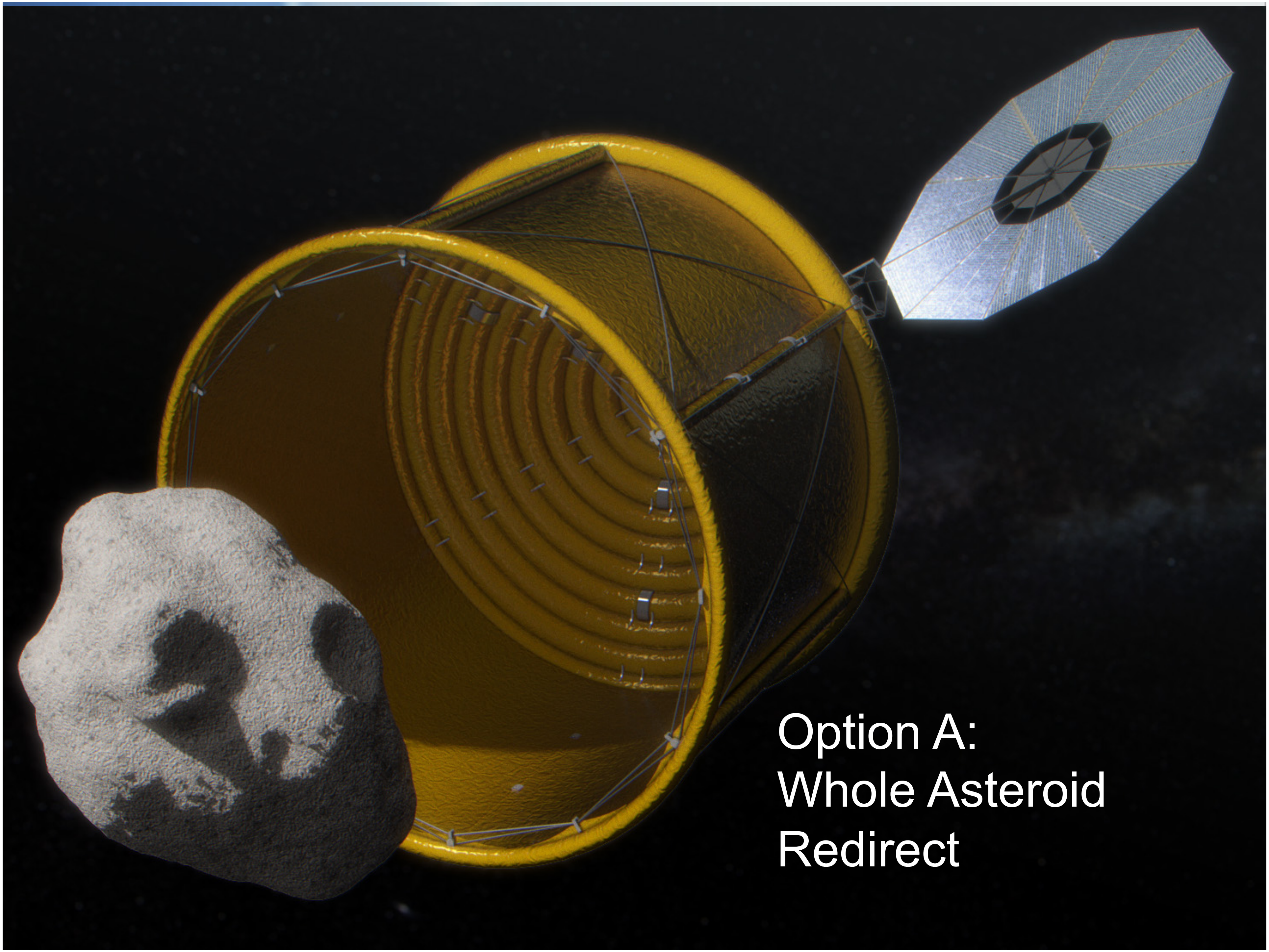


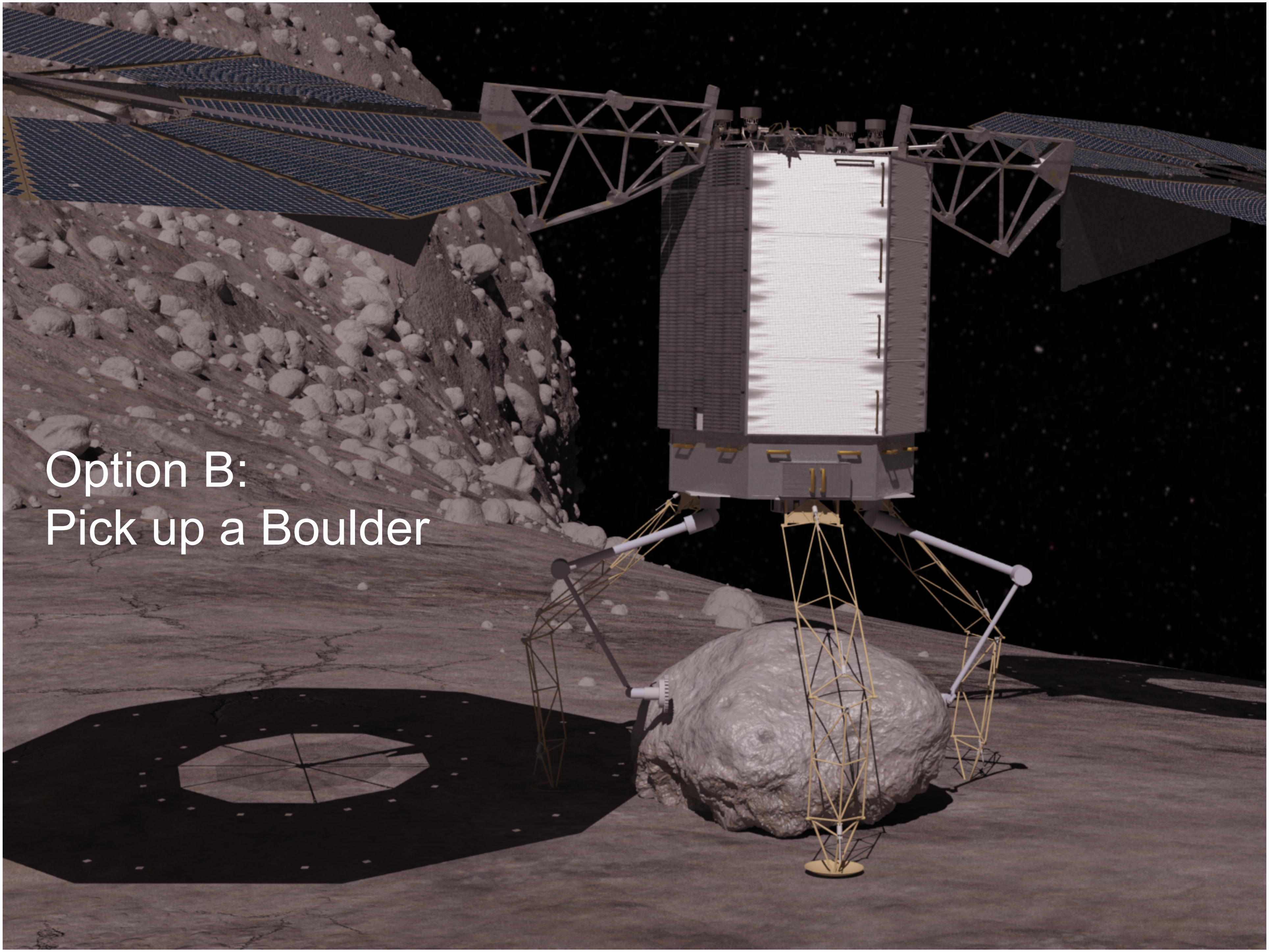
Spacecraft Flight System

Mission will require a 40-50 kW solar electric propulsion system and an “asteroid catcher”

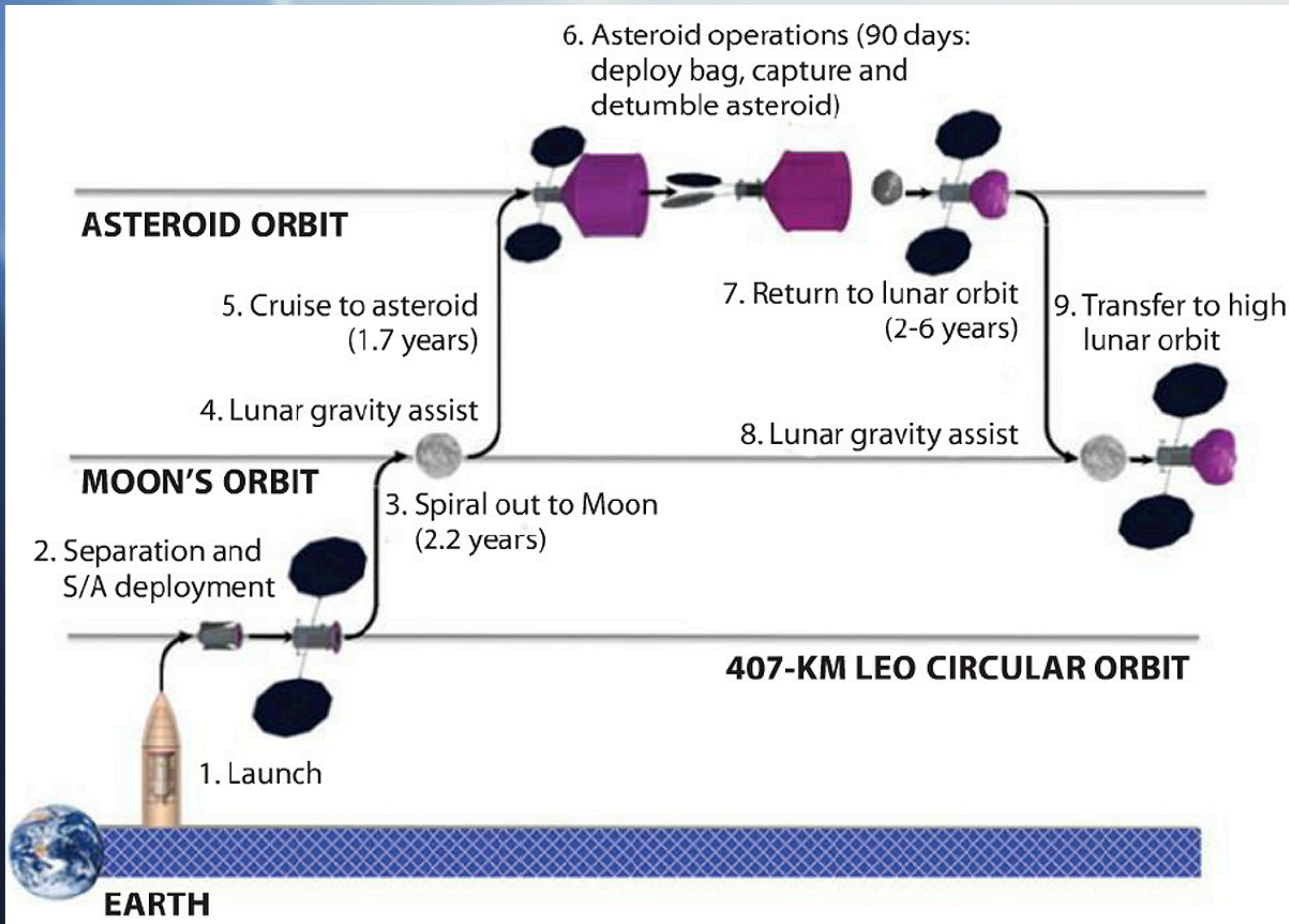




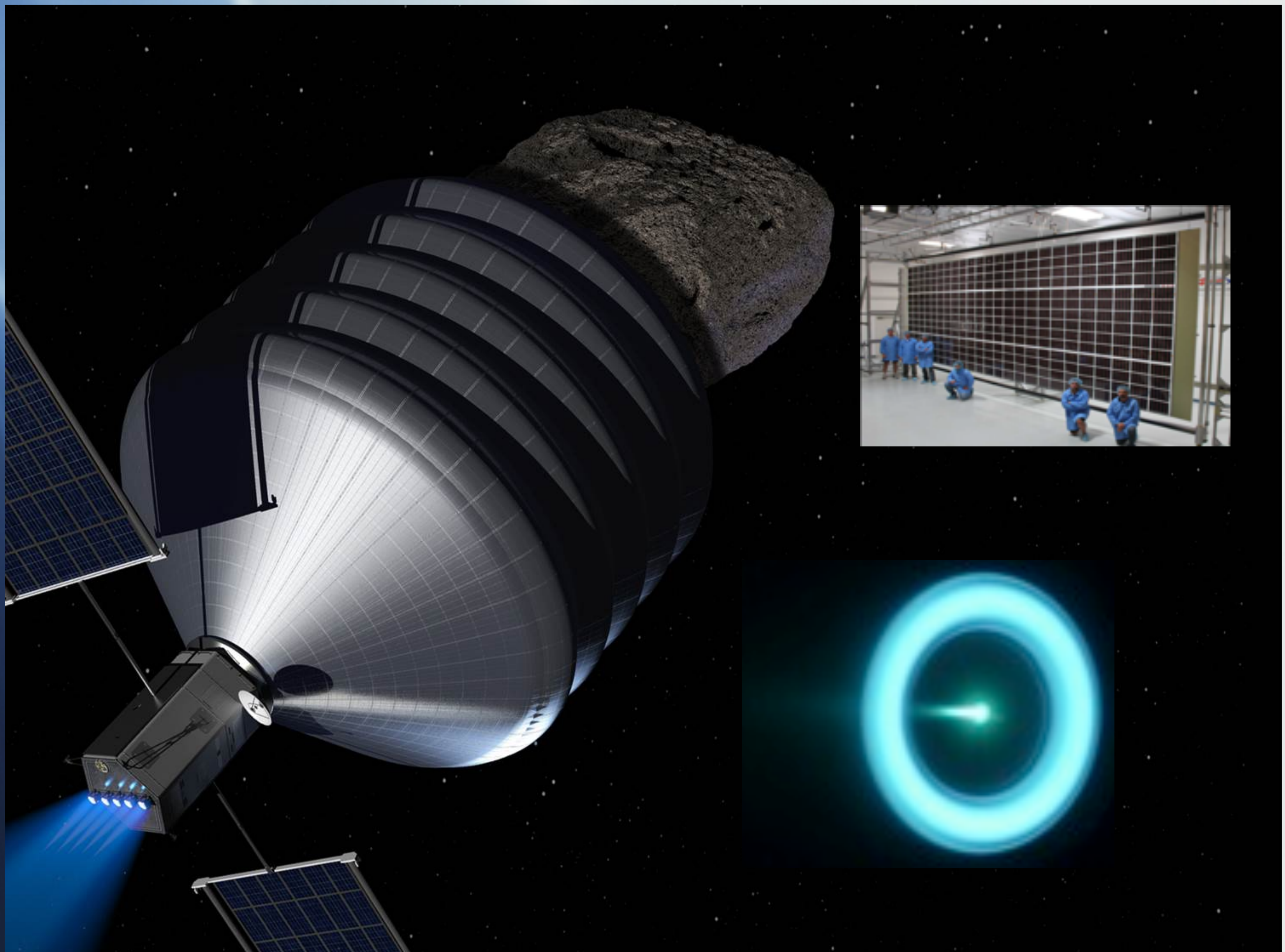

Option A:
Whole Asteroid
Redirect


Option B:
Pick up a Boulder

Asteroid Retrieval Concept



SEP is Enabling for ARM



Asteroid Mining Spacecraft
How? (more how anyway)

- Mission concept has a 40 kW solar array and uses 4-operating and 1-redundant electric thrusters each capable of 10 kW

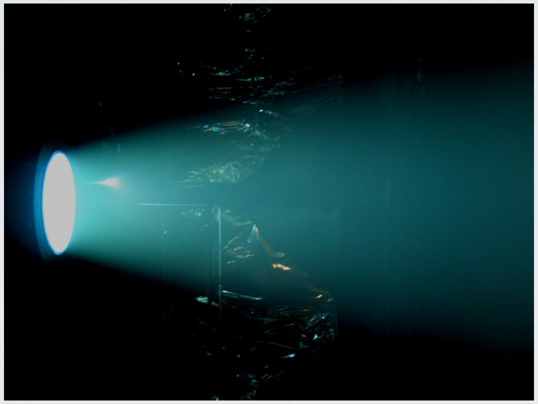
  highest power electric thruster to fly is 4.5 kW

- The mission will be approximately 10 years long with the thrusters operating most of the time

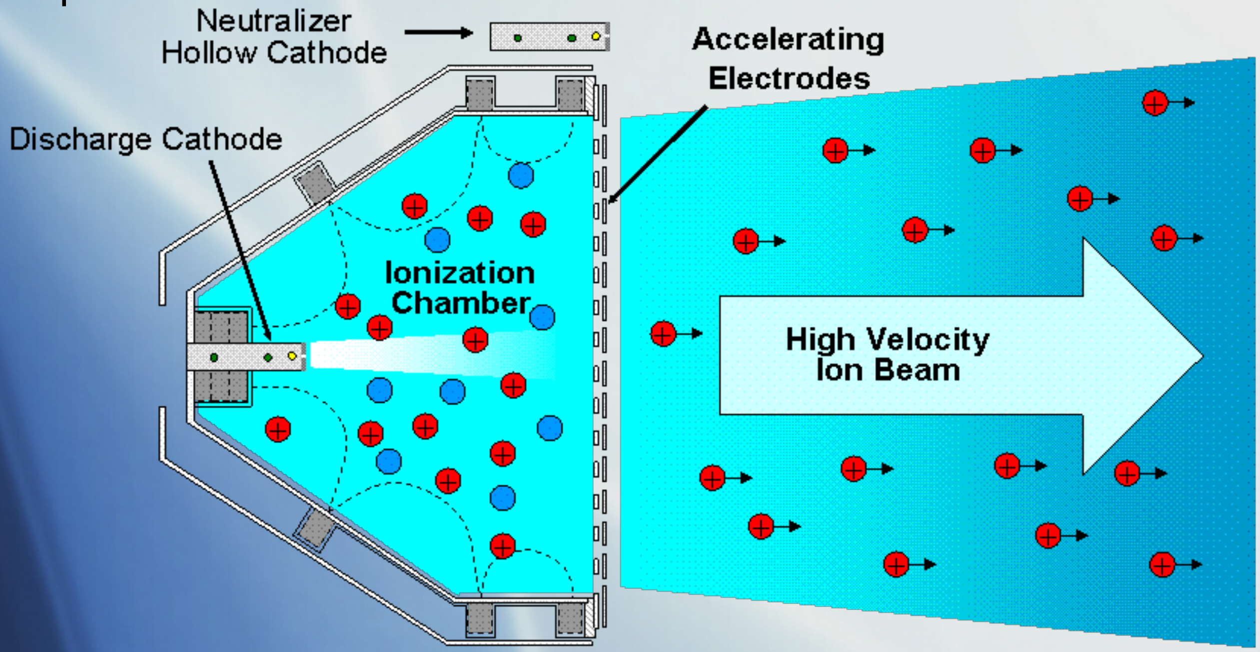
  longest operating time for an ion thruster is 4 years
  longest operating time for a Hall thruster is 1.2 years

So what do we have to do to get thrusters for this mission?

How Does an Ion Thruster Work?

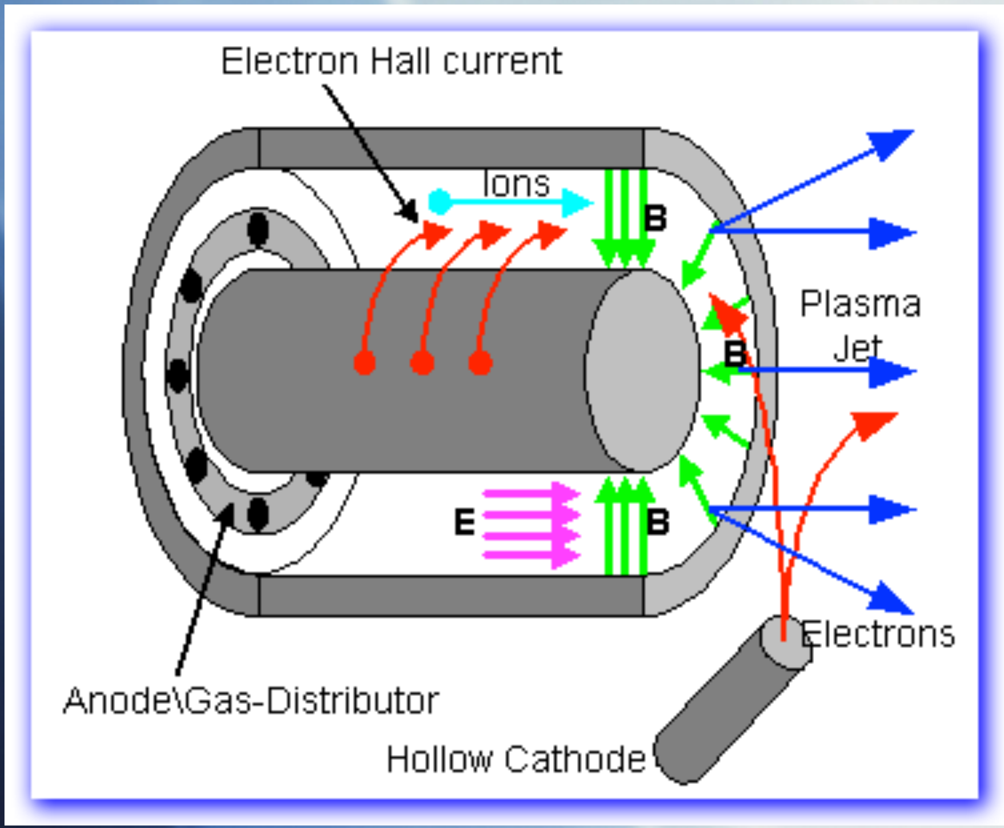


- Ion thrusters have three basic components:
  - discharge chamber where ionization occurs
    - Several different ionization techniques are used
  - accelerator grids to produce the high velocity thrust beam
  - neutralizer cathode to provide charge neutralization of the spacecraft

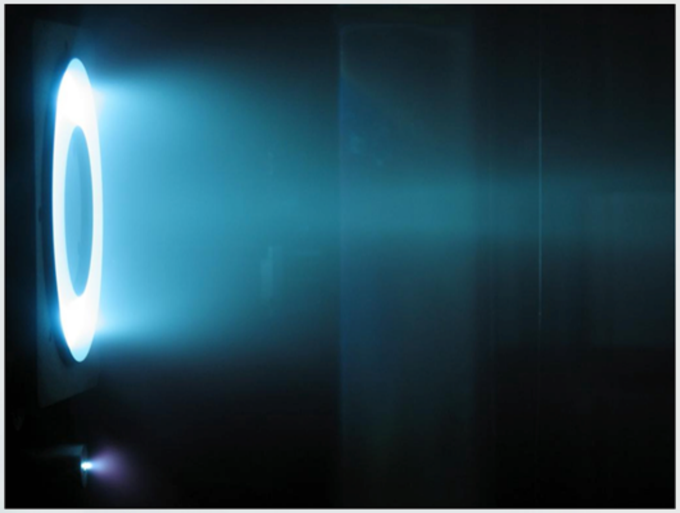


Runs at higher Isp and lower thrust than a Hall thruster

How Does a Hall Thruster Work?



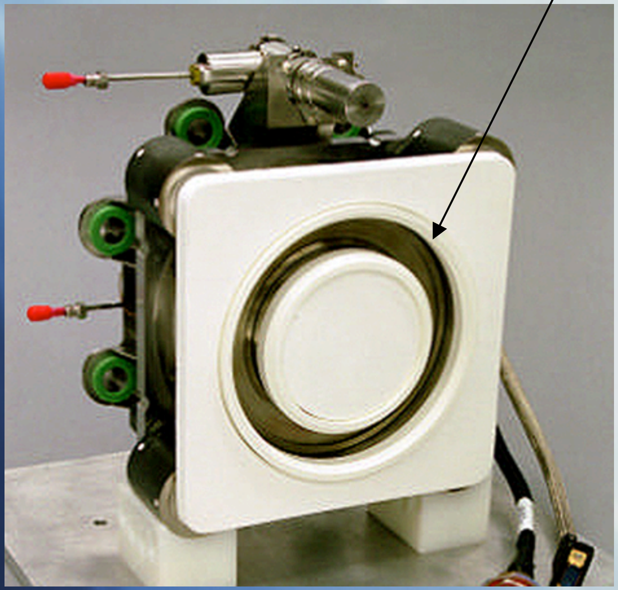
1. Electrons from the cathode are trapped in an azimuthal drift by the applied electric (E) and magnetic fields (B).
2. Neutral propellant gas is ionized by electron bombardment.
3. Ions are accelerated by the electric field producing thrust.
4. Electrons from cathode neutralize ion beam.



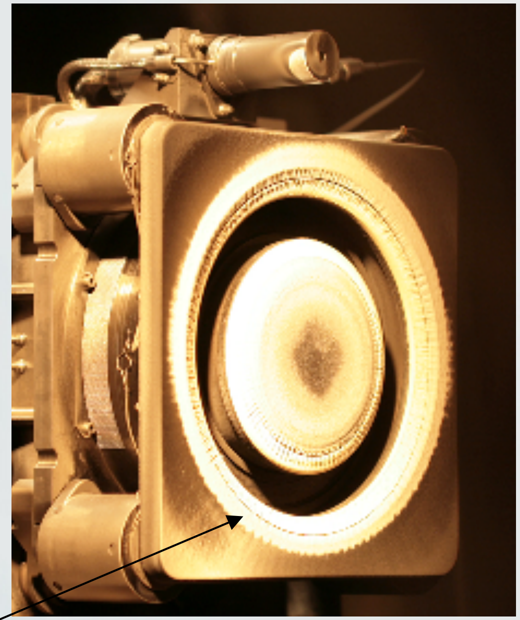
Higher thrust than a ion thruster means shorter trip time…desirable!

Life is Limited by Ion Bombardment of the Walls

- Some of the plasma flows along the radial magnetic field and strikes the walls, causing sputtering
- When the wall is gone the thruster life is finished.



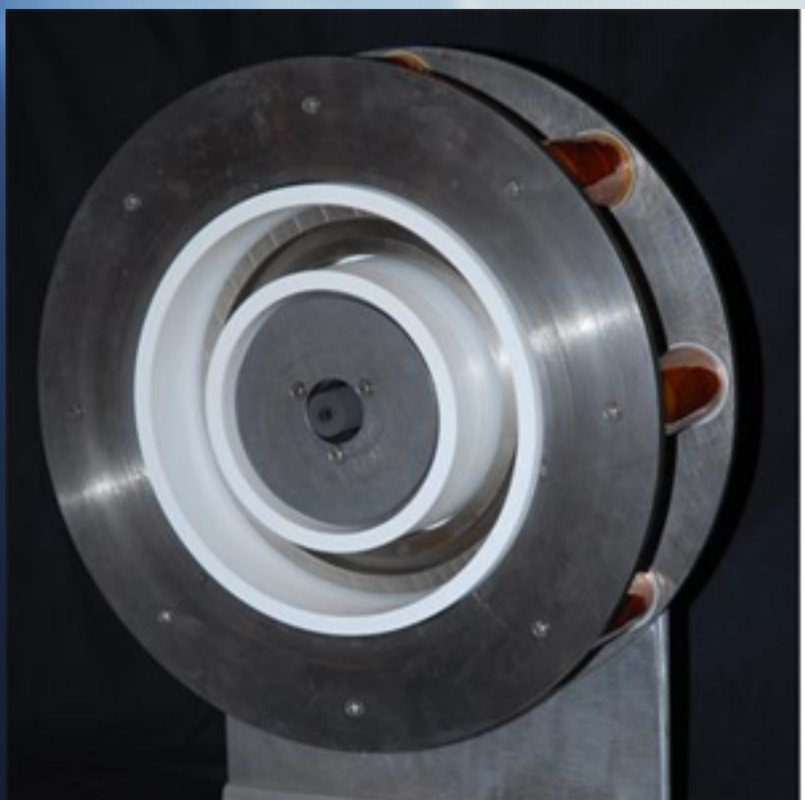
Aerojet BPT-4000 thruster



Channel wall erosion after 6700 hrs

Development of "*Immortal Hall Thrusters*" at JPL

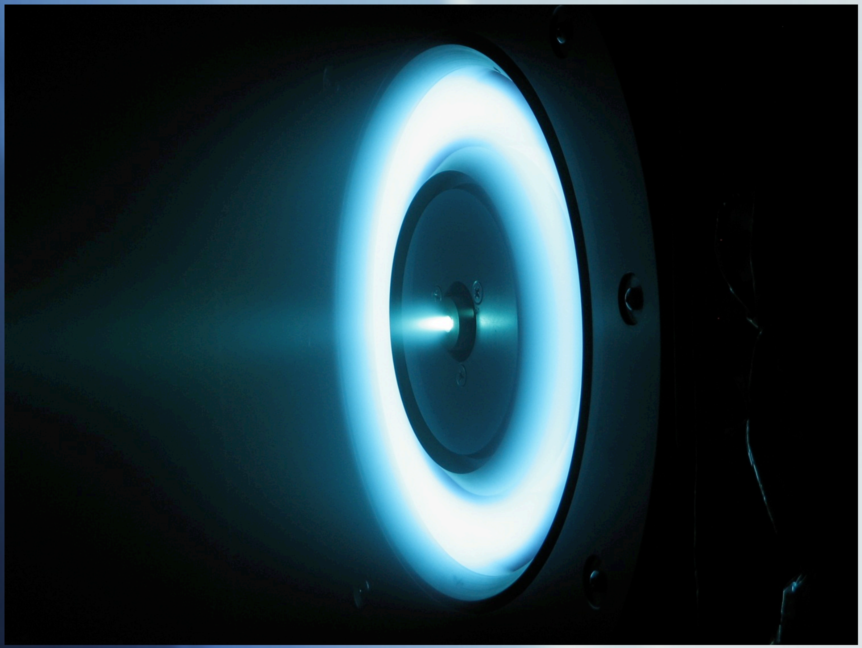
- A "standard design" 6 kW Hall thruster was modified to bend the magnetic field lines at the wall to Magnetically Shield the ceramic walls

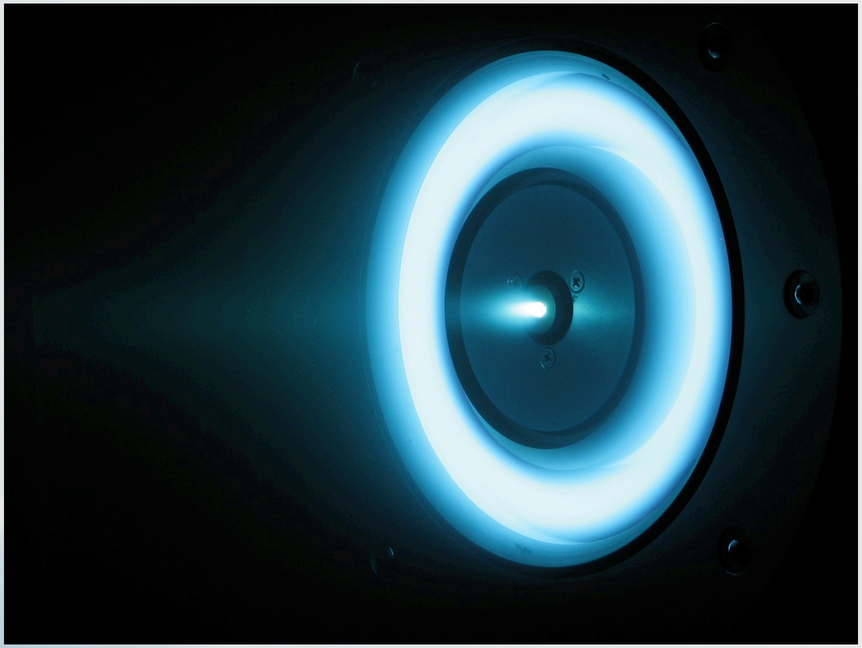


Standard H6

Magnetically Shielded H6

H6MS Operating

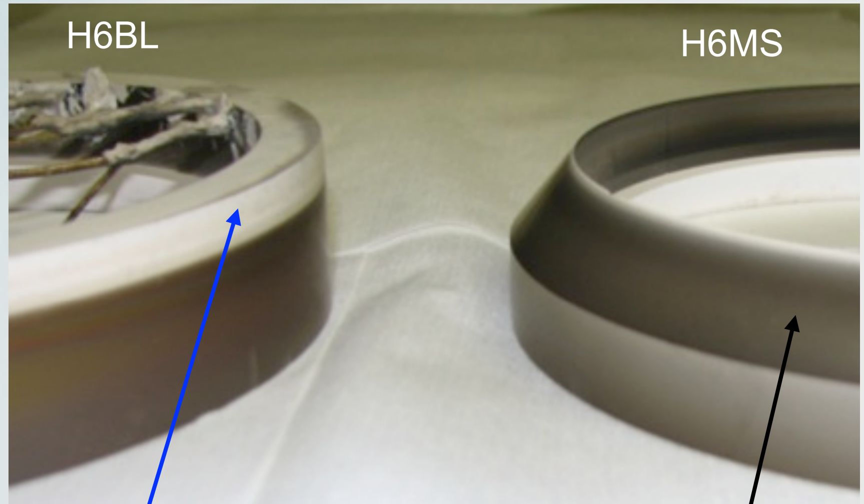


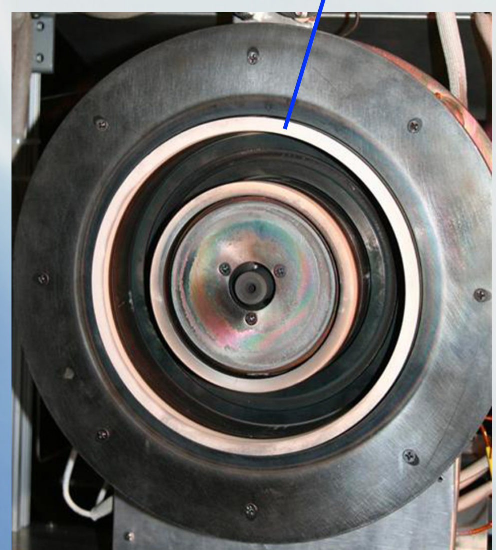


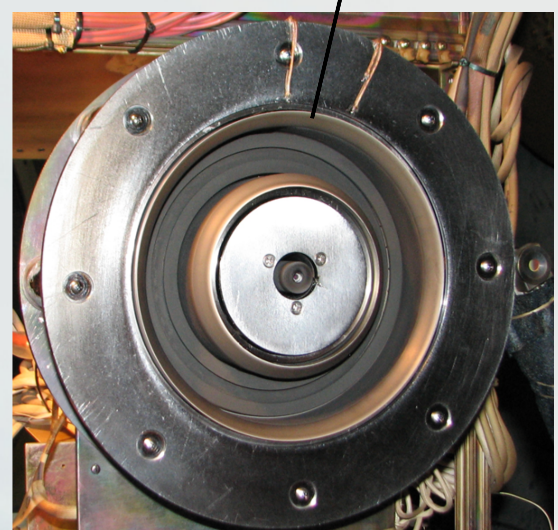
Performs identical to the normal H6
……***except***…..

No Erosion of Magnetically Shielded Ceramics

- Top Left: Inner insulator with baseline (BL) magnetics. A ~4 mm erosion band is present.
- Top Right: Inner insulator with magnetically-shielding (MS) pole pieces. Carbon backsputter covers almost the entire insulator.



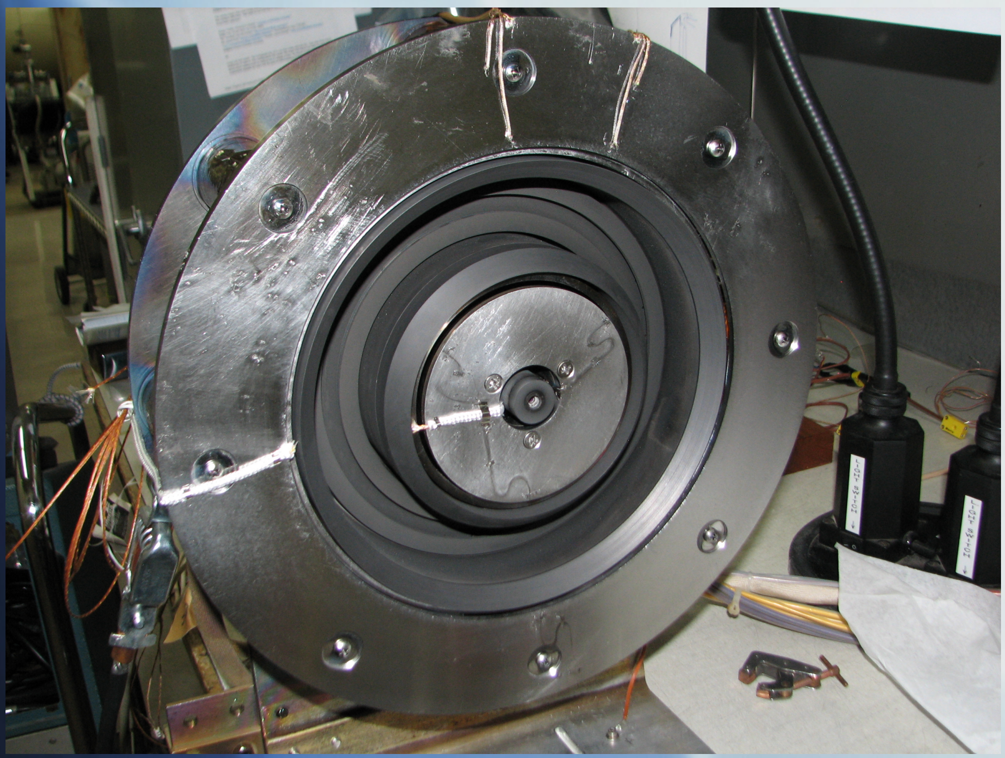


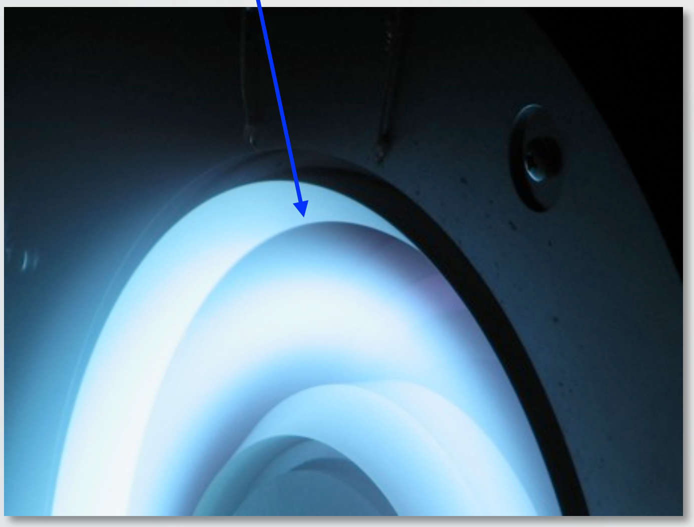


Reduced erosion by x100

Wall Material Replacement

- Since the ceramic walls aren't in contact with the plasma, who needs them?
- Installed walls made of graphite (*1st time ever*)
- Thruster is good for 10 kW now due to better heat rejection!



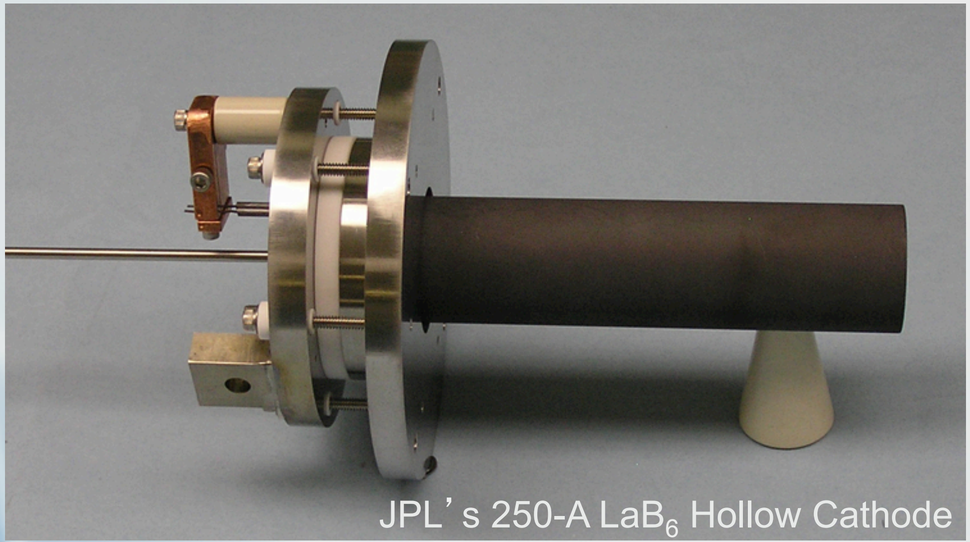


The Black Edition

Magnetically Shielded Hall Thrusters Enable the Asteroid Return Mission (ARM)

- 10 kW Hall thrusters with 100,000 hour life (>11 years) are in development at JPL….*enabling ARM*

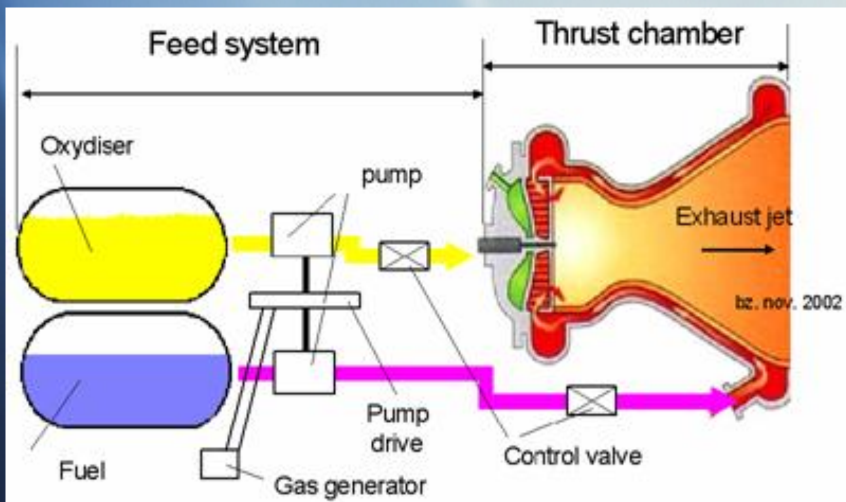
- Long life hollow cathodes to run these thrusters are also in development at JPL



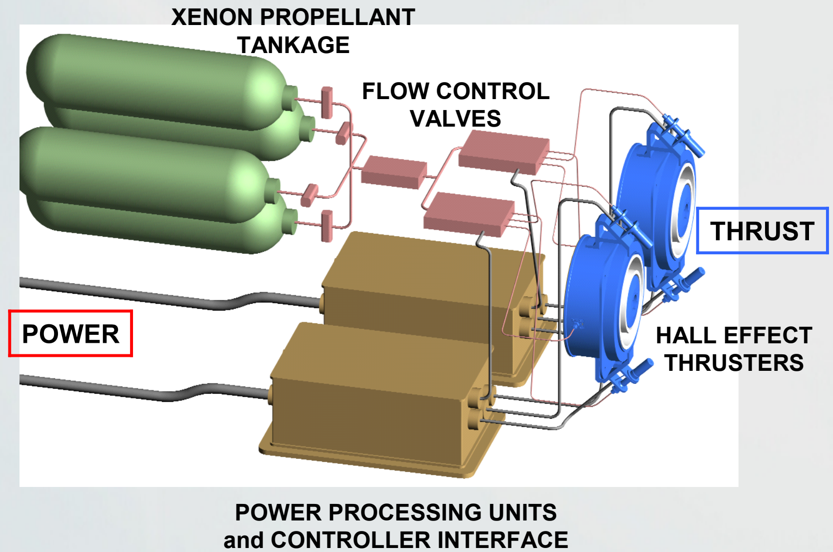
JPL's 250-A LaB_6 Hollow Cathode

Electric Thruster Systems are Different than Chemical Rocket Systems

Chemical Liquid Propulsion System



Hall Electric Propulsion System

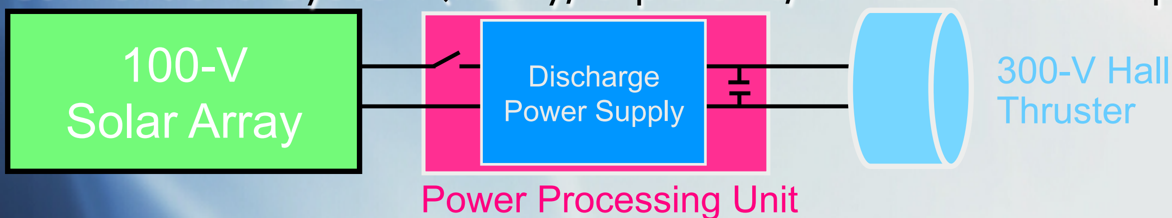


- ***Main difference is the Power Processing Units*** to interface the solar array power to the thrusters
  - these are large, heavy, and expensive $$

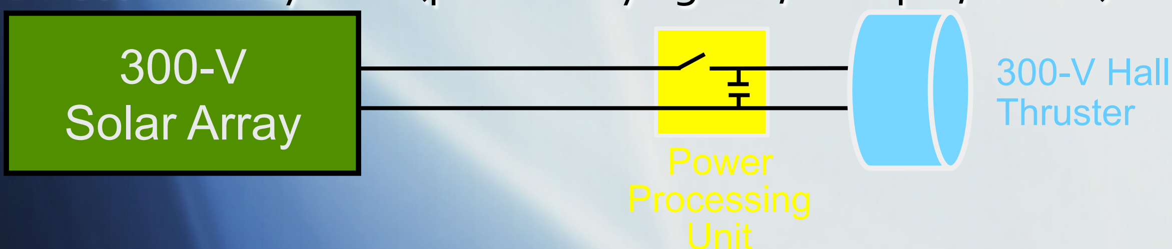
Direct-Drive

Matches a 300-V solar array with a 300-V Hall thruster

Conventional System (heavy, expensive, difficult to develop)



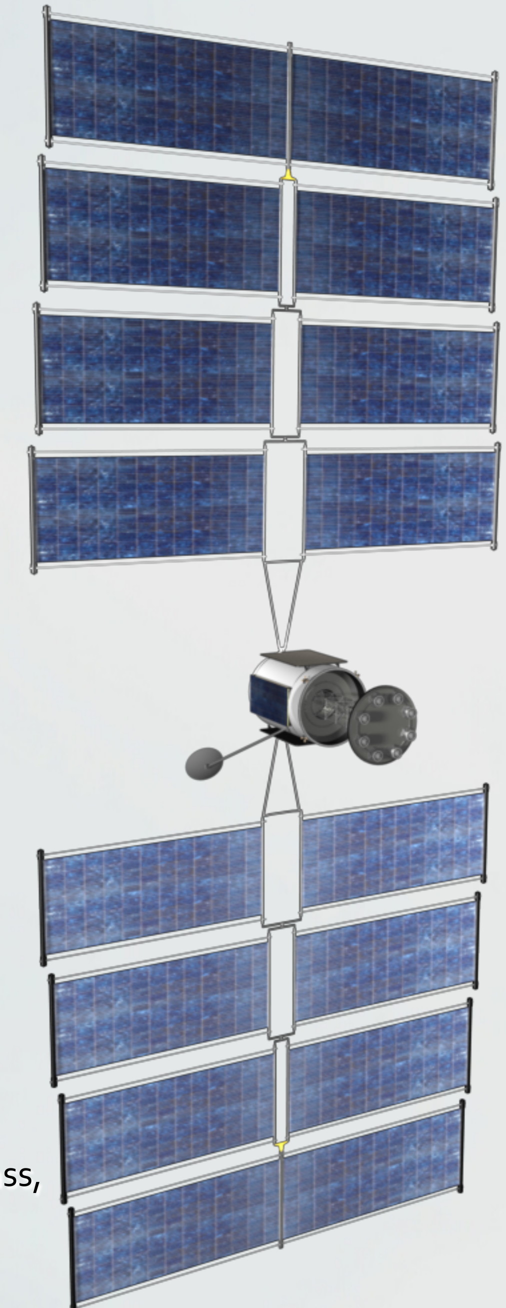
Direct-Drive System (potentially lighter, cheaper, easier)



Direct-Drive:

- Improves the power system efficiency to ~99%
- Reduces the PPU mass by 70%
- Reduces the radiator mass by 80%
- Reduces the solar array mass, propellant mass, tankage mass, and structure mass

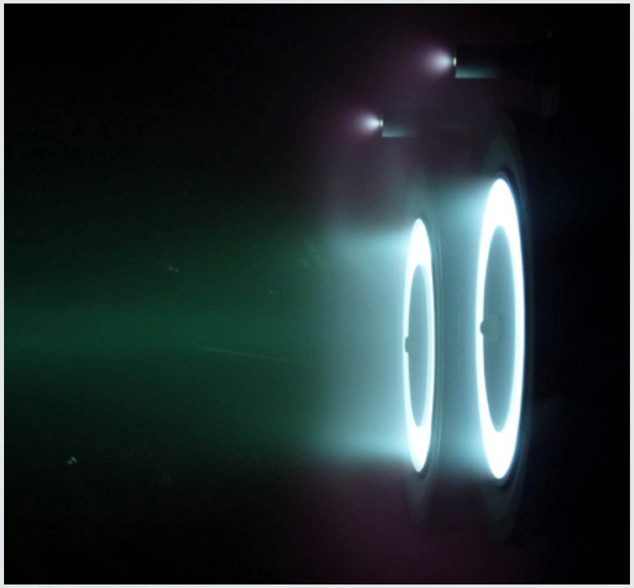
A real advantage for the Asteroid Mission!



300-kW SEP Vehicle for Crew Transport in Deep Space

National Direct Drive Test Facility at JPL

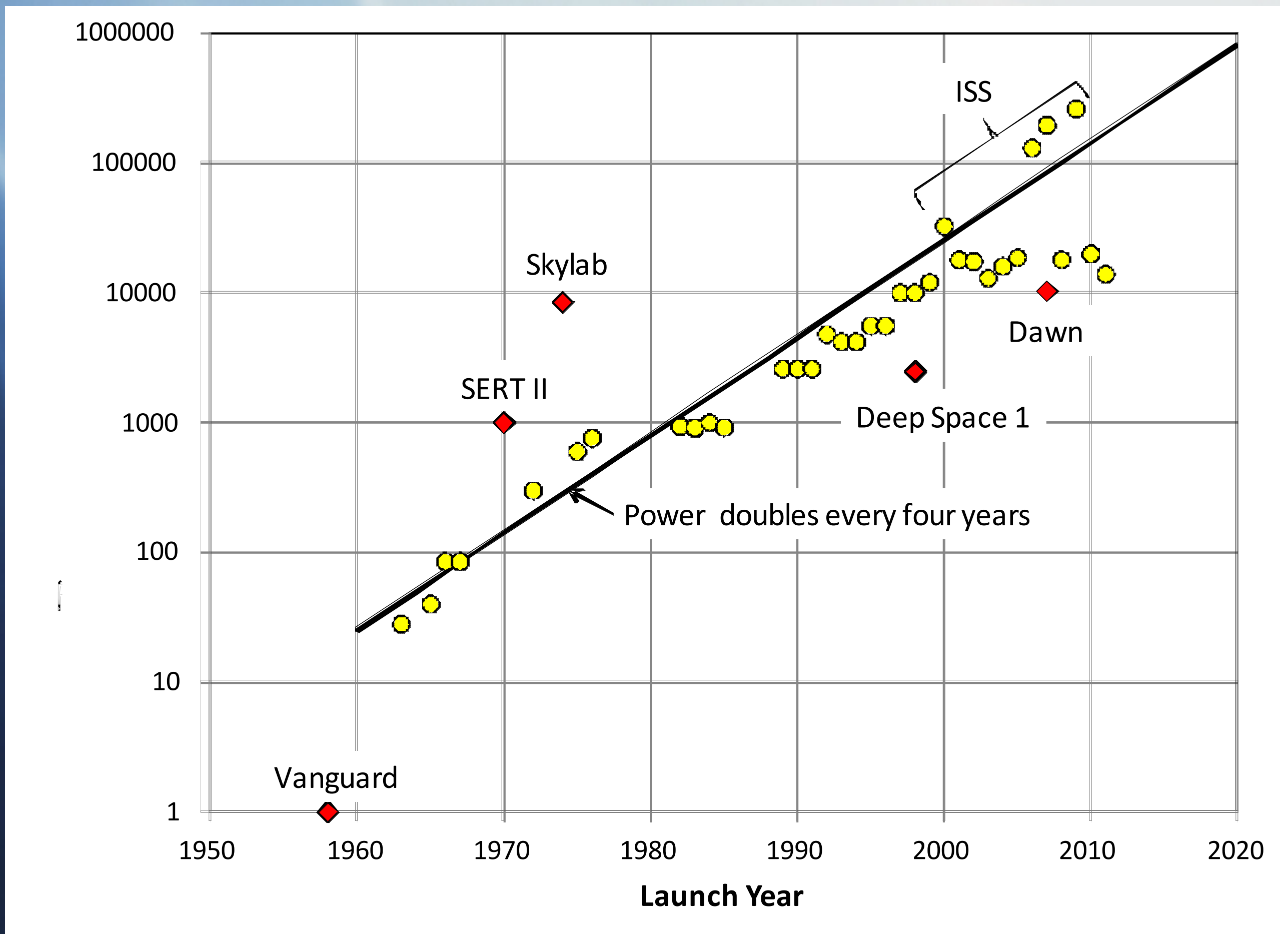
- A 10 kW solar array was installed on the roof of the JPL EP test lab
- This array is being used to run the Hall thrusters for ARM and test direct drive concepts



Thrusters running on Direct Drive solar array

Why Now? (finally)

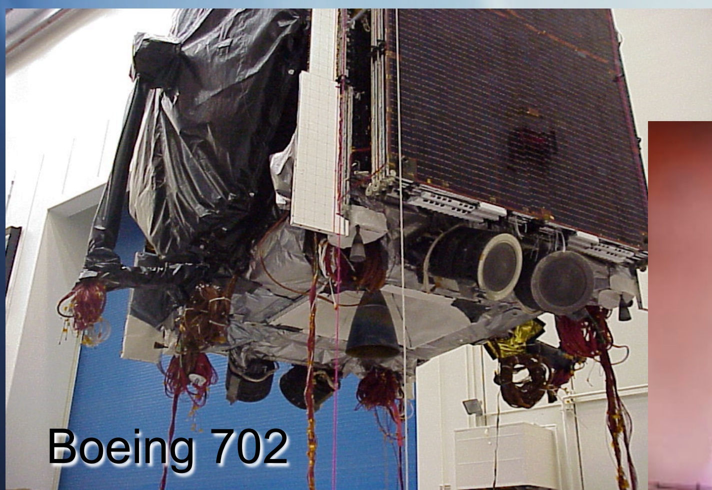
- What has limited implementation of electric propulsion is the available power in space (need many kilowatts)



Space power is growing and lots is available now

High Power SEP Spacecraft

- The ***communications satellite industry*** already flies 24 kW systems and are poised to fly 30 kW systems…so it's not a big stretch to 40 kW



Lockheed Martin

Conclusion

- An ***Asteroid Return Mission*** is conceivable
  - power is available and people are already flying it
  - once you've got an asteroid, then you can figure out how to mine it!

- Using SEP, Immortal Hall thrusters and Direct Drive enables a cost-effective mission to be launched this decade

- This high power SEP technology is directly applicable to the envisioned human exploration program to move astronauts and cargo to NEOs and to Mars….

Run ARM video from YouTube