National Aeronautics and Space Administration

Propulsion Technology Assessment: Science and Enabling Technologies to Explore the Interstellar Medium

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Mission Statement

Interstellar Probe Mission:

Trade and determine the best propulsion system from the following options in order to reach the Heliopause (100 AU) in 10 years:

- Magnetically Shielded Miniature (MaSMi) Hall thruster
- Solar sail
- Electric sail (E-Sail)

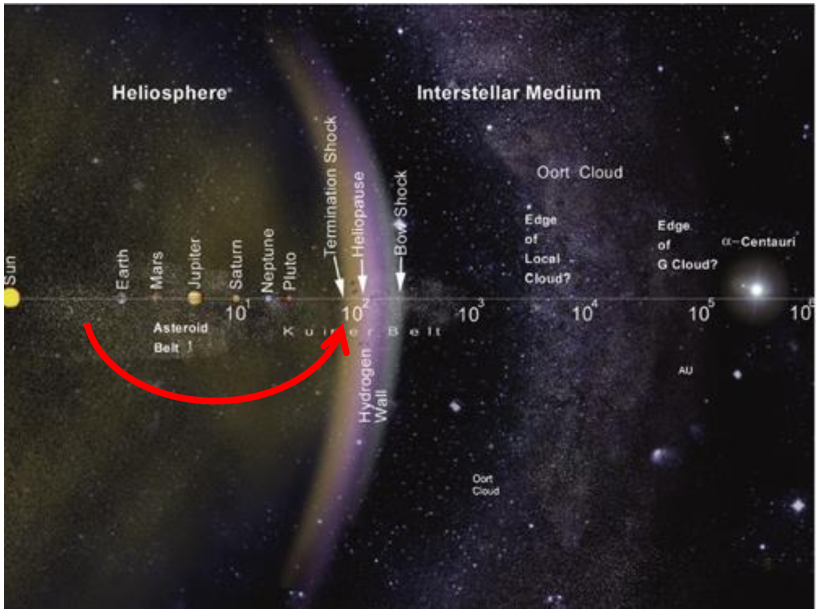


Figure 1. Solar system and interstellar distances.
(Image credit: JHU APL)

Team Infrastructure

Study Management

Ben Beers	ED04

Launch Vehicle

Ben Beers	ED04

Mission Analysis

Randy Hopkins	ED04
Dan Thomas	ED04

Spacecraft Propulsion

Dan Thomas	ED04
Andy Heaton	EV33

Ground Rules & Assumptions

Spacecraft	JPL / Cal Tech
Launch Vehicle	MSFC
Propulsion	MSFC

Subject Matter Expertise

Launch Vehicle	Barney Holt
	Jessica Garcia
MaSMi Hall thruster	Dan Thomas
E-Sail Propulsion	Bruce Wiegmann
	Andy Heaton
Solar Sail Propulsion	Les Johnson

Space Transportation Options

- In-space high-thrust stages:
  - 1 to 2 solid rocket motors (SRM) in SLS stack
- Onboard low-thrust Advanced Propulsion Systems (APS):
  - MaSMi Hall thruster
  - Solar sail
  - E-Sail

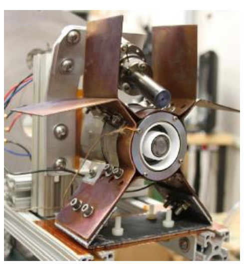


Figure 2. MaSMi Hall thruster. (Image credit: UCLA)

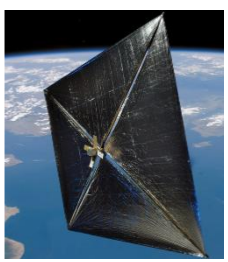


Figure 3. NanoSail-D solar sail. (Image credit: NASA Science News)

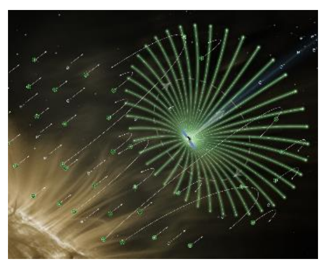


Figure 4. Electric sail (E-Sail). (Image credit: Szames)

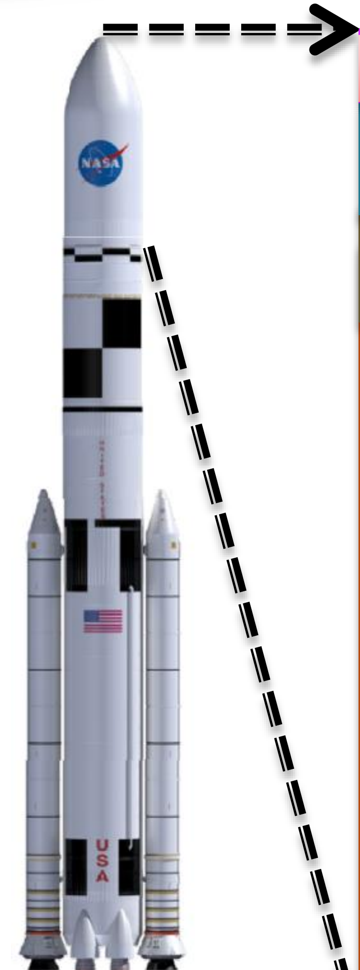
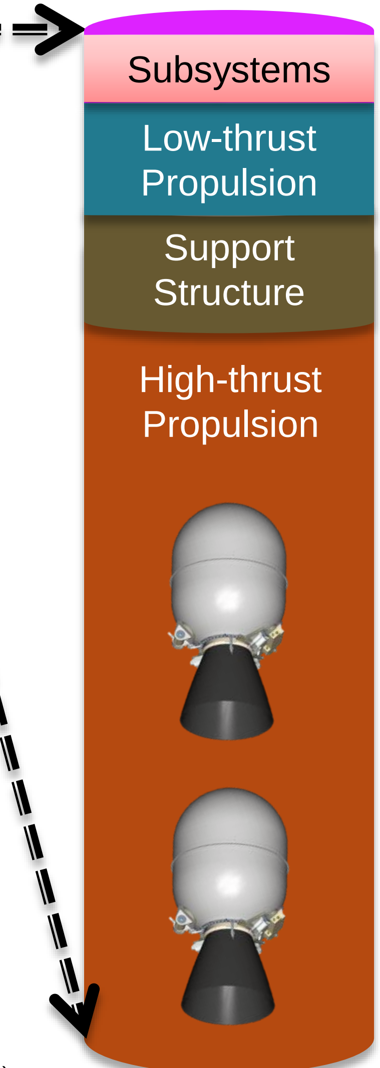



Figure 5. SLS Block 1B with EUS and 8.4m PLF. (Image credit: The Boeing Company)

Space Transportation Approaches Used to Compare Onboard Propulsion Options

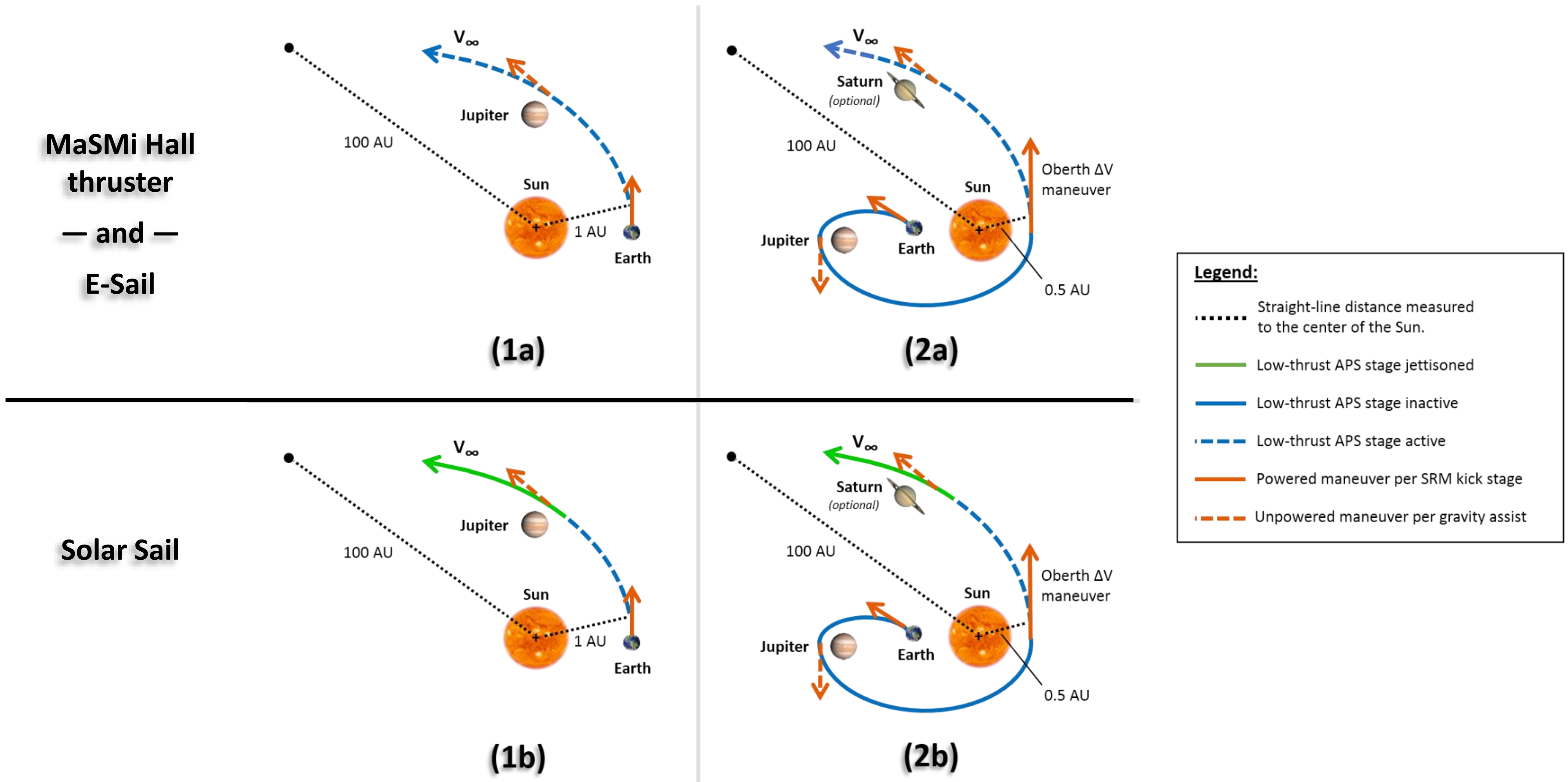


Figure 6. Mission trajectory profile options considered.

Ground Rules & Assumptions (GR&A)

Table 1. Highlighted system-level ground rules and assumptions.

Item	Assumption	Notes
Miss performance	100+ AU in 10 years	
Launch window	2025 – 2030	
Launch vehicle	SLS Block 1B + EUS + 8.4 m PLF	- C_3 energy for SLS Block 1B + EUS 5.0m Payload Fairing (PLF) was not released until after conclusion of study, so C_3 energy from 8.4m PLF configuration was used out of necessity. - Payload Attach Fitting (PAF) bookkept within net payload mass.
Spacecraft mass*	380 kg ($838\ lb_m$)	Includes all components except an onboard propulsion system.
Spacecraft heat shield†	300 kg ($661\ lb_m$)	Mass scaled from Solar Probe Plus heat shield (with conservatism).
Spacecraft power	450 W	Provided by an eMMRTG

* Mass includes all components except onboard low-thrust propulsion systems.

† Mass scaled from that of Solar Probe Plus heat shield.

Figure 7. SLS Block 1B with EUS and 8.4m PLF.
(Image credit: The Boeing Company)

Ground Rules & Assumptions (GR&A)
(cont.)

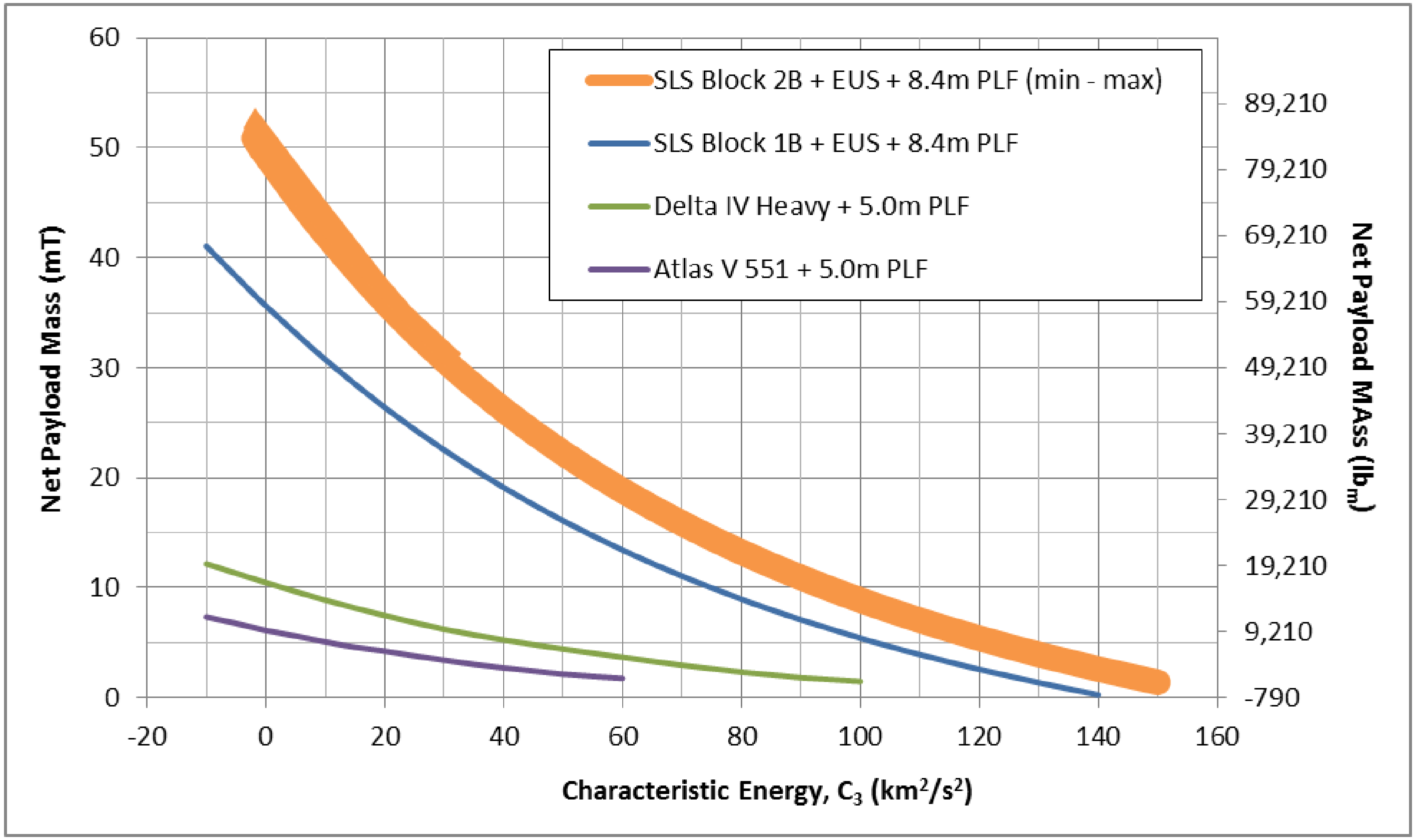


Figure 8. C_3 Energies for SLS and other large launch vehicles. [1, 2]

Ground Rules & Assumptions (GR&A)
(cont.)

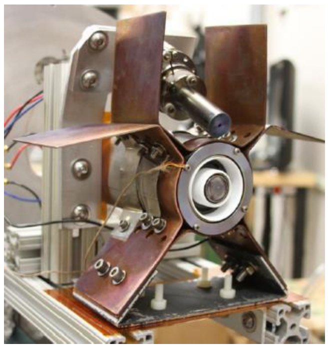


Figure 9. MaSMi Hall thruster.
(Image credit: UCLA)

Table 2. MaSMi Hall thruster GR&A.

Item	Description
Maximum lifetime	50,000 hours
Thrust	19 mN (0.004 lb_f)
Specific Impulse, I_{sp}	1,870 sec

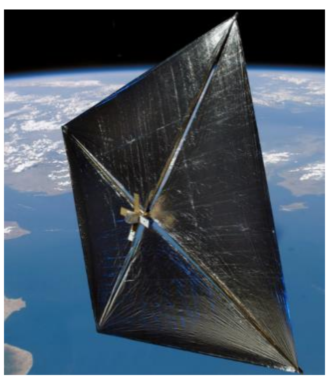


Figure 10. NanoSail-D solar sail.
(Image credit: NASA Science News)

Table 3. Solar sail GR&A.

Item	Description	
Reflectivity	0.91	
Minimum thickness	2.0 μm	
Maximum size (per side)	200 m (656 ft)	
Sail material	CP1	
Aerial density *	3 g/m^2	10 g/m^2
Characteristic acceleration	0.426 mm/s^2	0.664 mm/s^2
System mass	120 kg (265 lb_m)	400 kg (882 lb_m)

* Assumes technology development. Current technology is approximately 25 g/m^2.

Electric Sail:
Concept of Operations & GR&A

- Wires deployed from main spacecraft bus while spacecraft rotates to keep wires taut.
- Electron gun used to keep spacecraft and wires in high positive potential.
- Positive ions in solar wind repulsed by the field and thrust is generated.

Table 4. E-Sail GR&A.

Item	Description	
System mass	120 kg (265 lb_m)	
Wire material (density)	Aluminum (2,800 kg/m^3)	
Wire diameter (gauge)	0.127 mm (36 gauge)	
Characteristic acceleration	1 mm/s^2	2 mm/s^2
Tether quantity	10	20
Individual tether length	20 km (12.4 mi)	20 km (12.4 mi)

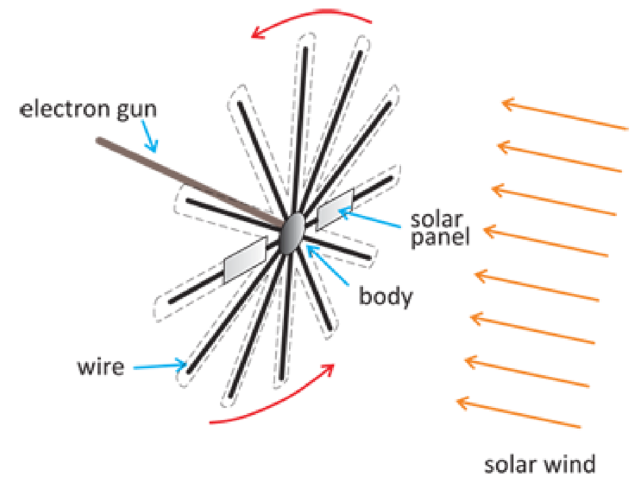
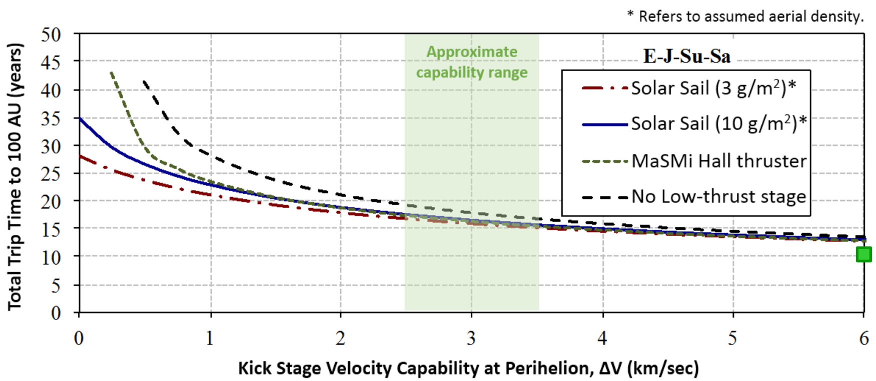


Figure 11. Cartoon schematic of E-Sail propulsion technology.
(Image credit: nextBIGFuture.com)

◆ Earth-Jupiter-Sun-Saturn trajectory:

Figure 12

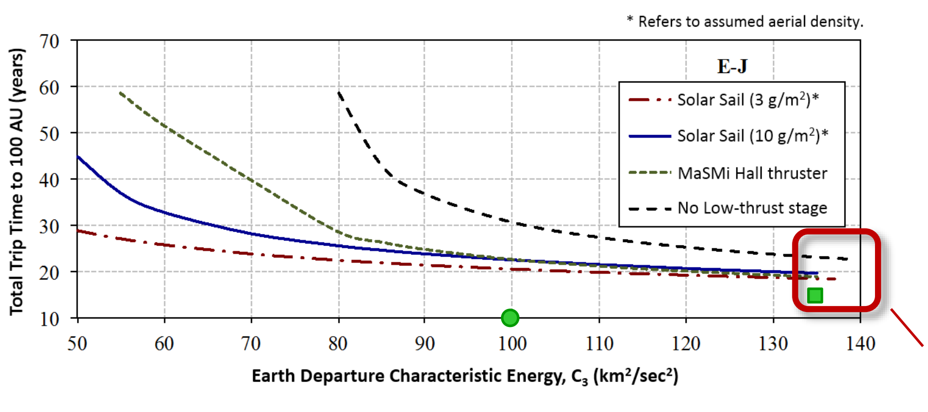


E-Sail Capability: *(also see p. 11)*

- ➢ 9.9 years
  - $\Delta V = 7$ km/s
  - 2 mm/s^2
- ■ 10.9 years
  - $\Delta V = 6$ km/s
  - 1 mm/s^2

◆ Earth-Jupiter trajectory:

Figure 13



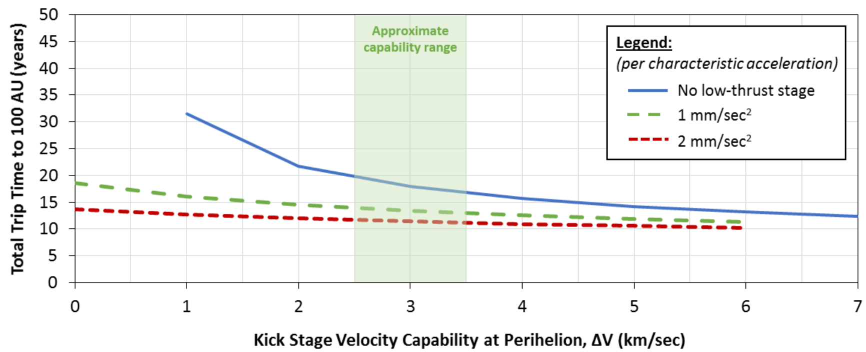
E-Sail Capability: *(also see p. 11)*

- ● 9.9 years
  - $C_3 = 100$ km^2/s^2
  - 2 mm/s^2
- ■ 12.5 years
  - $C_3 = 135$ km^2/s^2
  - 1 mm/s^2

Comparative Results (E-Sail only)
(cont.)

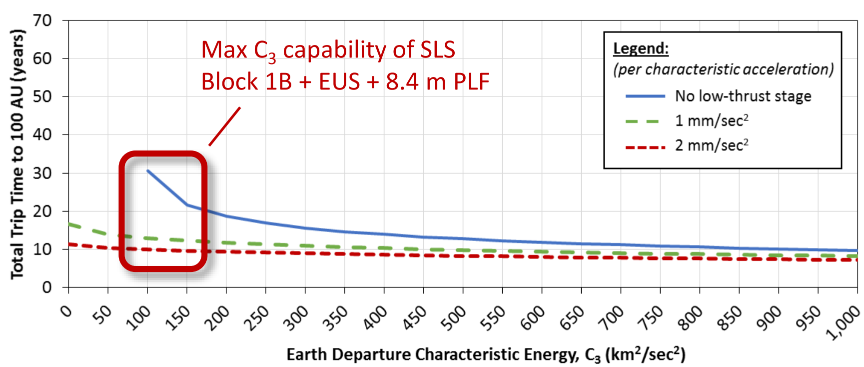
- Earth-Jupiter-Sun-Saturn trajectory:

Figure 14



- Earth-Jupiter trajectory:

Figure 15



Additional Payload Insight

Total Payload Mass:

5,699 kg (12,564 lb_m)	**6,470 kg (14,263 lb_m)**	**7,742 kg (17,068 lb_m)** or	**7,740 kg (17,064 lb_m)**

Including:

- Spacecraft
- Low-thrust stage
- Heat shield
- SRM kick stage(s)

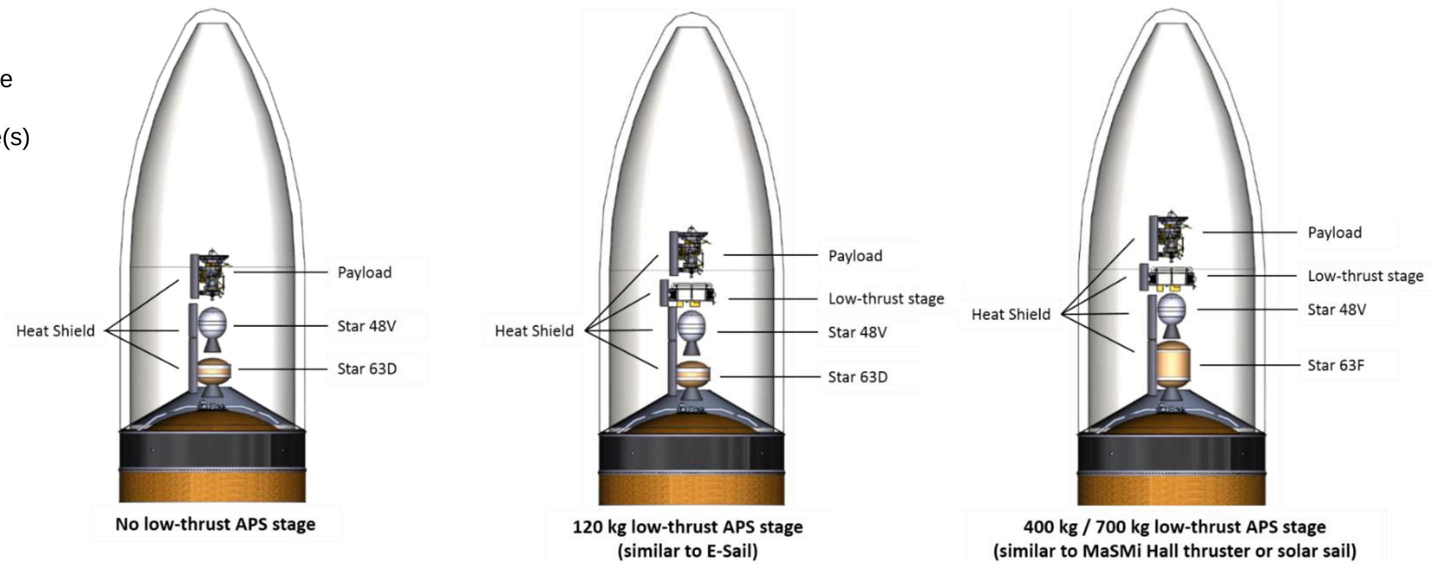


Figure 16. Approximate envelope of payload and SRM kick stages inside SLS 8.4 m PLF per stowed Voyager configuration volume.

Table 5. SRM kick stages chosen for the *E-Ju-Su-Sa* trajectory option.

Low-thrust APS Mass	Impulsive Burn 1 (Earth departure)	Impulsive Burn 2 (Perihelion)	Notes
0 kg (0 lb_m)	Star 63D	Star 48V	Star 63D – 20% of propellant offloaded.
120 kg (265 lb_m)	Star 63D	Star 48V	No propellant offloaded for either SRM
400 kg (882 lb_m)	Star 63F	Star 48V	Star 48V – 5% of propellant offloaded.
700 kg (1,543 lb_m)	Star 63F	Star 48V	Star 48V – 20% of propellant offloaded.

Future Work / Concerns

- **Future work:**
  - Analyze trajectories employing an ion thruster propulsion system.
  - Consider C_3 energy curve for SLS Block 1B + EUS + 5.0 m PLF.

- **Concerns:**
  - Survival of the heat shield closest to the SRM nozzle burning during the impulsive maneuver at perihelion.

REFERENCES

References

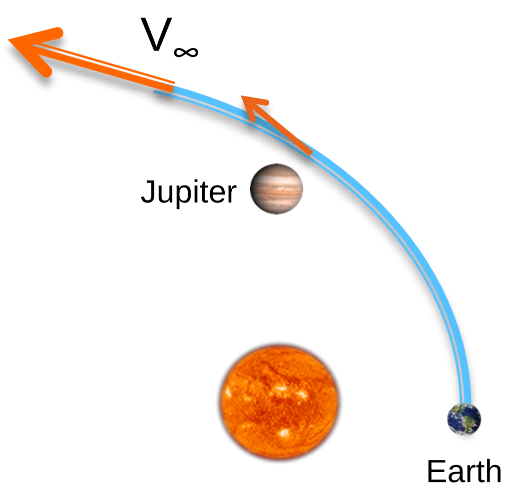
1) "Space Launch System (SLS) Program Mission Planner's Guide (MPG) Executive Overview," SLS-MNL-201, Version 1, NASA MSFC, August 22, 2014.
2) Donahue, B., Sigmon, S., "The Space Launch System Capabilities with a New Large Upper Stage," AIAA 2013-5421, Boing Defense, Space & Security (BDS), 2013.
3) Conversano, R. W., Goebel, D. M., Hofer, R. R., Matlock, T. S., Wirz, R. E., "Magnetically Shielded Miniature (MaSMi) Hall Thruster," University of California, Los Angeles (UCLA), Department of Mechanical and Aerospace Engineering Plasma and Space Propulsion Laboratory.
4) Quarta, A. A. and Mengali, G., "Electric Sail Mission Analysis for Outer Solar System Exploration," University of Pisa, Pisa, Italy.
5) McNutt, Jr., R. L., "Enabling Interstellar Probe with Space Launch System (SLS)," IAC-14-D.4.4.2, 65th International Astronautical Congress (IAC), Johns Hopkins University (JHU) Advanced Physics Laboratory (APL) and The Boeing Company, page 6, 2014.
6) "Enhanced Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) Concept," NASA, URL: https://solarsystem.nasa.gov/rps/docs/eMMRTG_onepager_LPSC20140317.pdf [cited 2 January 2015].

Acronyms & Symbols

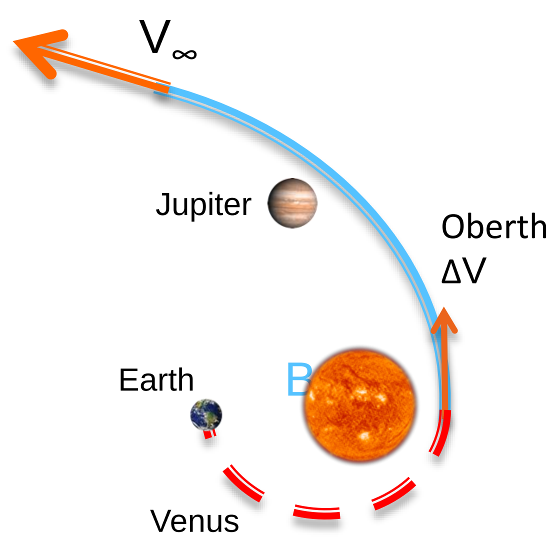
APL	Applied Physics Laboratory
APS	Advanced Propulsion System
AU	Astronomical Unit
BDS	Boeing Defense, Space and Security
C_3	Characteristic energy
eMMRTG	Enhanced Multi-Mission Radioisotope Thermoelectric Generator
E	Earth
E-Sail	Electric Sail
EUS	Exploration Upper Stage
GR&A	Ground rules & Assumptions
IAC	International Astronautical Congress
JAXA	Japanese Aerospace eXploration Agency
JHU	Johns Hopkins University
JGA	Jupiter Gravity Assist
JPL	Jet Propulsion Laboratory
Ju	Jupiter
MaSMi	Magnetically Shielded Miniature [hall thruster]
MPG	Mission Planner's Guide
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
PAF	Payload Attach Fitting
PLF	Payload Fairing
PMF	Propellant Mass Fraction
Sa	Saturn
SLS	Space Launch System
SRM	Solid Rocket Motor
Su	Sun
UCLA	University of California, Los Angeles

BACKUP

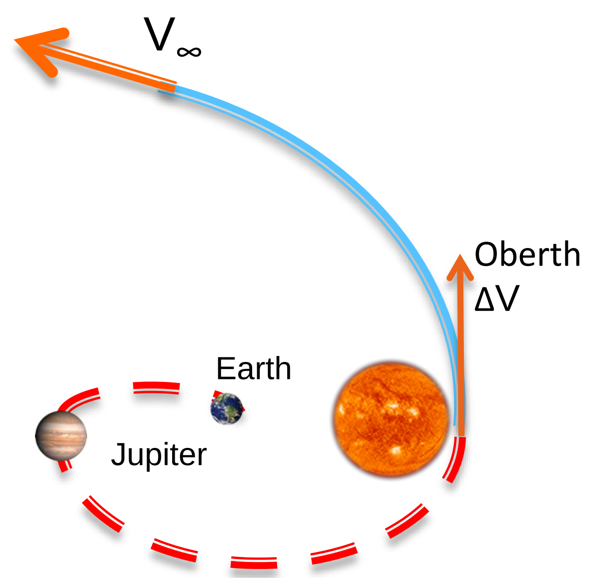
Space Transportation Approaches Used to Compare Onboard Propulsion Options



Direct escape using SLS, Jupiter Gravity Assist (JGA) and onboard in-space propulsion system.



Sun dive using SLS for Oberth maneuver and onboard in-space propulsion system.



JGA to Sun dive using SLS and onboard in-space propulsion system.

Additional GR&As

- Optimized solar sail and electric propulsion trajectories to 100 AU
  - Two-dimensional
  - Sail angle (and electric propulsion thrust angle) maximizes orbital energy gain
  - Payload mass = 380 kg
  - Sail parameters:
    - Reflectivity = 0.91
    - Square sail: side = 200 m
    - Sail aerial density trades:

Aerial density = 10 g/m^2

Characteristic accleration = 0.4256 mm/s^2

Sail mass = 400 kg

Total spacecraft mass = 780 kg

Aerial density = 3 g/m^2

Characteristic accleration = 0.6639 mm/s^2

Sail mass = 120 kg

Total spacecraft mass = 500 kg

  - MaSMi (assume maximum lifetime = 50,000 hrs)
    - Assume powered by 450 W eMMRTG
    - Total spacecraft initial mass = 800 kg
    - Thrust = 19 mN
    - I_{sp} = 1870 s

Additional GR&As
(cont.)

- Two mission cases
  - *E-J-Su-Sa*
    - Earth to Jupiter with gravity assist (at 18.72 Jupiter radii) to reduce perihelion to 11 solar radii (~ 0.05 AU).
      - Time from Earth to perihelion = 2.97 years
    - Kick stage performs ΔV at perihelion
    - Drop stage and heat shield and deploy sail at 0.5 AU (after perihelion passage)
    - Drop sail before Saturn flyby
      - Assume circular Saturn orbit at 9.583 AU
      - Flyby radius = 2.67 Saturn radii
  - *E-J*
    - Depart Earth with enough energy to perform Jupiter gravity assist
      - Initial velocity set by given C3 (SLS Block 1B + EUS + 8.4m PLF)
      - Assume circular Jupiter orbit at 5.203 AU
      - Flyby radius = 4.89 Jupiter radii
    - Deploy sail at 1 AU
    - Drop sail before Jupiter flyby

- Departure velocity at Earth:
  - Optimal split between SLS and kick stage depends on kick stage PMF.
  - Plot shows that for a PMF of 0.90, optimal split is to let SLS insert the payload into an escape trajectory with C_3 of 67.766 km^2/s^2.

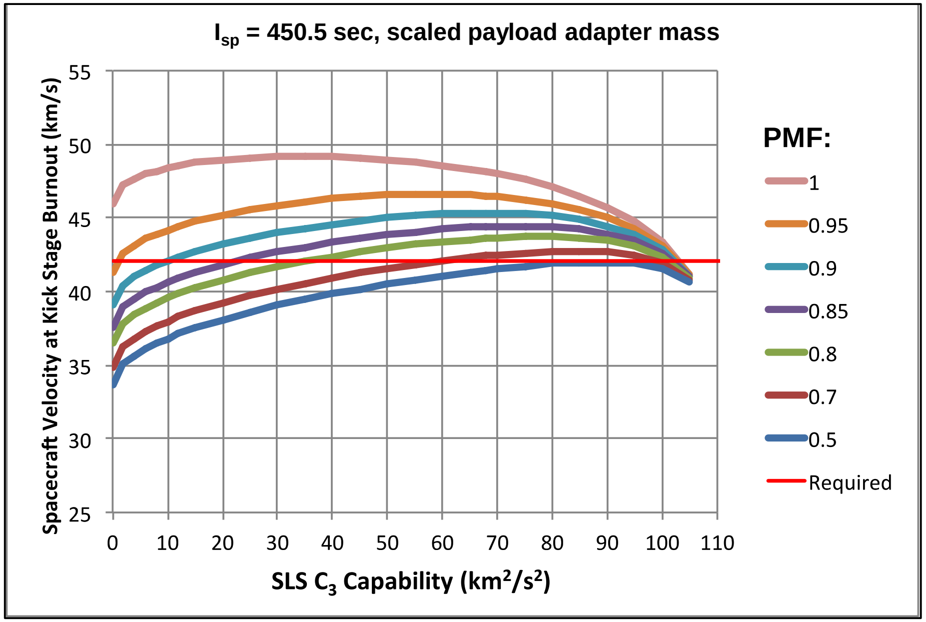


Figure 17. Spacecraft velocity at kick stage burnout for various PMF values.

Previous Interstellar Probe Study
(cont.)

- Why choose Jupiter?
  - It's huge!
  - It's closer than Saturn, so (1) the assist occurs sooner and (2) the spacecraft is going faster, sooner.
  - Table 6 compares possible gravity assist equivalent ΔV values.
    - Data is for skimming the planet's surface and are therefore for comparison only. Data only provides magnitude of ΔV available.
    - Perihelion before flyby is 1 AU for all cases.
    - Circular planetary orbits assumed.

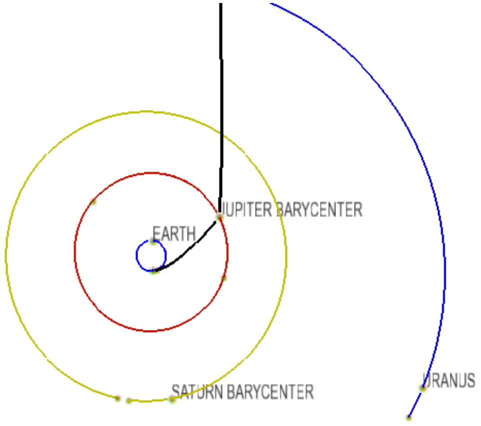


Figure 18. Jupiter trajectory plot from Copernicus.

Table 6. Estimate of maximum ΔV from Planetary Flyby.*

Planet	Earth Masses	Aphelion before assist (AU)		
		10	30	100
Jupiter	318	22.5	27.6	29.0
Saturn	95	11.4	19.3	20.8
Uranus	15	N/A	11.9	14.0
Neptune	17	N/A	N/A	12.7

*** NOTE: A portion of the ΔV goes into turning the trajectory.**

- Multiple gravity assist trajectories:
  - Based on planetary alignment at time of launch, only multi-body gravity assist available with gas giants.
  - Probable Jupiter-Saturn opportunity in mid 2030's, but date is out of scope of this analysis.

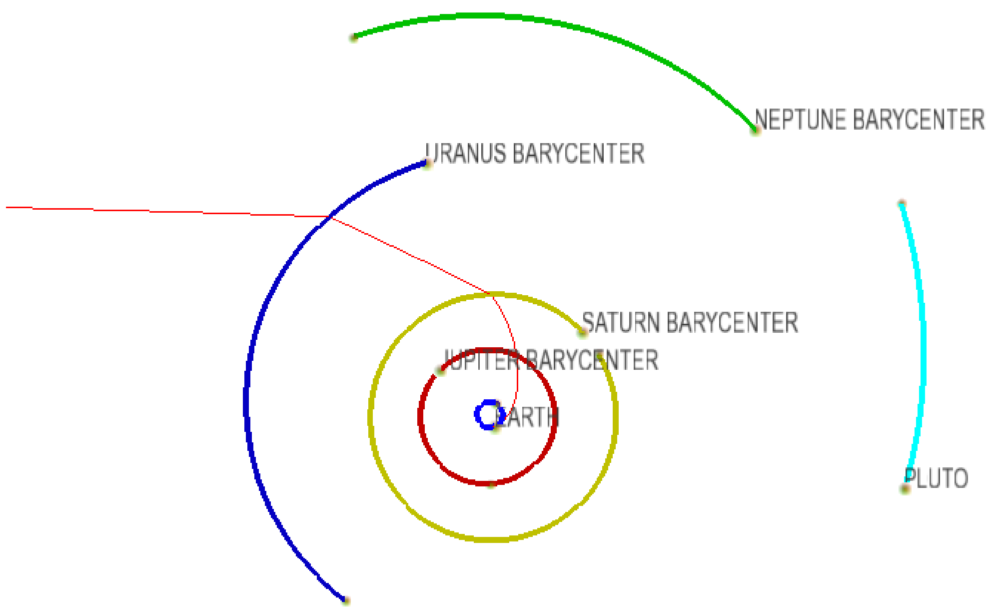
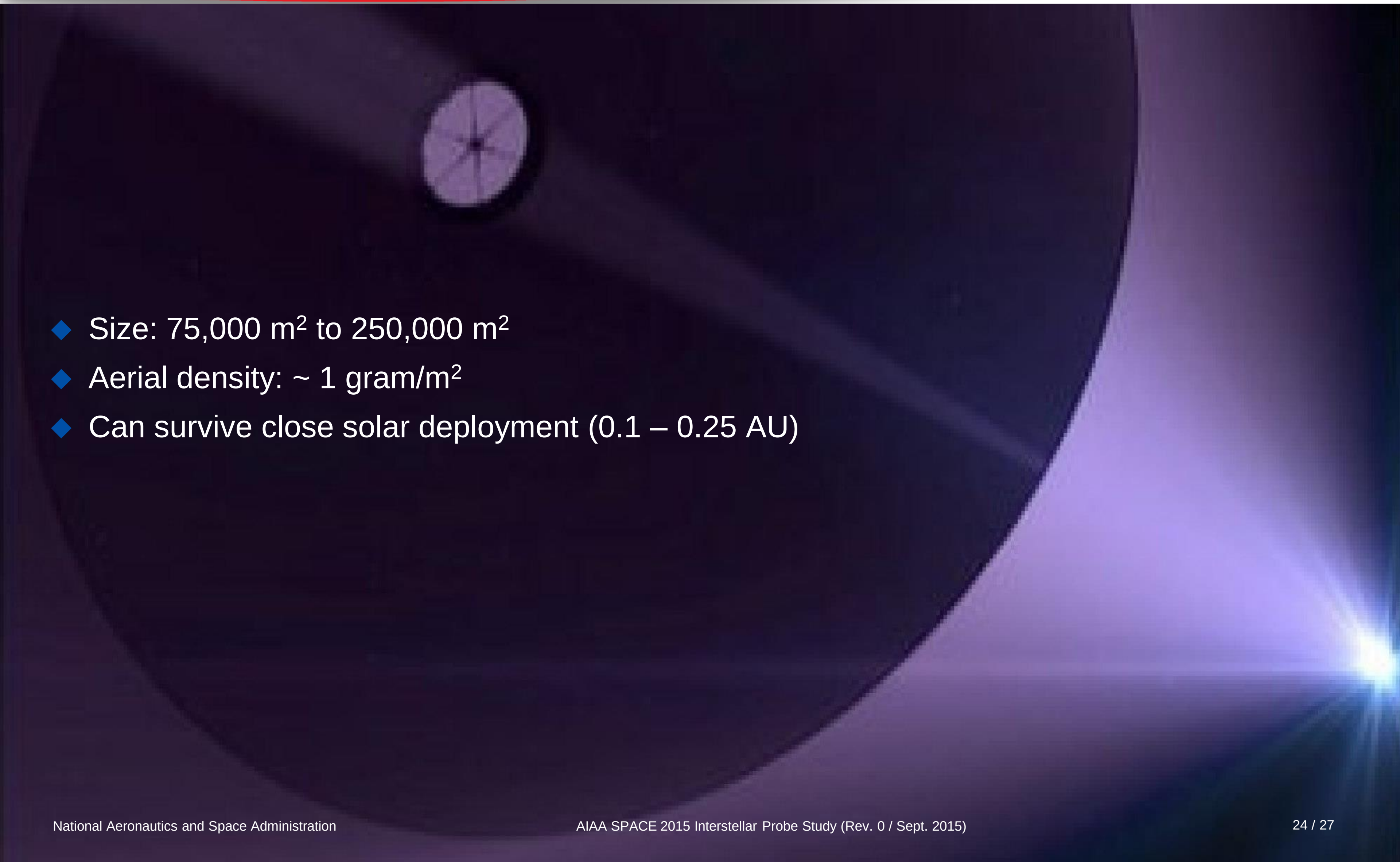


Figure 19. Saturn-Uranus trajectory plot from Copernicus.

The Sails We Need

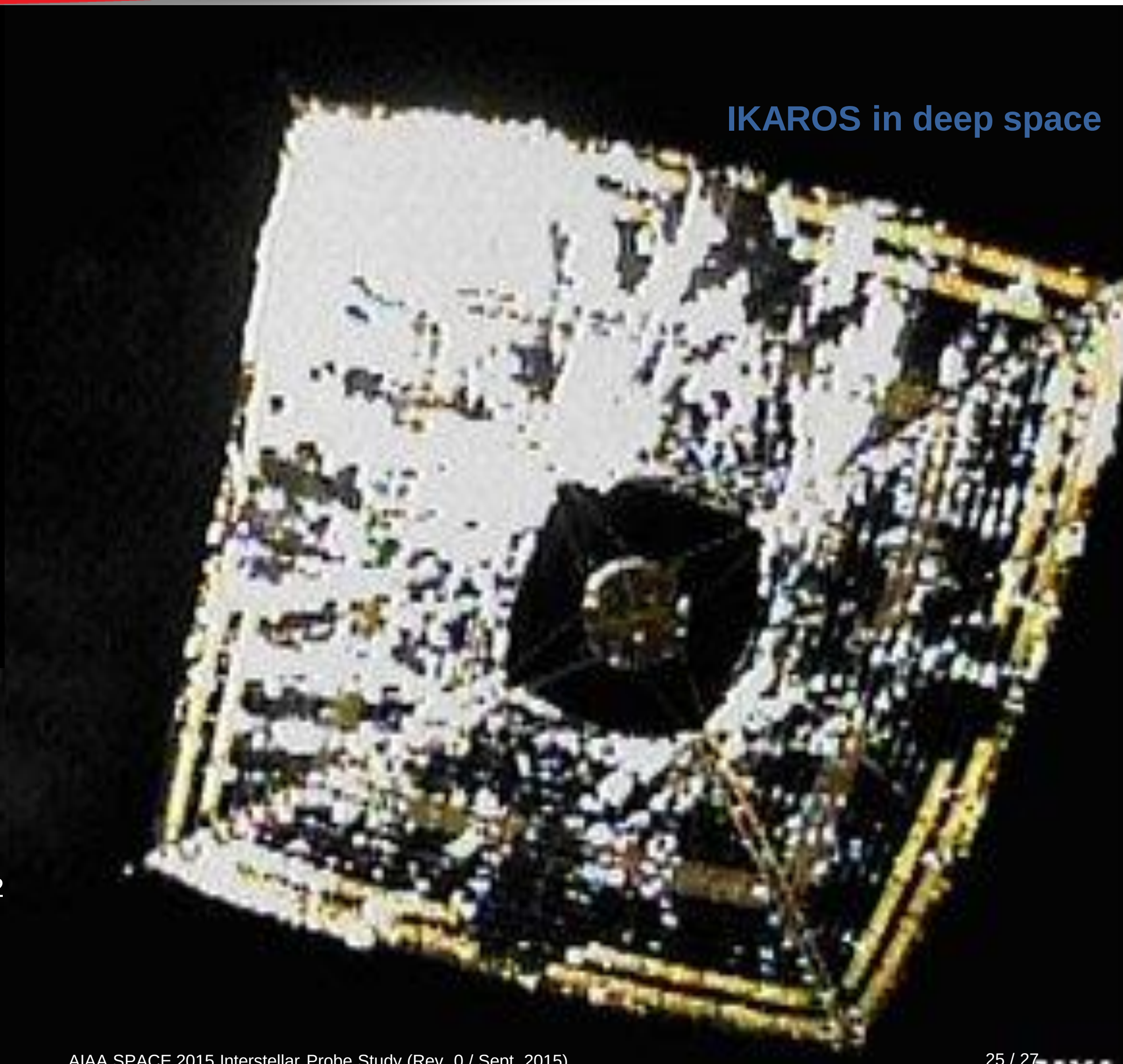


- Size: 75,000 m^2 to 250,000 m^2
- Aerial density: ~ 1 gram/m^2
- Can survive close solar deployment (0.1 – 0.25 AU)

The Sails We Have

NanoSail-D as seen from the ground

IKAROS in deep space



- Size: 100 m^2 to 200 m^2
- Aerial density: 25 – 300 gram/m^2
- Can survive 0.5 AU deployment

Electric Sail: Technical Justification

- Has the potential to fly payloads out of the ecliptic and into non-Keplerian orbits, place payloads in a retrograde solar orbit, flyby missions to terrestrial planets and asteroids and position instruments for off-Lagrange point space weather observation.
- Low mass / low cost propulsion system.
- Electric sail thrust extends deep into the solar system.
- Can be packaged in a small spacecraft bus.
- E-Sail = MSFC interplanetary CubeSat propulsion portfolio
  - Iodine drive, solar sails, green propellants

NASA