National Aeronautics and Space Administration

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

January 2015

Les Johnson / NASA MSFC / ED04

MSFC Advanced Concepts

www.nasa.gov

Mission Statement

Interstellar Probe Mission:

Trade and determine the best propulsion system for reaching 100 AU in 10 years:

- SLS only
- MaSMi Hall thruster
- Solar sail
- Electric sail (E-Sail)

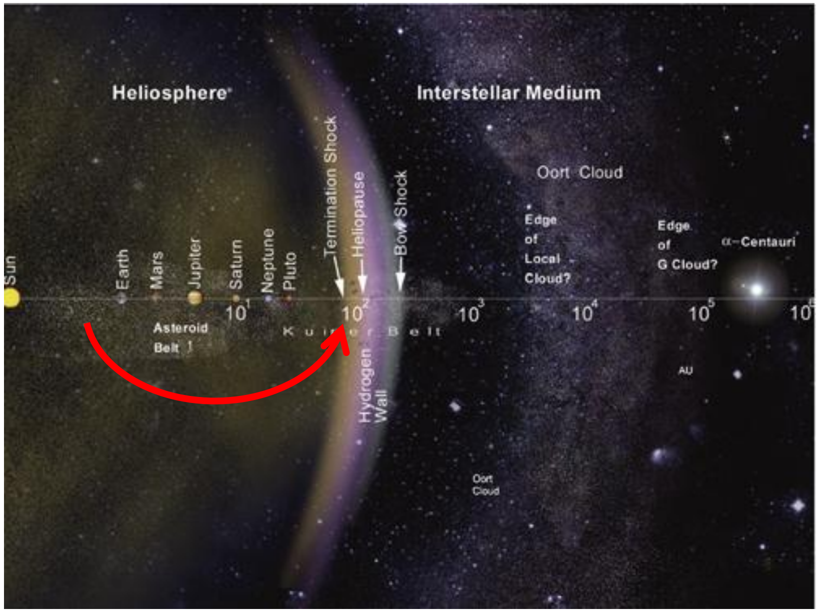


Figure 1. Solar system and interstellar distances. [1]

MSFC Team Architecture

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 Approaches Used to Compare Onboard Propulsion Options

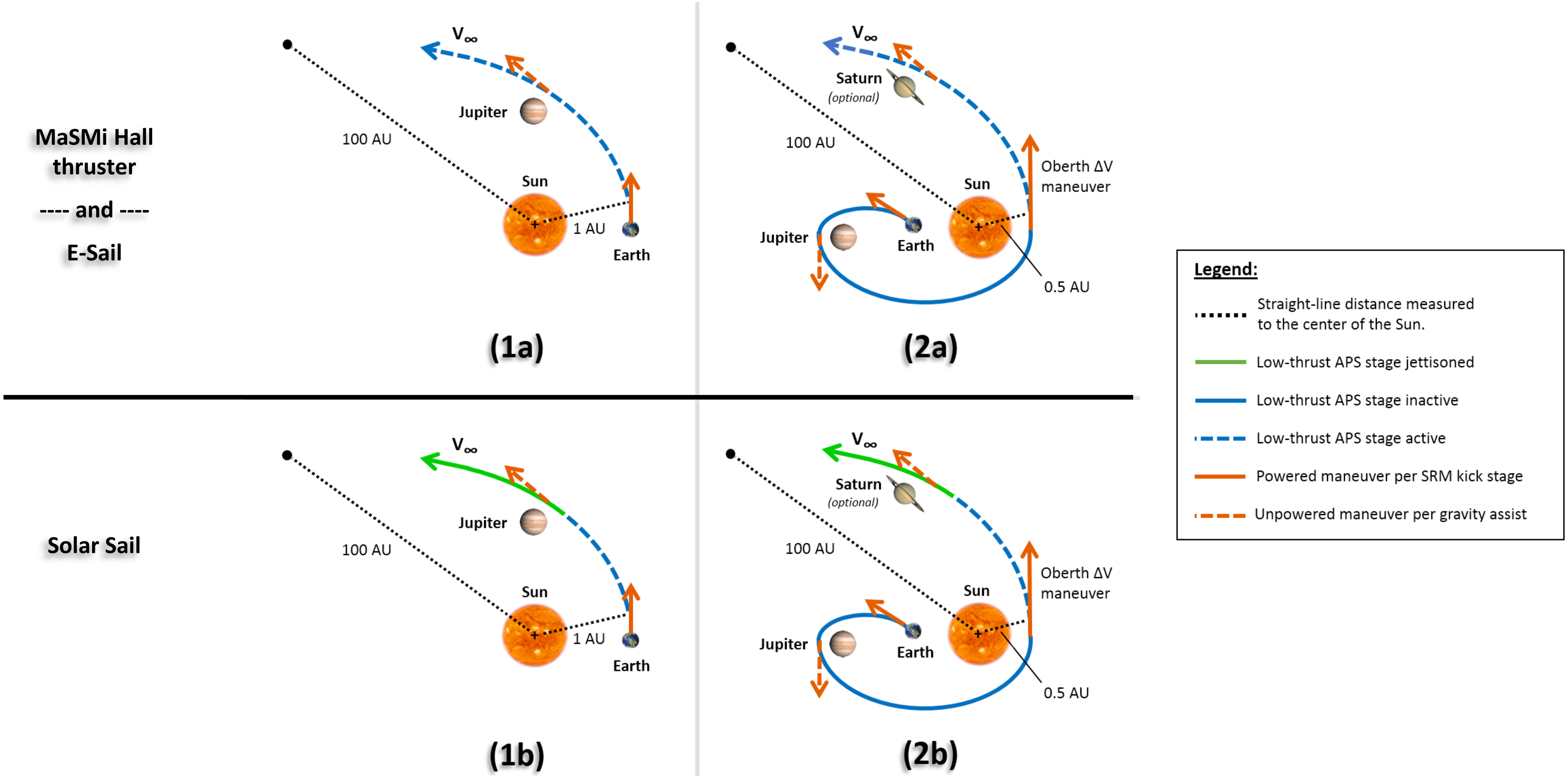


Figure 2. Mission trajectory profile options considered.

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

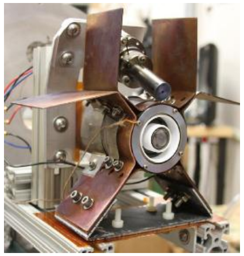


Figure 3. MaSMi Hall thruster. [2]

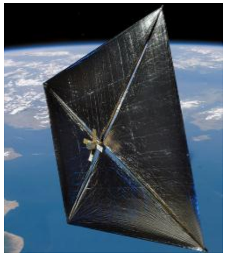


Figure 4. NanoSail-D solar sail. [3]

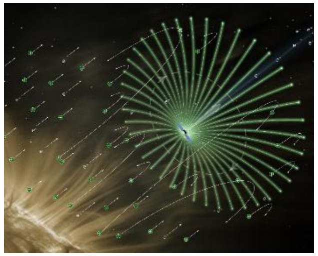


Figure 5. Electric sail (E-Sail). [4]

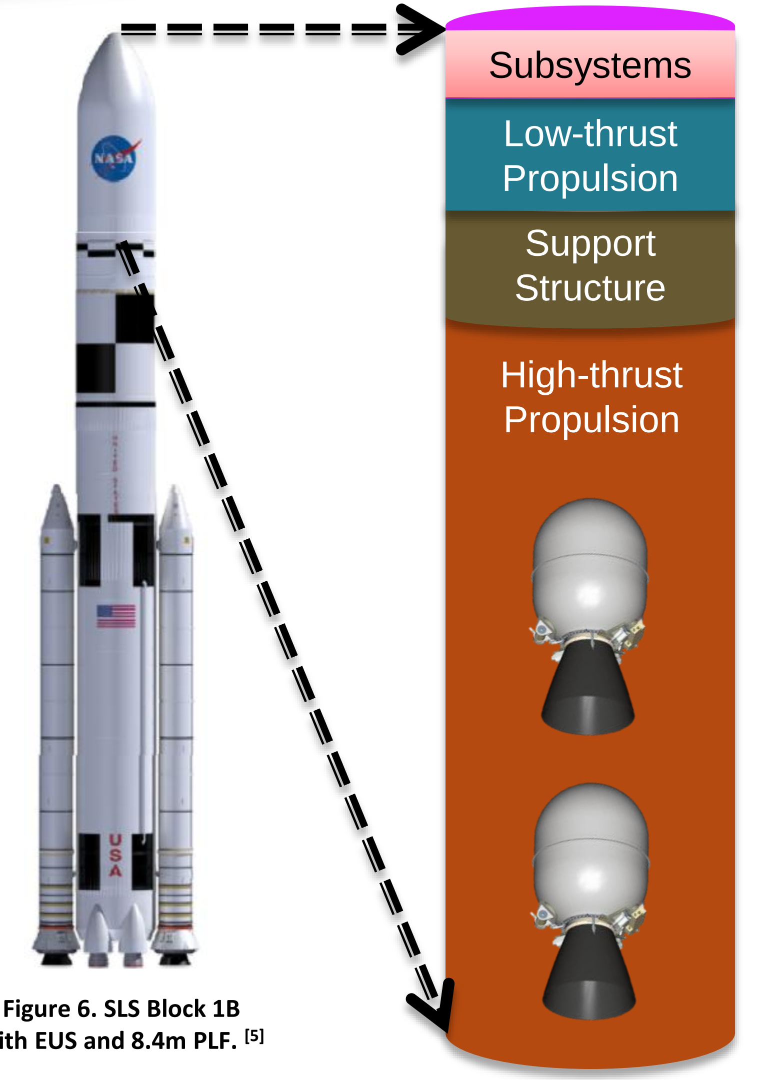


Figure 6. SLS Block 1B with EUS and 8.4m PLF. [5]

Additional Payload Insight

Total Payload Mass:

Including:

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

680 kg (1,499 lb_m)	800 kg (1,764 lb_m)	1,080 kg (2,381 lb_m) or 1,380 kg (3,042 lb_m)

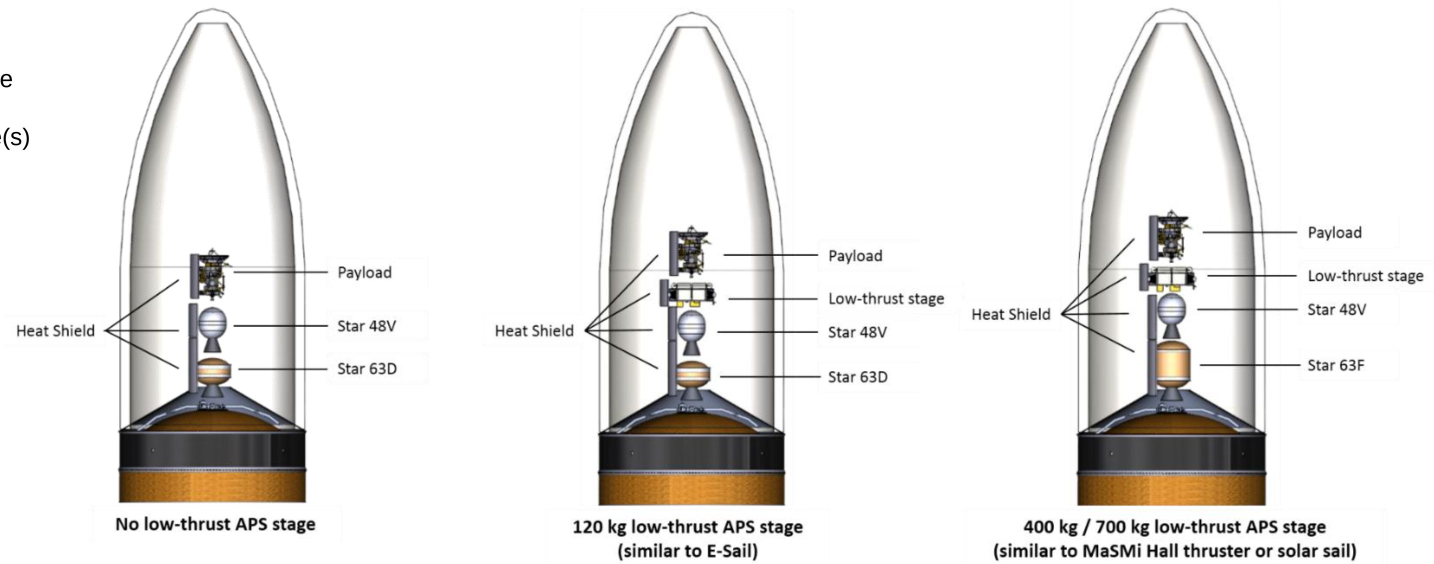


Figure 16. Approximate envelope of payload and SRM kick stages inside SLS 8.4 m PLF per stowed Voyager configuration volume.

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

Low-thrust Stage 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 63F	Star 48V	Star 48V– 5% of propellant offloaded.
400 kg (882 lb_m)	Star 63F	Star 48V	Star 48V– 20% of propellant offloaded.
700 kg (1,543 lb_m)	Star 63D	Star 48V	No propellant offloaded for either SRM

Ground Rules & Assumptions (GR&A)

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

Item	Assumption	Notes
Launch vehicle	SLS Block 1B + EUS + 8.4 m PLF	
Launch window	2025-2030	
Spacecraft mass	380 kg ($838\ lb_m$)	Includes all components except an onboard propulsion system.
Spacecraft power	450 W	Provided by an eMMRTG
Spacecraft heat shield	300 kg ($661\ lb_m$)	Mass scaled from Solar Probe Plus heat shield (with conservatism).

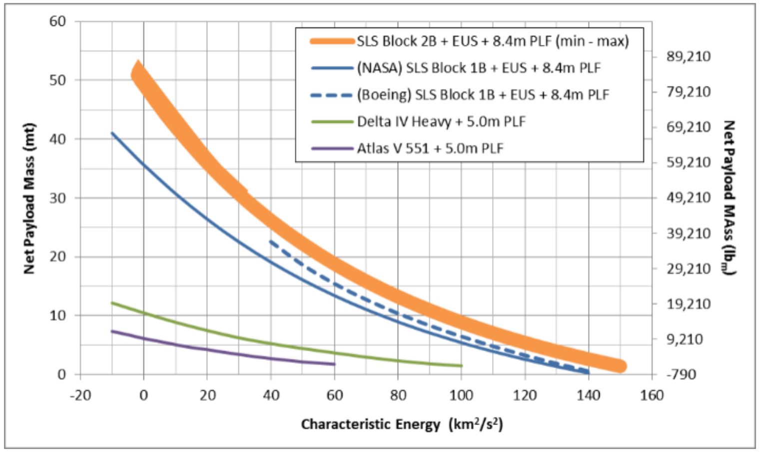


Figure 7. C3 Energies for SLS and other large launch vehicles. [5,6] * †

* C3 energy for SLS Block 1B + EUS + 5.0m PLF will not officially be released until Feb. 2015 timeframe, after the current PLF adapter study is completed; so, only 8.4m PLF C3 energies is currently being used for this study.

† Payload Attach Fitting (PAF) (i.e., payload adapter) is bookkept within net payload mass.

Figure 8. SLS Block 1B with EUS and 8.4m PLF. [5]

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

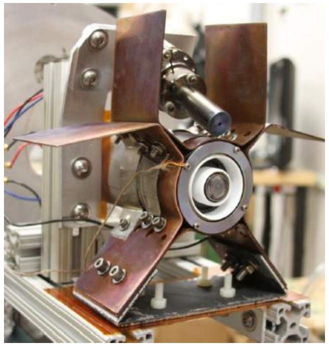


Figure 9. MaSMi Hall thruster. [2]

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

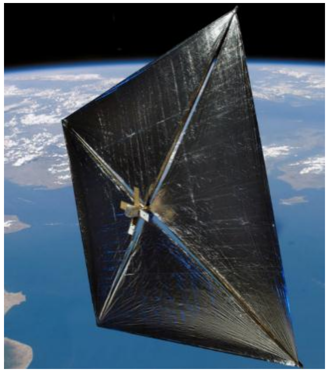


Figure 10. NanoSail-D solar sail. [3]

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	400 kg (882 lb_m)	120 kg (265 lb_m)

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

Electric Sail:
Concept of Operations & GR&A

- Wires are deployed from the main spacecraft bus and the spacecraft rotates to keep wires taut.
- An electron gun is used to keep the spacecraft and wires in a high positive potential.
- Positive ions in the solar wind are 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)

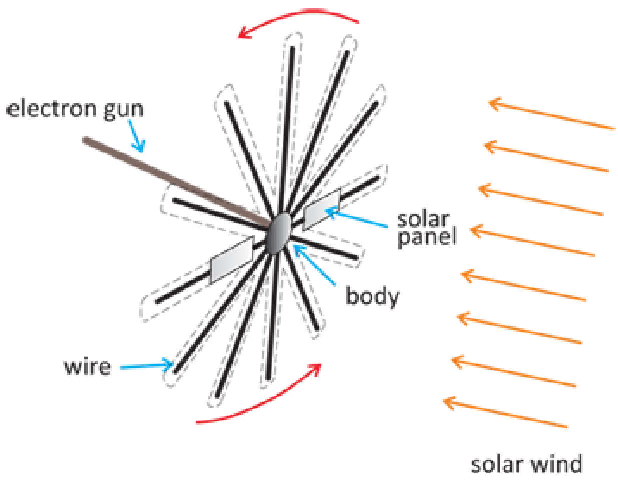
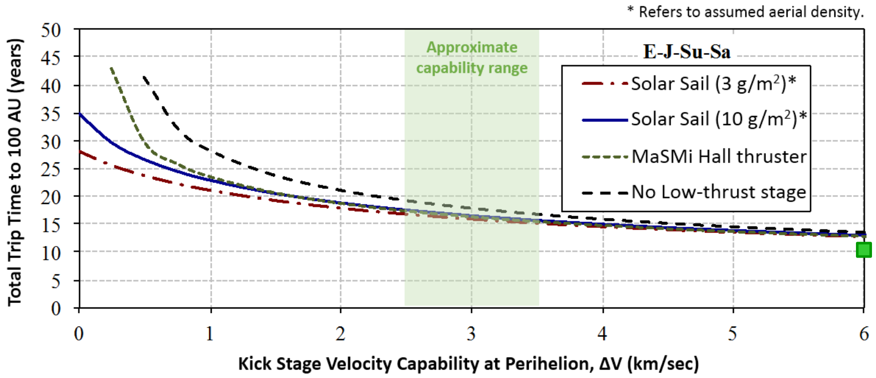


Figure 11. Cartoon schematic of E-Sail propulsion technology. [7]

Comparative Results

◆ Earth-Jupiter-Sun-Saturn trajectory:

Figure 12

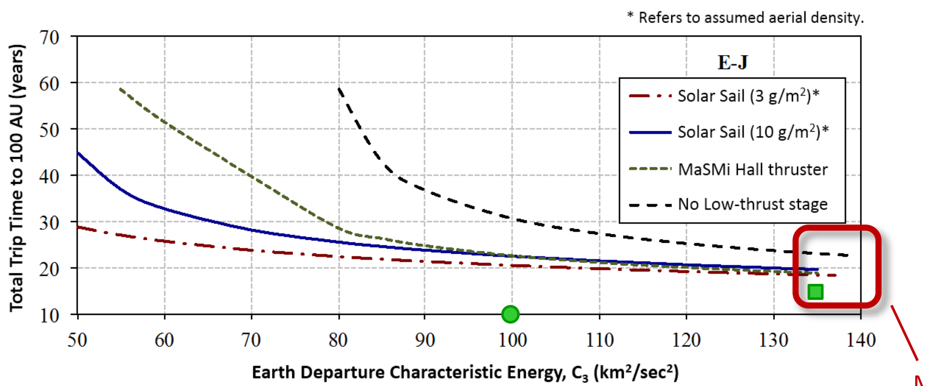


E-Sail Capability: *(see p. 11)*

- 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



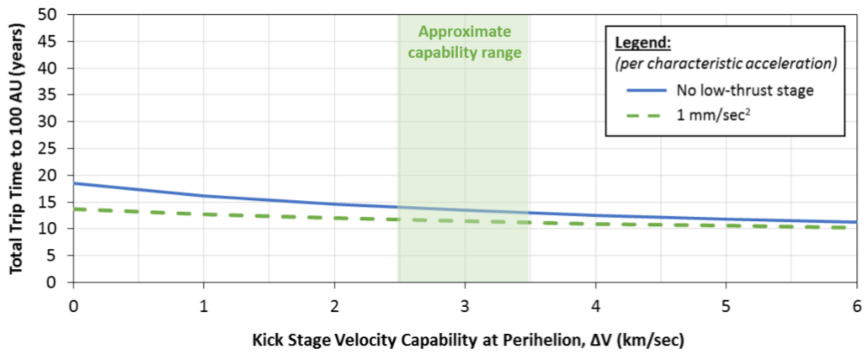
Max C_3 capability of SLS Block 1B + EUS + 8.4 m PLF

E-Sail Capability: *(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

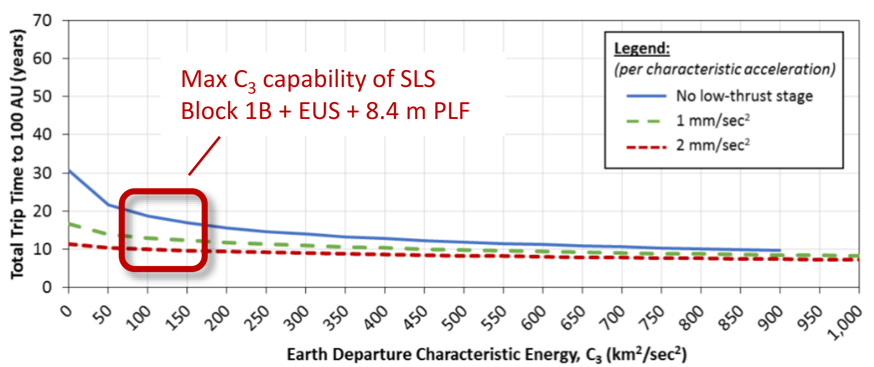
- Earth-Jupiter-Sun-Saturn trajectory:

Figure 14



- Earth-Jupiter trajectory:

Figure 15



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 (further than a solar sail).
- Can be packaged in a small spacecraft bus

Future Work / Concerns

- **Future work:**
  - Analyze trajectories employing an ion thruster propulsion system.
  - Consider C3 energy curve for SLS Block 1B + EUS + 5.0 m PLF when data becomes available *(estimated for end of Feb. 2015)*.

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

REFERENCES

References

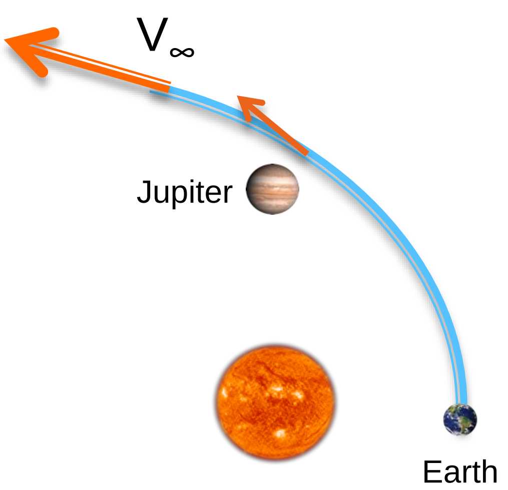
1) "Innovative Interstellar Explorer – A Mission to Interstellar Space," NASA JPL and JHU APL, referenced November 2014. http://interstellarexplorer.jhuapl.edu/index.php
2) Conversano, R. W., Goebel, D. M., Hofer, R. R., Matlock, T. S., Wirz, R. E., "Magnetically Shielded Miniature (MaSMi) Hall Thruster," University of California, Los Angeles (UCLA), Department of Mechanical and Aerospace Engineering Plasma and Space Propulsion Laboratory.
3) Phillips, T., "Solar Sail Stunner," NASA Science News, January 24, 2011. http://science.nasa.gov/science-news/science-at-nasa/2011/24jan_solarsail/
4) Szames, A., "Electric solar wind sail spacecraft propulsion," Kumpula Space Center, 2006. http://www.electric-sailing.fi/
5) Donahue, B., Sigmon, S., "The Space Launch System Capabilities with a New Large Upper Stage," AIAA 2013-5421, Boing Defense, Space & Security (BDS), 2013.
6) "Space Launch System (SLS) Program Mission Planner's Guide (MPG) Executive Overview," SLS-MNL-201, Version 1, NASA MSFC, August 22, 2014.
7) Wang, B., "Fast Electric space sail Uranus entry probe mission," nextBIGFuture.com, January 17, 2014. http://nextbigfuture.com/2014/01/fast-electric-space-sail-uranus-entry.html
8) Quarta, A. A. and Mengali, G., "Electric Sail Mission Analysis for Outer Solar System Exploration," University of Pisa, Pisa, Italy.
9) Hopkins, R., "Interstellar Probe Preliminary Mission Analysis, Version 2" (presentation), NASA MSFC ED04.

Acronyms

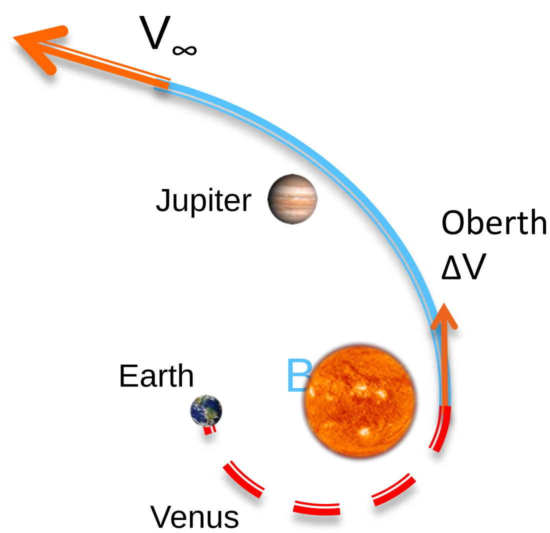
AU	Astronomical Unit
eMMRTG	Enhanced Multi-Mission Radioisotope Thermoelectric Generator
E-Sail	Electric Sail
EUS	Exploration Upper Stage
JGA	Jupiter Gravity Assist
JPL	Jet Propulsion Laboratory
MaSMi	Magnetically Shielded Miniature [hall thruster]
MPG	Mission Planner's Guide
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
PAF	Payload Attach Fitting
PLF	Payload Fairing
PMF	Propellant Mass Fraction
SLS	Space Launch System
SRM	Solid Rocket Motor

BACKUP MATERIAL

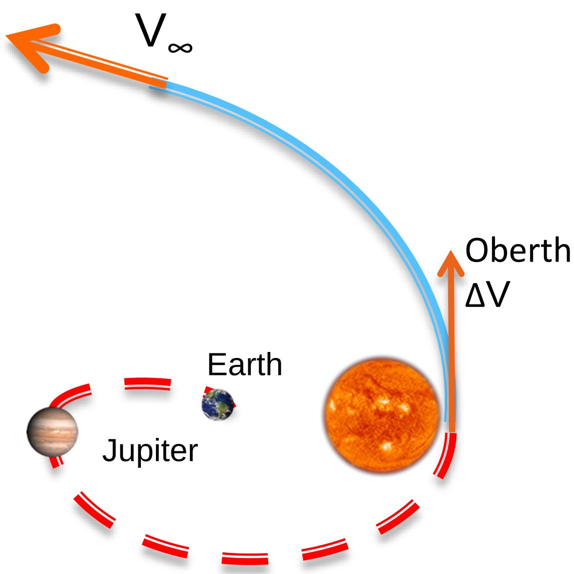
Space Transportation Approaches Used to Compare Onboard Propulsion Options



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 EP thrust angle) maximizes orbital energy gain
  - Payload mass = 380 kg
  - Sail parameters:
    - Reflectivity = 0.91
    - Square sail: side = 200 m
    - Sail areal density trades:
      - ***Areal density = 10 g/m^2***
        - Characteristic accleration = 0.4256 mm/s^2
        - Sail mass = 400 kg
        - Total spacecraft mass = 780 kg
      - ***Areal 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
    - Isp = 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 = 3.26 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

Previous Interstellar Probe Study

- Departure Velocity at Earth: [9]
  - The optimal split between SLS and the kick stage depends on the kick stage PMF.
  - Plot shows that for a PMF of 0.90, the optimal split is to let SLS insert the payload into an escape trajectory with C3 of 67.766 km^2/s^2.

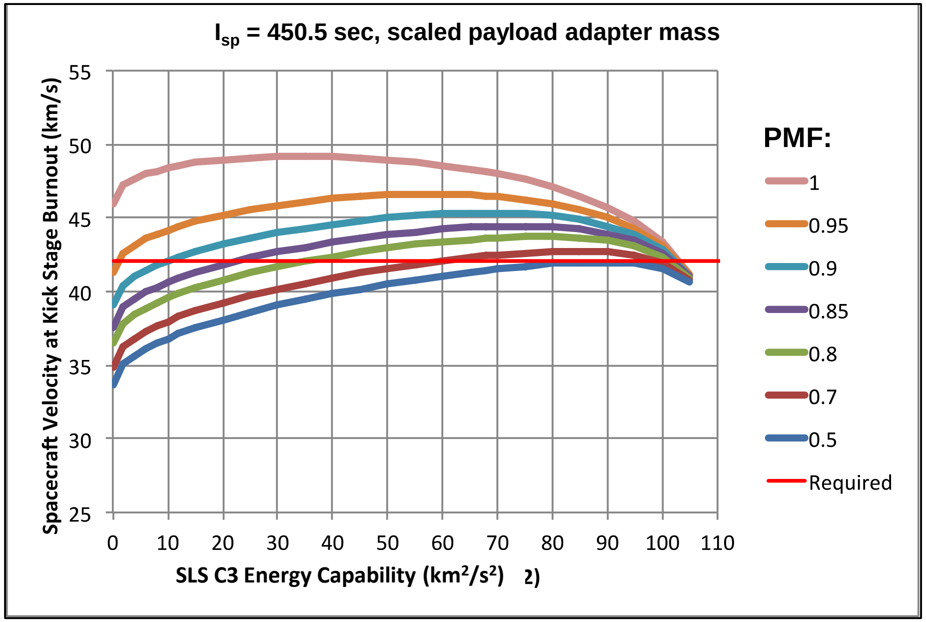


Figure 17. Spacecraft velocity at kick stage burnout for various PMF values.

- Why choose Jupiter? [9]
  - It's HUGE!
  - It's closer than Saturn, so the assist occurs sooner, and you are going faster sooner.
  - Table below right compares the possible gravity assist equivalent ΔV values.
    - These are skimming the planet's surface, and are for comparison only, just to give an idea of the magnitude of the ΔV available.
    - Perihelion before flyby is 1 AU for all cases.
    - Circular planetary orbits.

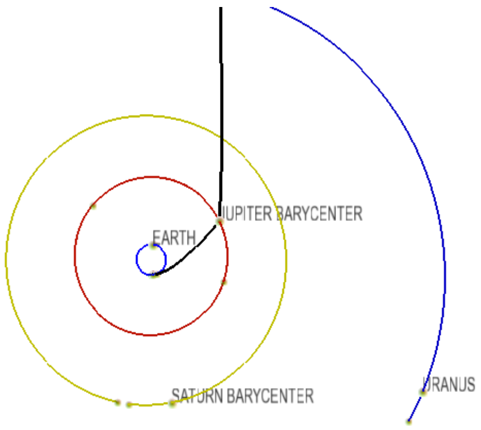


Figure 18. Jupiter trajectory plot from Copernicus.

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.**

Previous Interstellar Probe Study
(cont.)

- Multiple gravity assist trajectories: [9]
  - Based on planetary alignment at the time of launch, this is the only multi-body gravity assist available with the gas giants.
  - Probable Jupiter-Saturn opportunity in mid 2030s, but that date is out of the scope of this analysis.

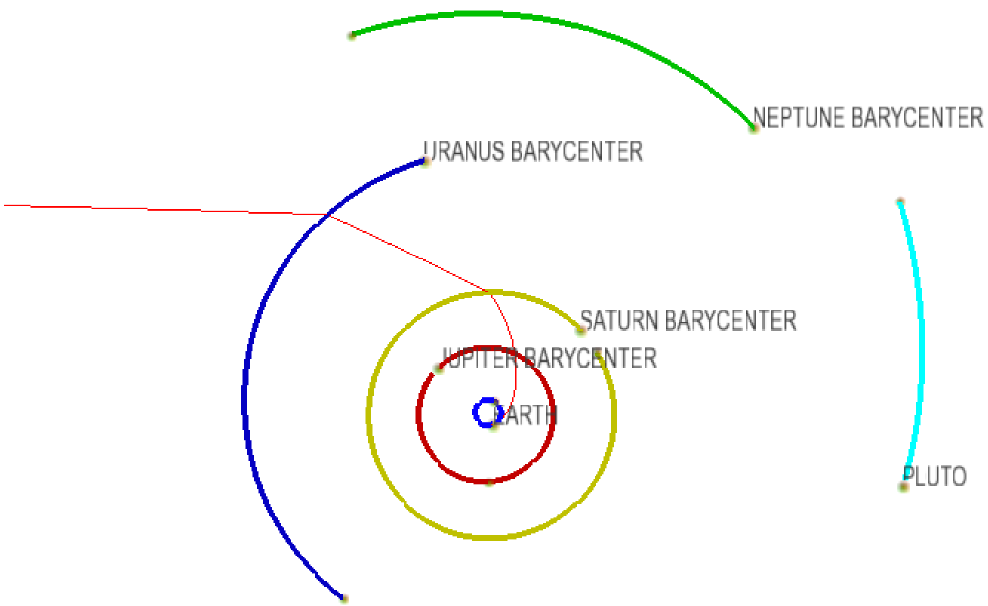


Figure 19. Saturn-Uranus trajectory plot from Copernicus.