Developing an Electric Sail to Propel a Spacecraft to the Edge of our Galaxy in 10 years

IEEE Industry Applications Society (IAS) 50th Annual Meeting

Dallas, TX
Oct 19, 2015

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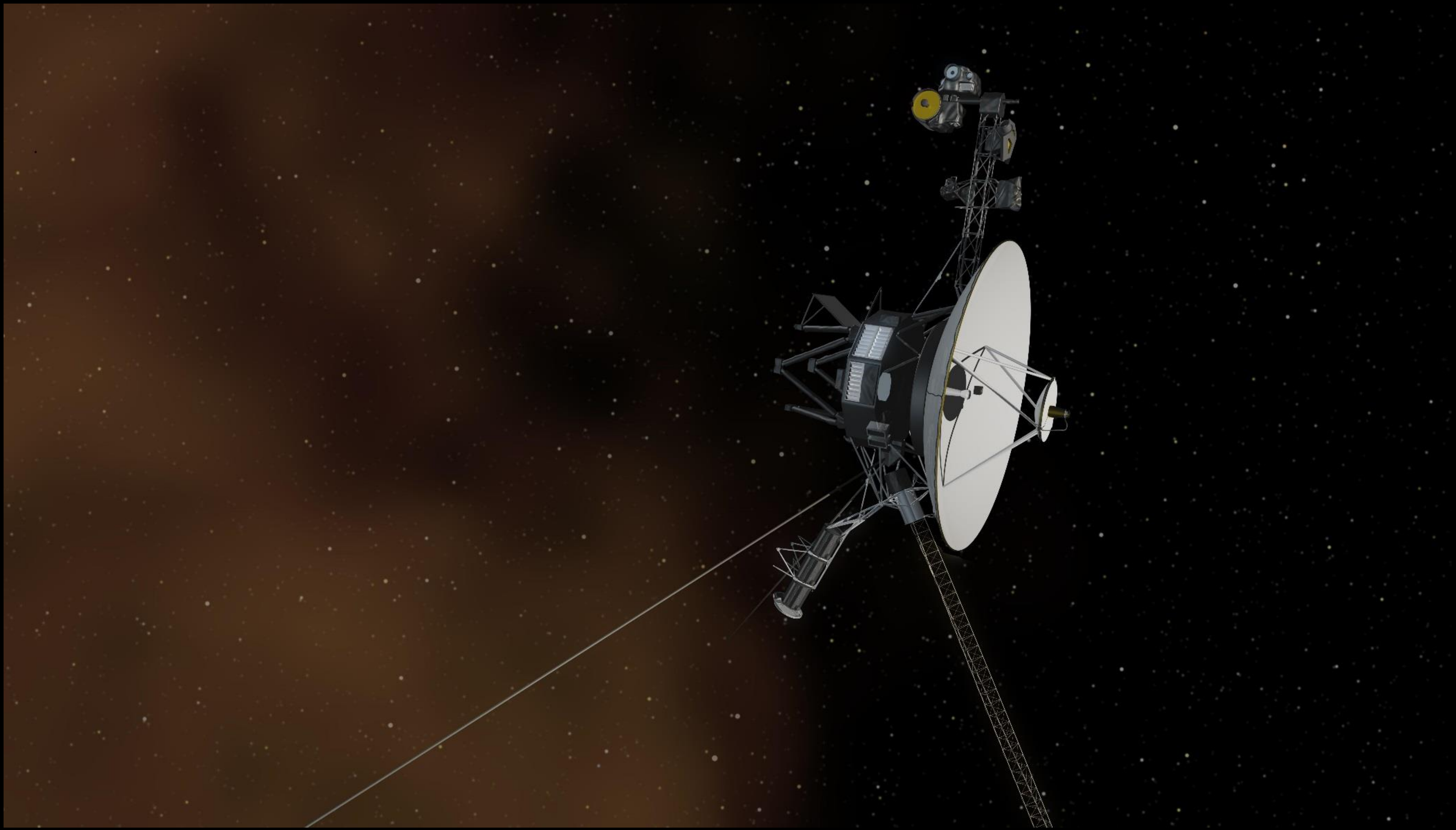
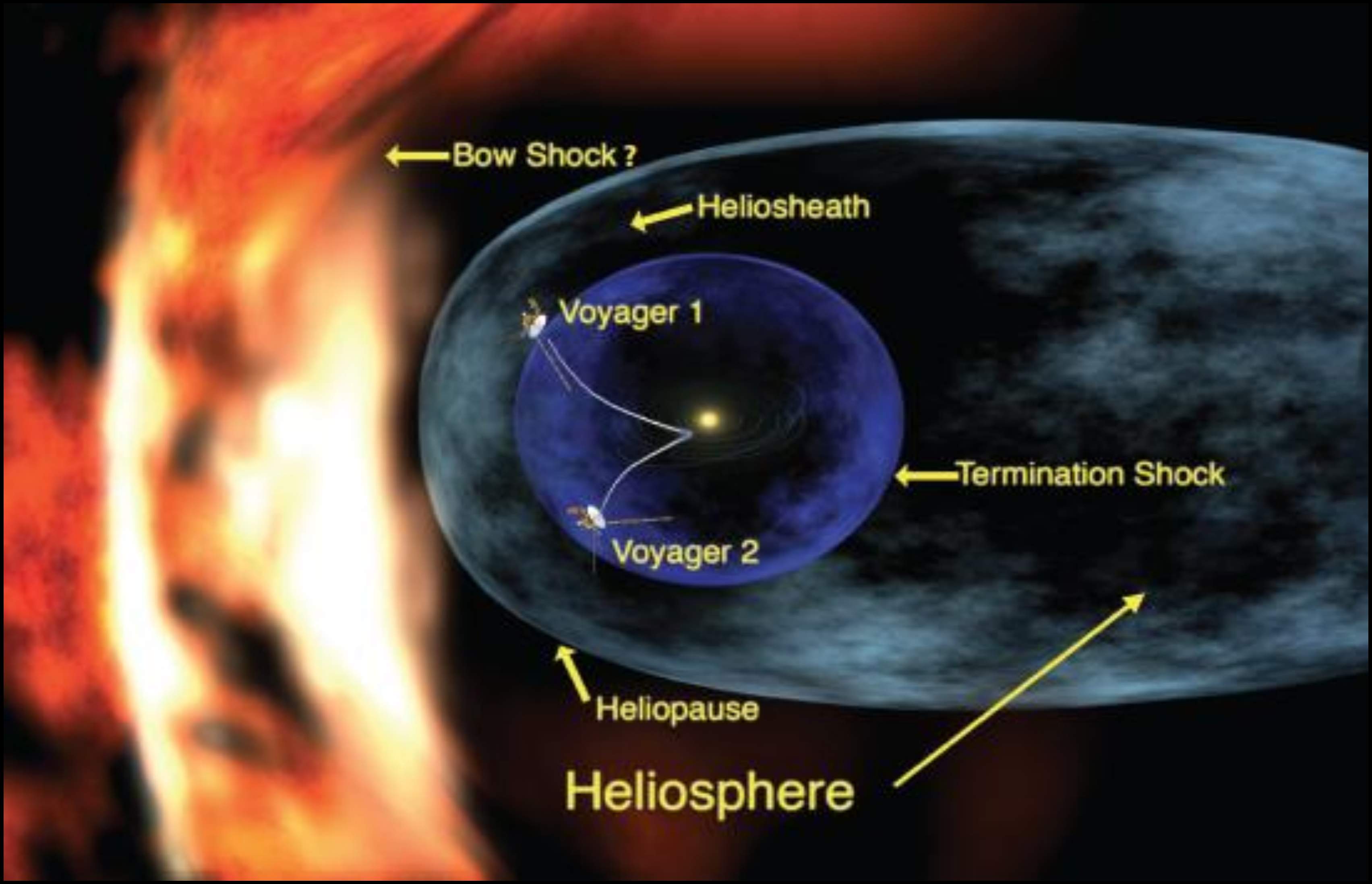
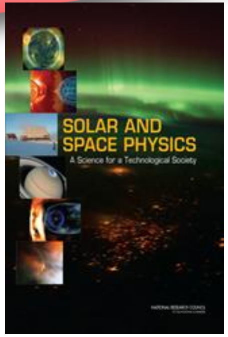
The Voyager Spacecraft
Vintage 1976



The Voyager Spacecraft and Heliopause



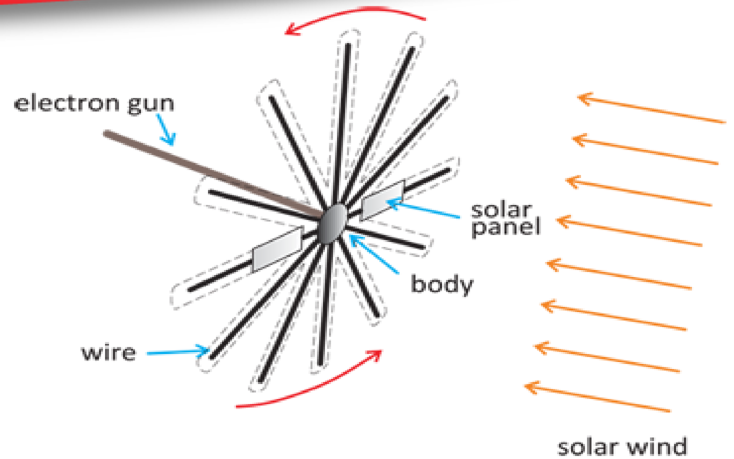
Why is Revolutionary Propulsion Needed?



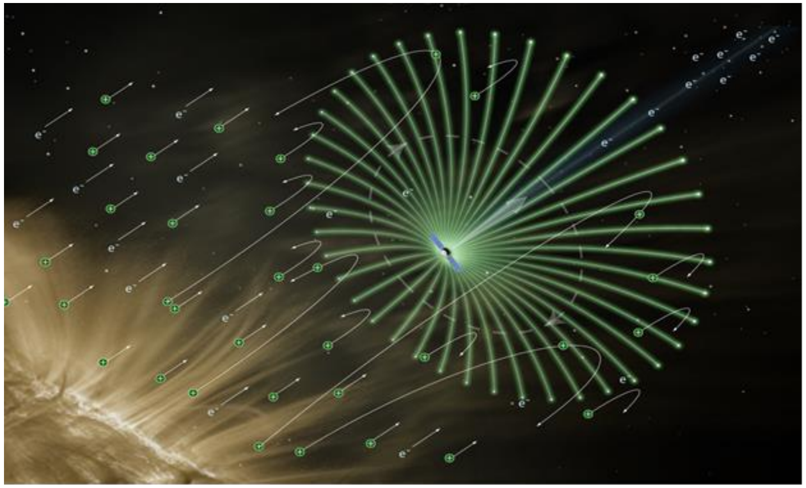
- The 2012 NASA Heliophysics Decadal Survey; Section 10.5.2.7 states:
  - *"… recent in situ measurements by the Voyagers, combined with all-sky heliospheric images from IBEX and Cassini, have made outer-heliospheric science one of the most exciting and fastest-developing fields of heliophysics…. The proposed Interstellar Probe Mission would make comprehensive, state-of-the-art, in situ measurements … required for understanding the nature of the outer heliosphere and exploring our local galactic environment." It goes on to say,* ***"The main technical hurdle is propulsion."***
  - *Advanced propulsion options should aim to reach the Heliopause considerably faster than Voyager 1 ($V_{mssn\ avg}$ of 3.6 AU/year)….*
  - *It has high priority for the Solar and Heliospheric Physics (SHP) Panel that* ***NASA develops the necessary propulsion technology*** *for visionary missions like The Solar Polar Imager (SPI) and Interstellar Probe to enable the vision in the coming decades."*

What is an Electric Sail Propulsion System?

- **Long wires are deployed from the main spacecraft bus and the spacecraft rotates to keep wires taut.**
- **The wires are biased at a high positive potential**
- **The bias is maintained by the ejecting of collected electrons by an electron gun**
- **Positive ions in the solar wind are repulsed by the field and thrust is generated.**
- **Propulsion system can propel spacecraft to either: Deep Space or to the Inner Solar System and is scalable.**

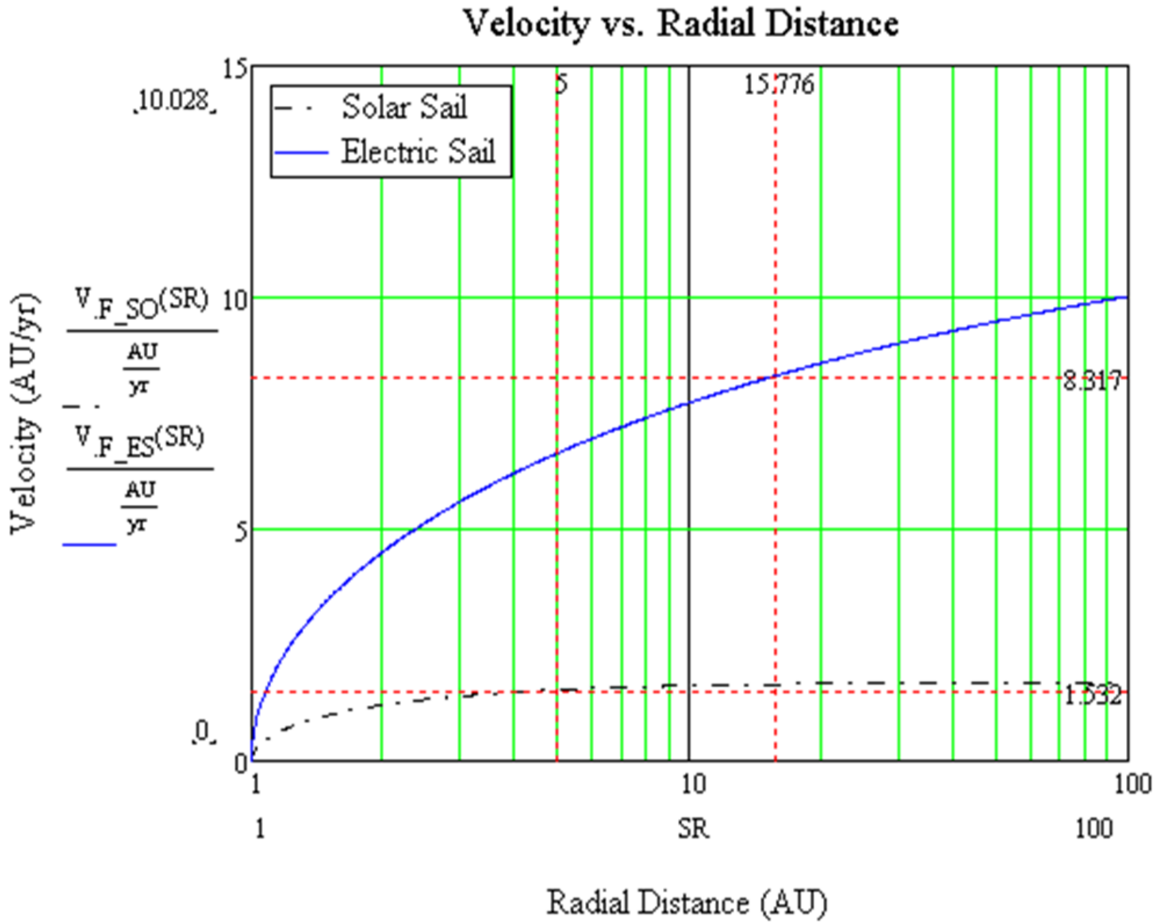


E-Sail propulsion system schematic



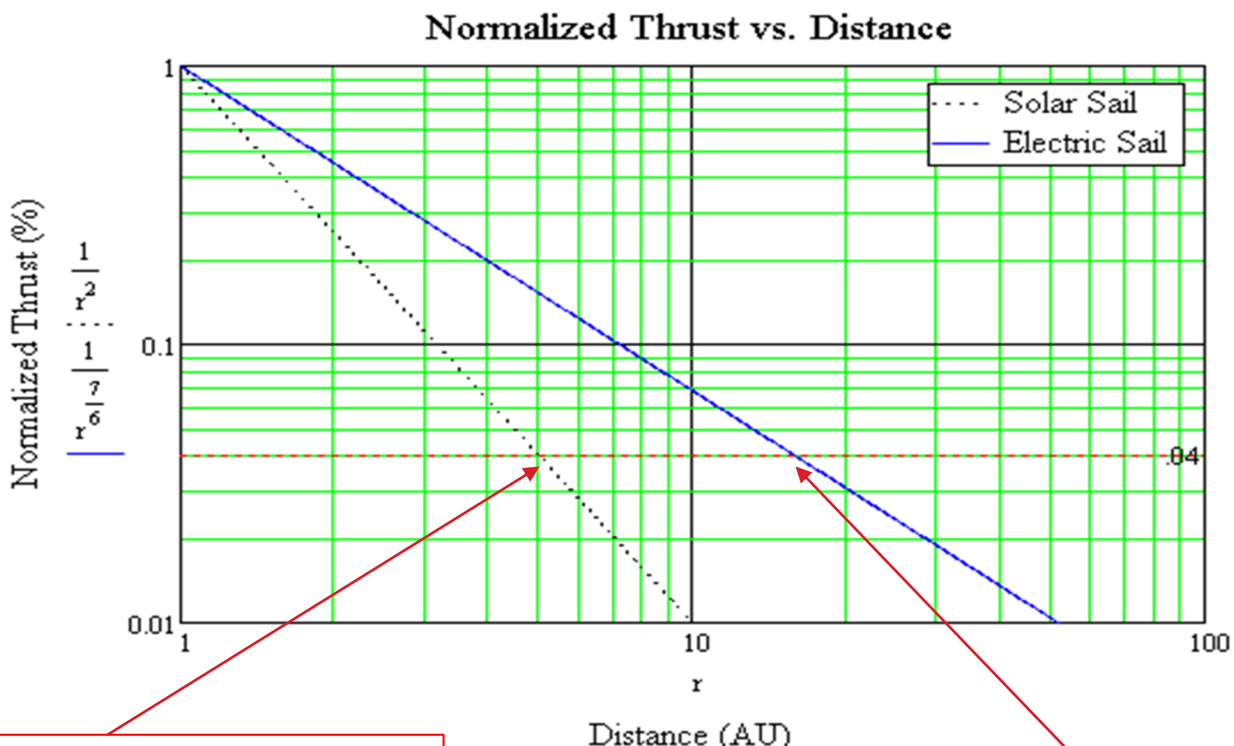
E-Sail Physics: Velocity vs. Radial Distance Comparison for Equal Mass Spacecraft

- Thrust assumed to drop as $1/r^2$ for the solar sail and $1/r^{7/6}$ for the electric sail



E-Sail Physics: Normalized Thrust Decay Comparison E-Sail vs Solar Sail

- Both concepts accelerated the spacecraft until thrust dropped to 4% of initial thrust at 1 AU



At a distance of 5 AU photonic pressure decays to the point that the Solar Sail stops accelerating

E-Sail continues to accelerate to a distance 3 times greater than the Solar Sail or 16 AU

E-Sail Physics: Thrust Decay

- Why $1/r^{7/6}$?
- Proton density decays at $1/r^2$
- Electron temperature decays at $1/r^{1/3}$
- The force per unit length is

$$\frac{dF}{dz} = \frac{K m_P n_o v^2 \, 2\sqrt{\dfrac{\varepsilon_o T_e}{n_o e^2}}}{\sqrt{\exp\left[\dfrac{m_P v^2}{eV_o} \ln\left(r_o / r_w\right)\right] - 1}}$$

- Removing the constants and exponent (small effect)

$$\frac{dF}{dz} \cong n_o \sqrt{\frac{T_e}{n_o}} \cong \sqrt{n_o T_e} \approx \sqrt{\frac{1}{r^2}\frac{1}{r^{1/3}}} \approx \left(\frac{1}{r}\right)^{7/6}$$

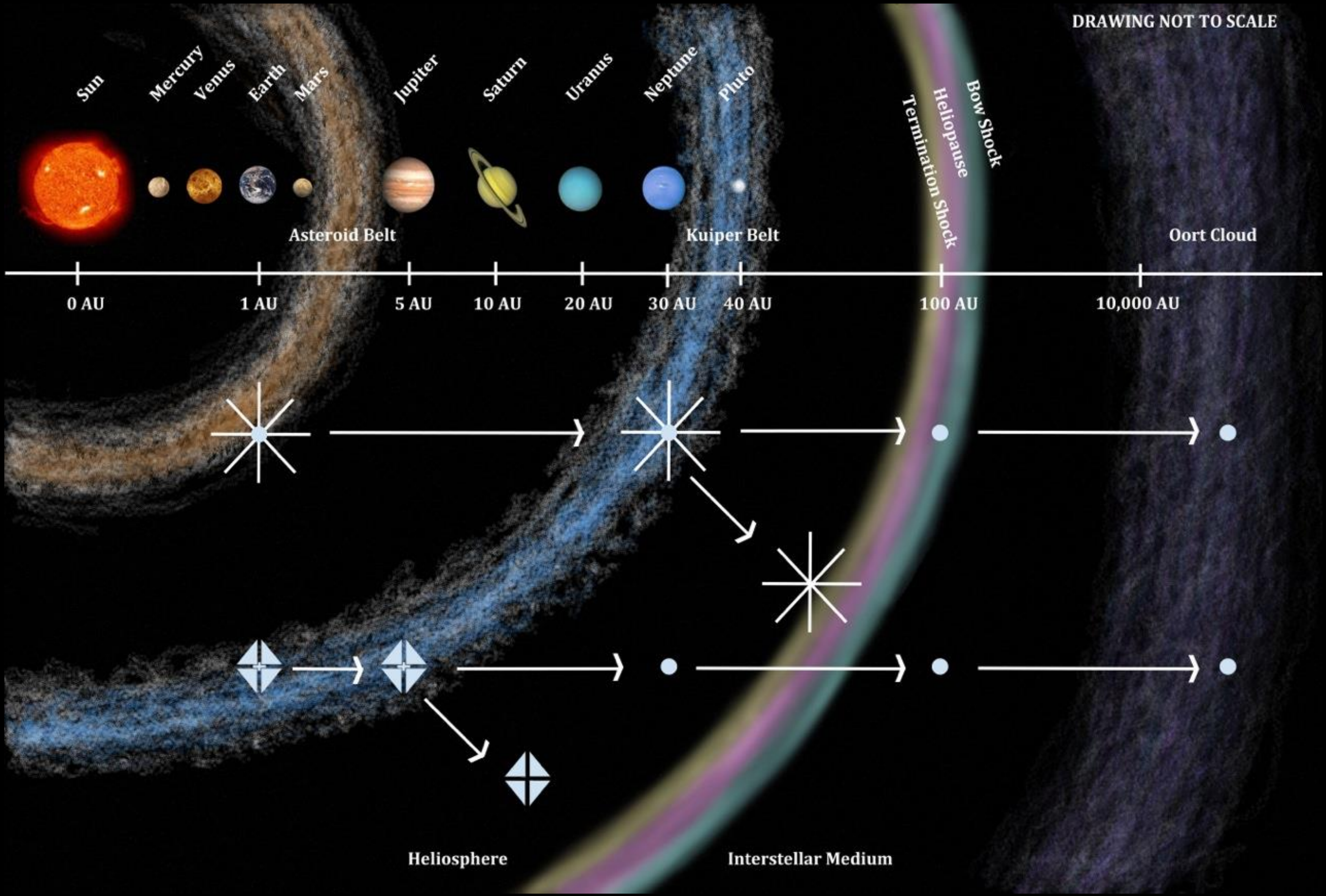
Propulsion Benefits of E-Sail vs. Solar Sail

- E-Sail effective area is a function of proton impact parameter, P, which is directly proportional to the magnitude of the applied positive potential and the Debye shielding distance, λ_D,

- As the HERTS spacecraft moves away from the Sun and the solar wind density decreases (as $1/r^2$, where r is radial distance from the Sun) the proton impact parameter increases,

- Thrust produced by Solar sail is asymptotic in nature and falls off - so at a distance of 5 AU - solar sails are jettisoned, whereas, HERTS thrust (also asymptotic) declines at a slower rate and continues to provide thrust to ~16 AU at a minimum
  - 3 times greater distance of applied acceleration to E-Sail spacecraft

The HERTS Mission



HERTS/E-Sail Elements, Current Technical Maturity, & Roadmap

Roadmap	Level 1	Level 2	Level 3	Level 4
Tether Deployment	Trade between satellite propulsion spin up system and e-sail	Trade between multiple individual deployers and single deployer	Subscale ground deployment test	Full scale deployment test (maybe shorter length)
Tether Configuration	How many? What length?	End-mass size and configuration		
Tether Material	Develop tether property requirements	Trade of tether materials	Test of structural performance	Test of electrical performance in ion chamber
Tether Dynamics	Analysis of E-Sail tether dynamics	Ground test of subscale tether dynamics		
High Voltage Subsystem	Analysis of optimal tether voltages	Design of a high voltage generation system		
High Voltage Switching	Trade between single system and multiple independent power systems	Trade between pulsed and analog system	EMI Analysis	
Momentum Management	Analysis of techniques for initial system spin-up	Analysis of techniques for adjusting system orientation after system is fully deployed	TRL 3	TRL 4
System spin up propulsion	Trade of different systems that could provide torque for tether deployment			
Attitude control system	Develop system requirements for ACS and propulsion prior to E-sail deployment	Trade of possible systems to perform these tasks	Ground test of the ACS and Propulsion systems	
Propulsion performance	Analyze E-sail propulsion performance for various configurations	Develop techniques for controlling propulsion direction and E-sail attitude	Subscale test of E-sail in plasma chamber	
Deep Space Comm	Develop requirements of telemetry data rate, contact duration and frequency	Trade possible communication systems	Develop a design for antenna configuration and articulation	
Bus accommodations	Conceptual design of E-sail bus configuration	Conceptual design of E-sail bus subsystems		
Electron elimination system	Develop requirements for the Electron Elimination System	Design of an Electron Elimination System		
Electron elimination power	Analysis of EES power required			

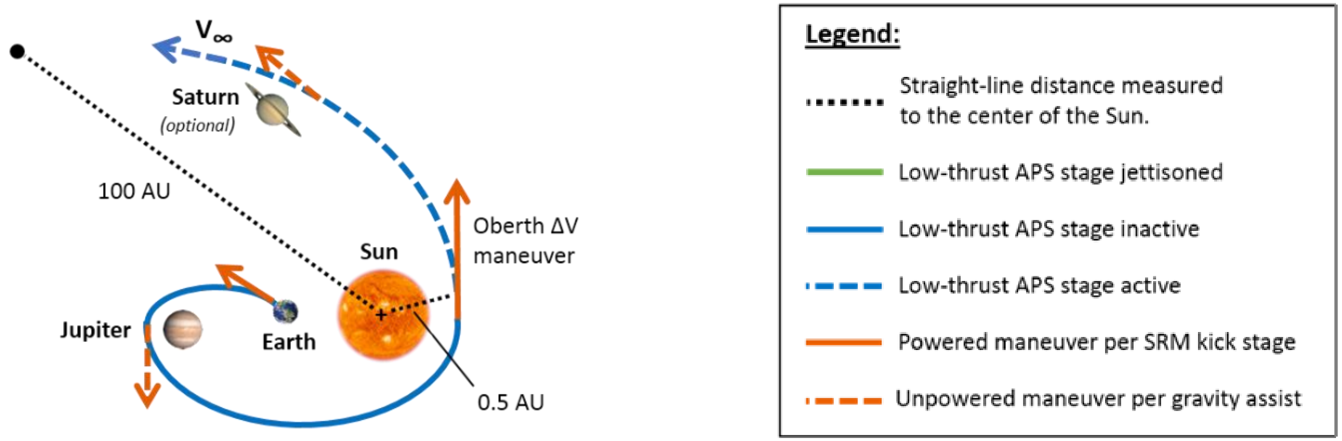
Current Work
Proposed Work
Future Work

Areas of Emphasis under NAIC Phase I

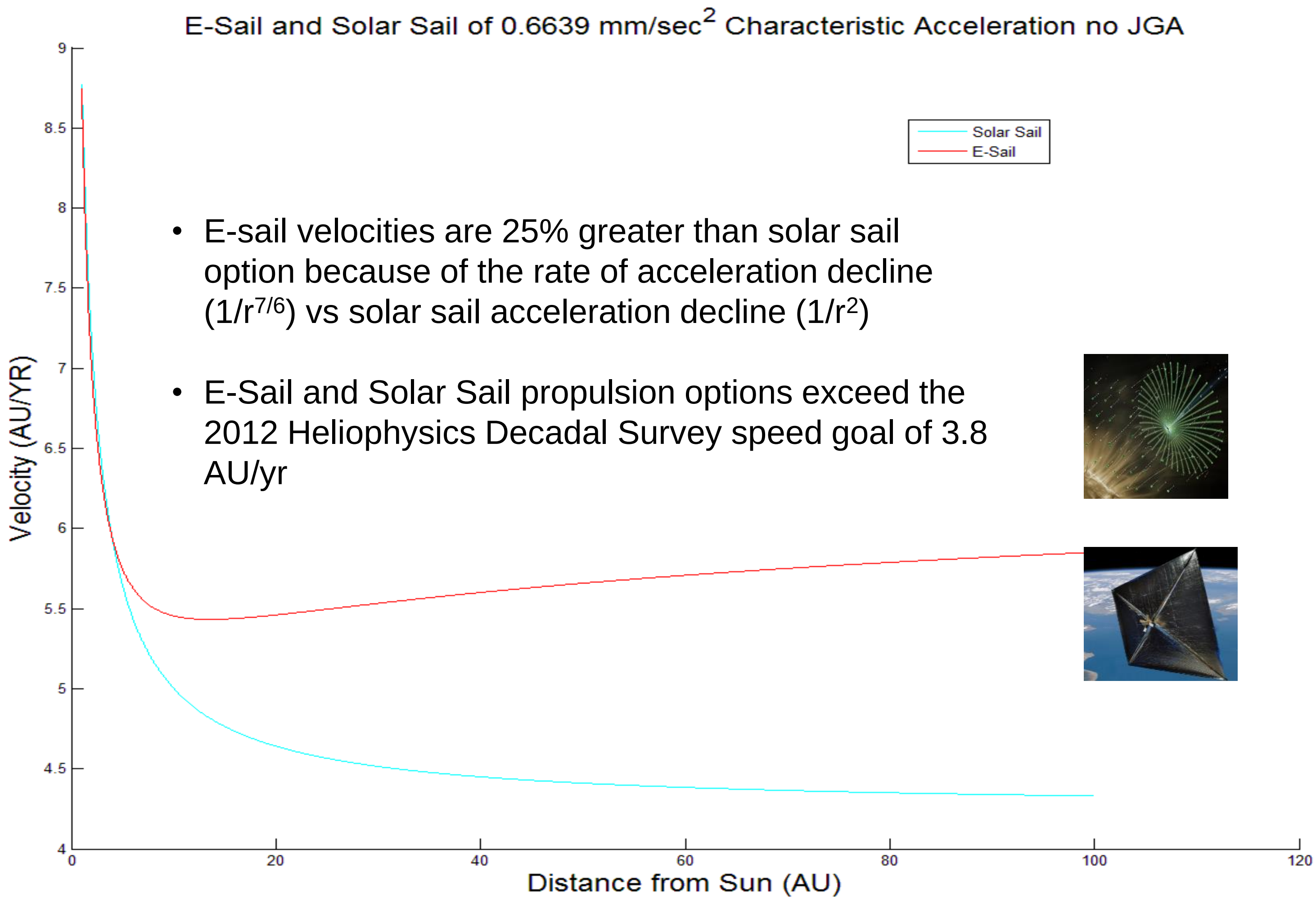
Dark green boxes reflect mature technology areas so development is focused on less mature areas

Impacts of Varying Mission Designs Investigated

- Investigated two primary mission options
  - Radially out to Heliopause
    - With Jupiter Gravity Assist (Earth/Jupiter to Heliopause (100 AU))
    - Without Jupiter Gravity Assist (Earth to Heliopause (100 AU))
  - Oberth Maneuver ((Earth/Jupiter/Sun/Saturn → Heliopause (100 AU))
    - Jupiter Flyby
    - Oberth Maneuver at sun at distance of 0.05 AU



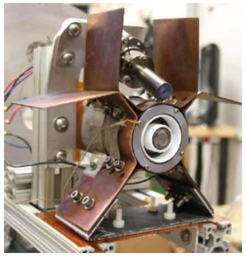
Velocity Comparison Between HERTS/E-Sail and Solar Sail



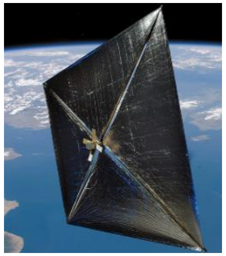
- E-sail velocities are 25% greater than solar sail option because of the rate of acceleration decline ($1/r^{7/6}$) vs solar sail acceleration decline ($1/r^2$)
- E-Sail and Solar Sail propulsion options exceed the 2012 Heliophysics Decadal Survey speed goal of 3.8 AU/yr

Investigated In-Space Propulsion Options

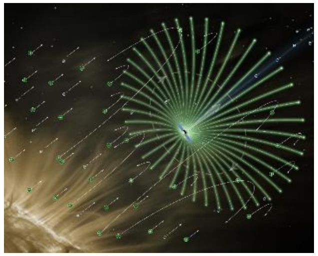
- **High-thrust propulsion option (All chem)**
  - 1 to 2 solid rocket motors (SRM) in SLS stack
- **Low-thrust propulsion options:**
  - MaSMi Hall thruster
    - 50,000 hr. life
  - Solar sail
    - @ 10 g/m^2; Characteristic Acceleration = 0.43 mm/sec^2
    - @ 3 g/m^2; Characteristic Acceleration = 0.66 mm/sec^2
  - Electric sail
    - Characteristic Acceleration = 2mm/sec^2
    - Characteristic Acceleration = 1mm/sec^2



MaSMi Hall thruster



Solar sail



Electric sail

SLS Block 1B with EUS and 8.4m PLF

E-Sail vs Solar Sail Propulsion System Properties as Examined

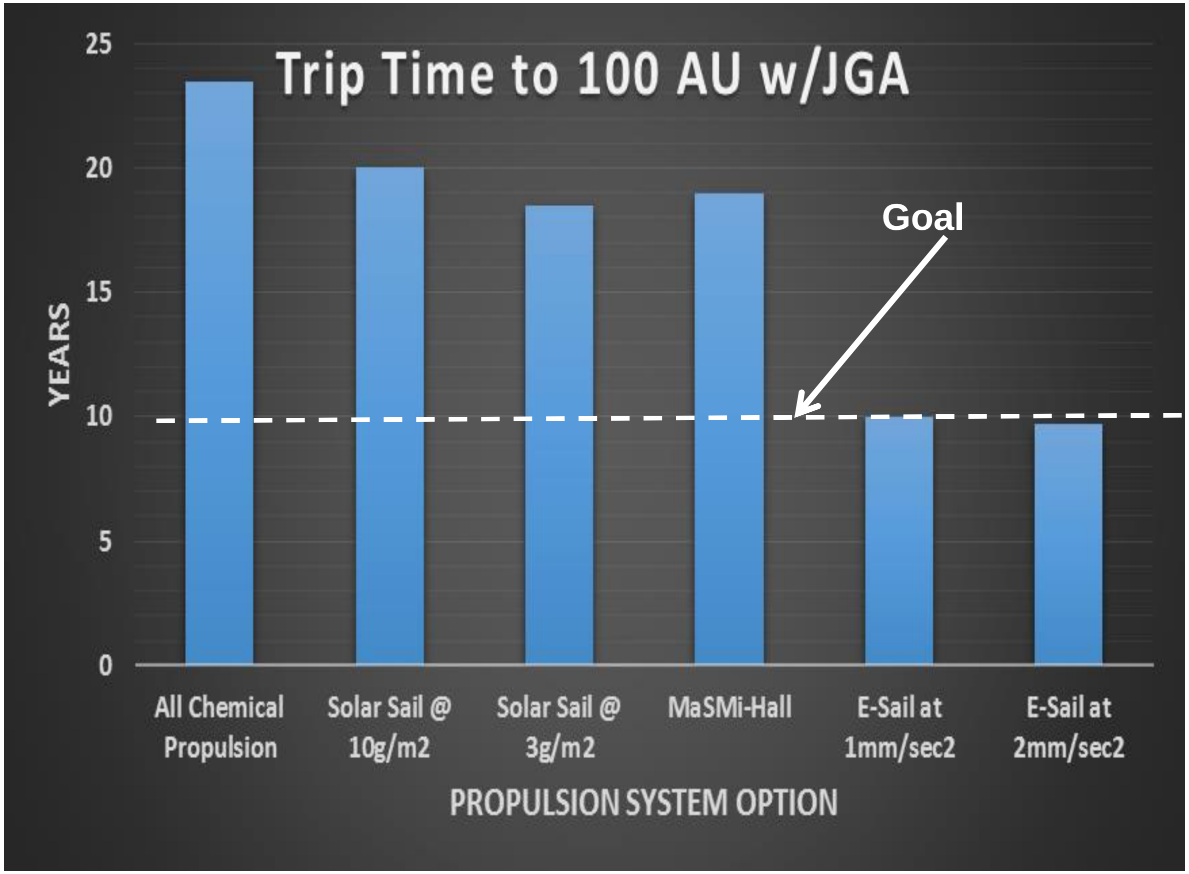
◆ E-Sail Propulsion System Properties

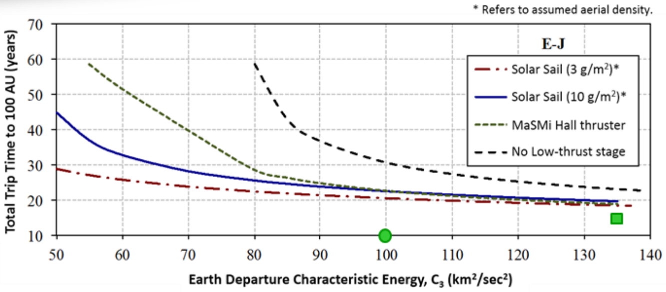
Item	Description	
Propulsion System Mass	120 kg (265 lb_m)	
Wire Material (Density)	Aluminum (2,800 kg/m^3)	
Wire Diameter (Gauge)	0.127 mm (36 gauge)	
Characteristic Acceleration	1 mm/s^2	2 mm/s^2
Tether Quantity	10	20
Individual Tether Length	20 km (12.4 mi)	20 km (12.4 mi)

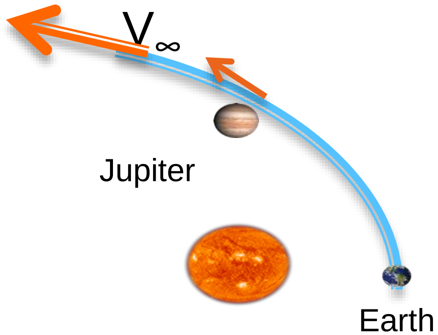
◆ Solar Sail Propulsion System Properties

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)

Results: Comparison of In-Space Propulsion Options







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

The HERTS/E-Sail option dramatically reduces trip times by ~50% to 100 AU

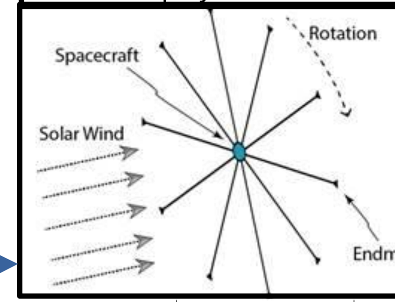
The Next Steps to a Heliopause Mission in 2025-2030

2014 Phase I NIAC

2015 Phase II NIAC recently won
- **Develop enhanced numerical modeling**
- **Perform ground tests to benchmark enhanced numerical codes**
- **Prototype tether & tether deployers**

MSFC Solar Wind Facility

Tether Deployment & Control



Multi tether E-Sail propulsion system demonstration flight (outside of Earth's Mag Field)

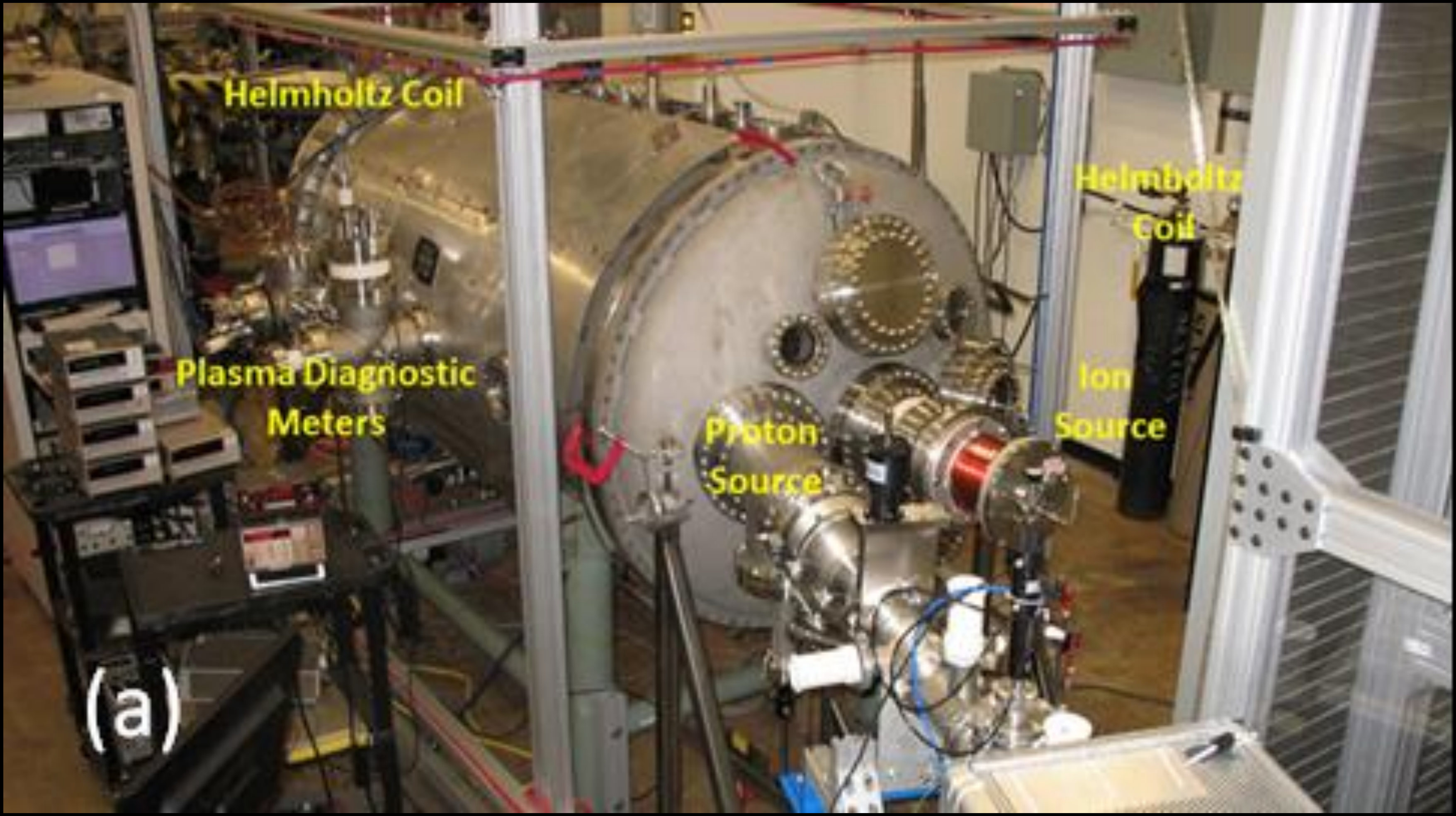
Incorporate design changes from demo flight for build of Deep Space flight hardware

Fabricate hardware for Heliophysics Mission (notional 2025-2030 launch)

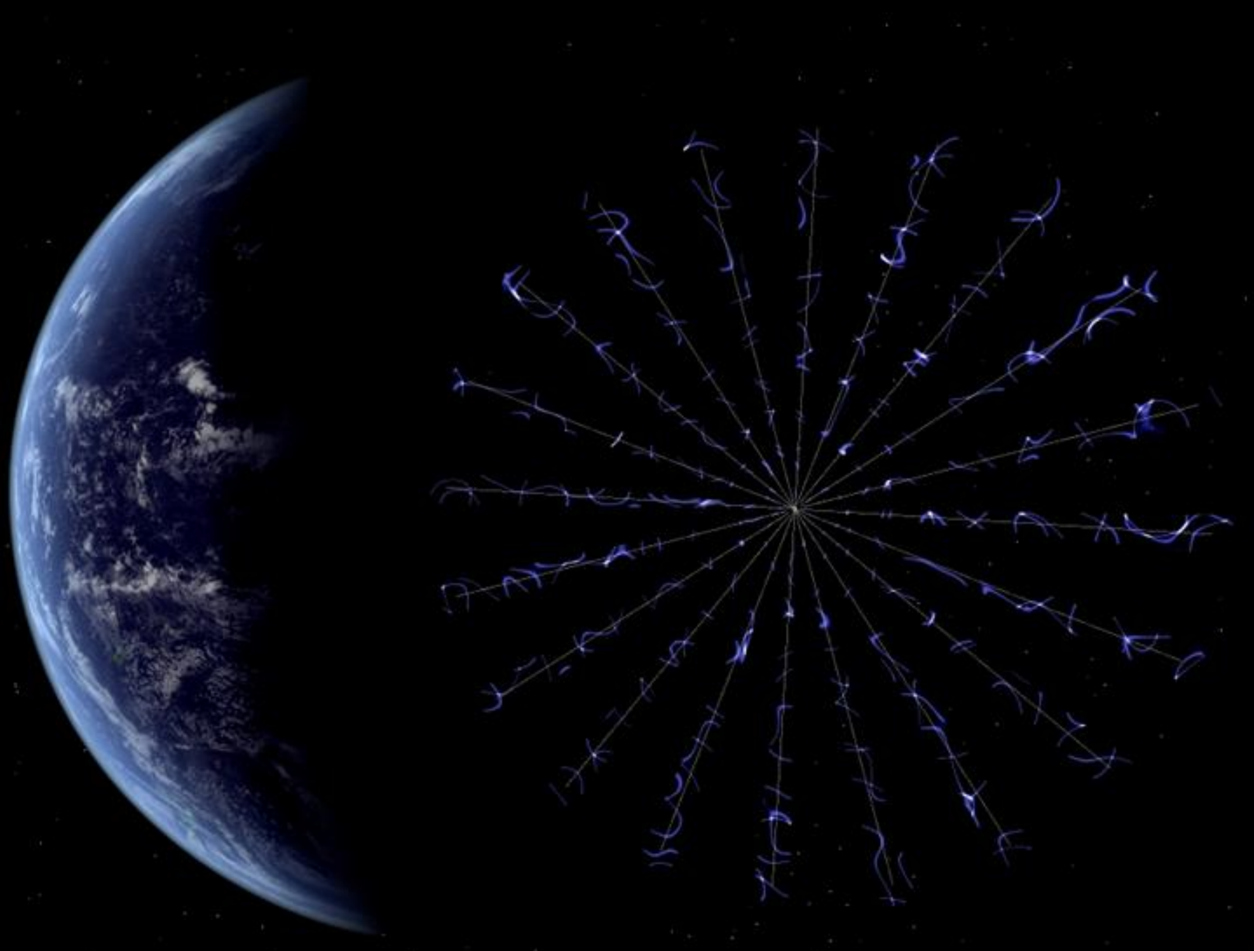
2014 **2016** **2018** **2020** **2022** **2024** **2026**

The Phase II NIAC HERTS Team

MSFC - Solar Wind Facility



End of Presentation: Animation Follows



BACKUP MATERIAL

Assumptions

- OML ---Orbital Motion Limited (OML) model was utilized in space plasma physics/charged wire with corresponding Debye sheath distances
  - Present standard for calculating current collection in space
  - Presently used to calculate electron collection for overall power requirements
- HERTS/E-Sail rotation rate ~ 1 rev/hr
- Mass of E-Sail propulsion system (~120 kg) assumed incorporation of AL wires.
  - Copper has other properties that may be better, but the mass grows
- Mass of wire end-masses assumed to be 50 grams each

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
  - Spacecraft bus & 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 acceleration = 0.4256 mm/s^2
        - Sail mass = 400 kg
        - Total spacecraft mass = 780 kg
      - ***Areal density = 3 g/m^2***
        - Characteristic acceleration = 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 = 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