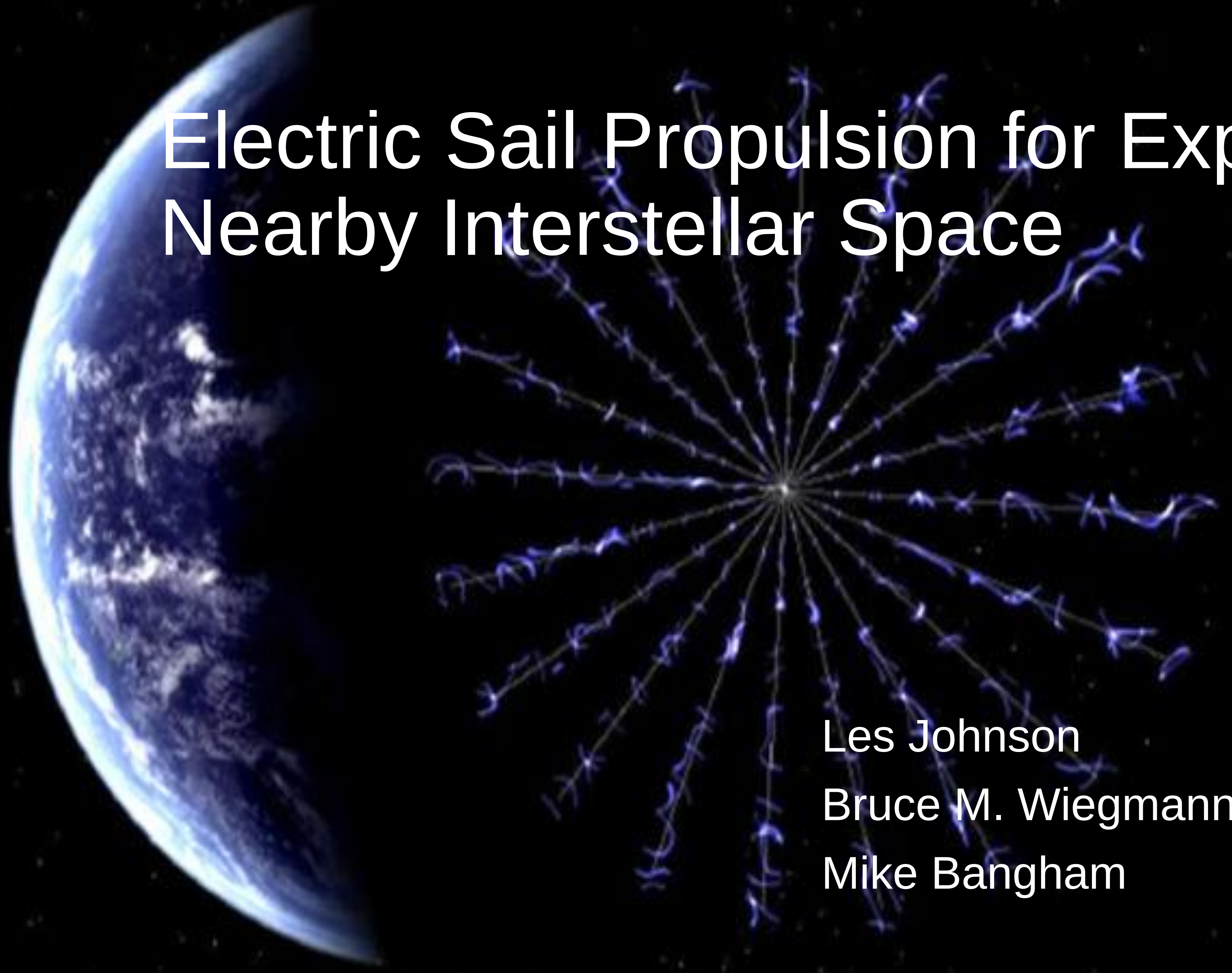
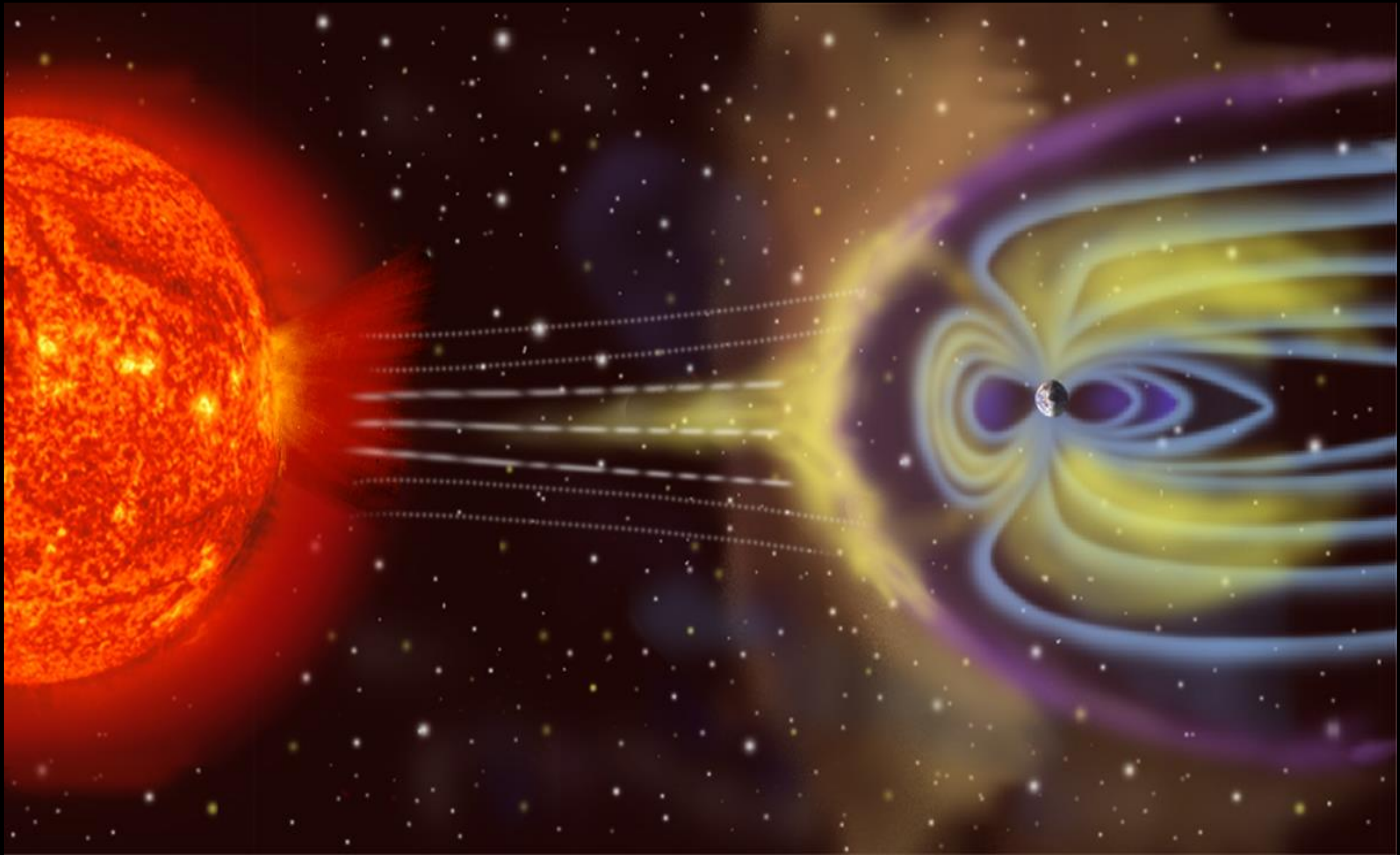


Electric Sail Propulsion for Exploring Nearby Interstellar Space

Les Johnson
Bruce M. Wiegmann
Mike Bangham

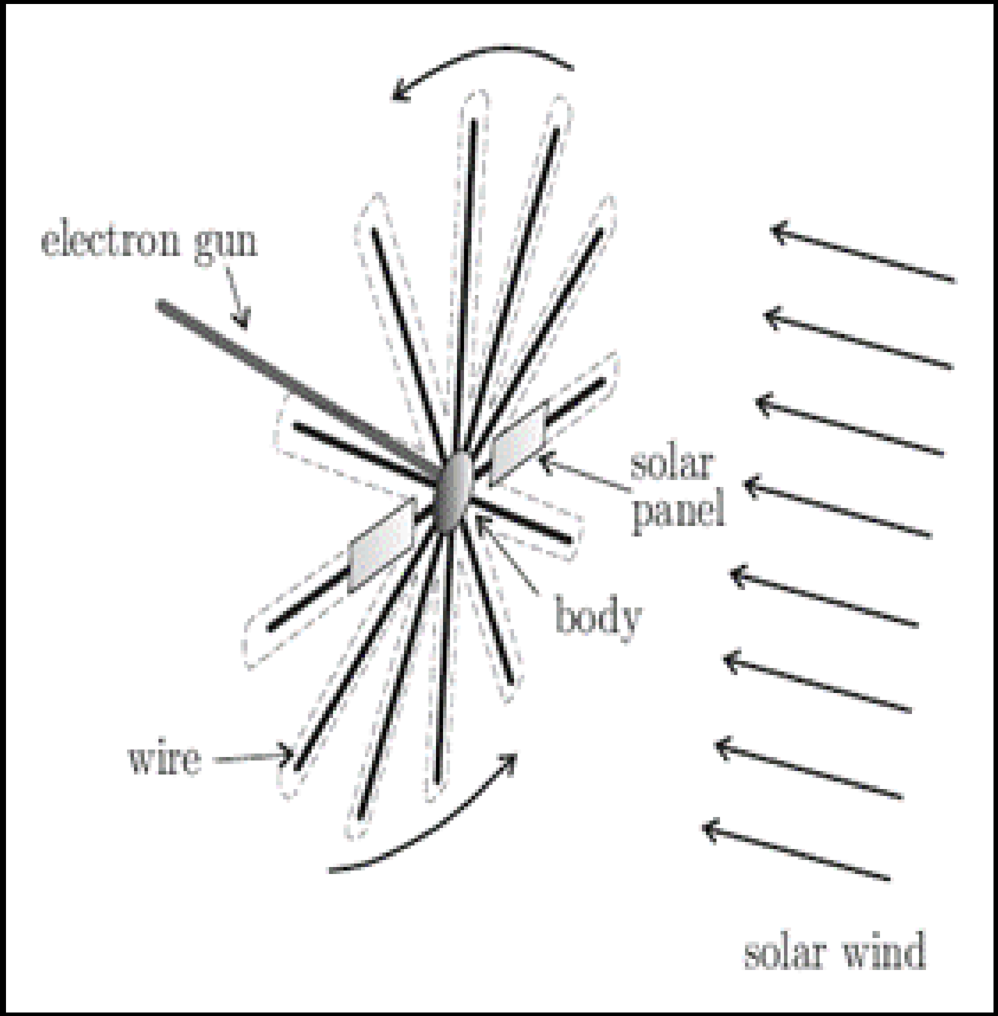
We tend to think of space as being big and empty…

Can we use the environments of space to our advantage?



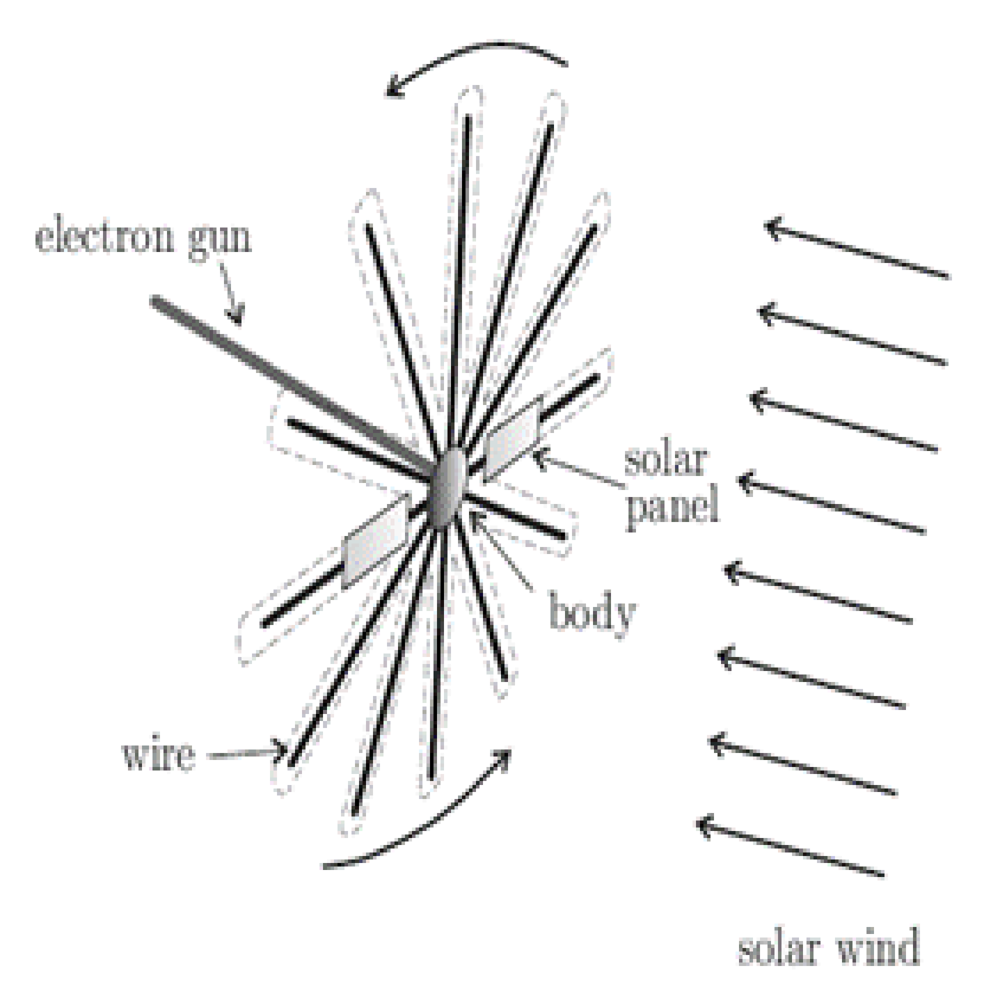
Electric Sail – Concept of Operations

- The e-sail consists of 10 to 100 conducting, positively charged, bare wires, each 1–50 km in length.
- 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.



Electric Sail – By The Numbers
An Example

- 10 – 100 wires
- 20 km long
- 25 microns thick
- Wires kept at 20 kV potential
- The electric field surrounding each wire extends ~ 10 meters into the surrounding plasma.
- ~1 mm/s^2 acceleration



Electric Sail Origins

The electric solar wind sail, or electric sail for short, is a propulsion invention made in 2006 at the Kumpula Space Centre by Dr. Pekka Janhunen.

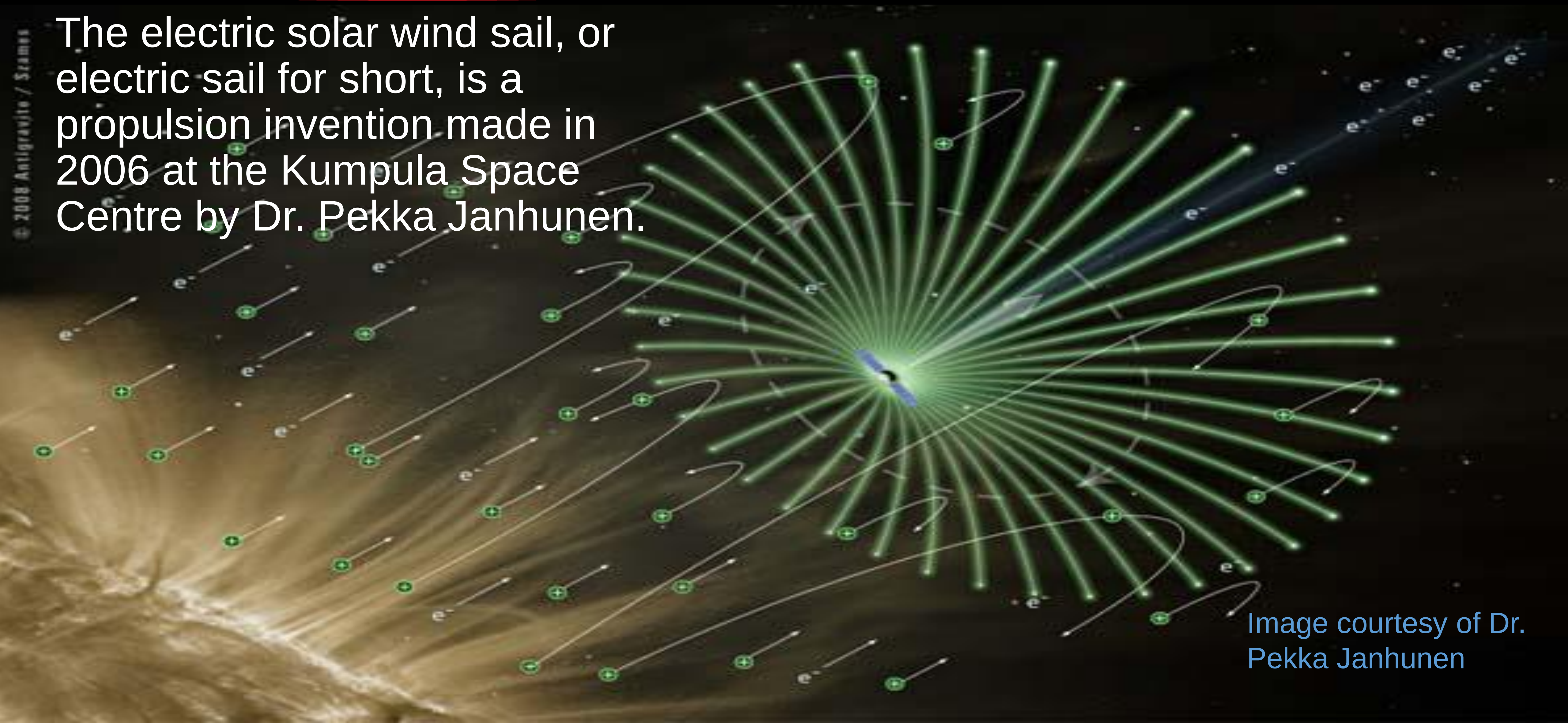


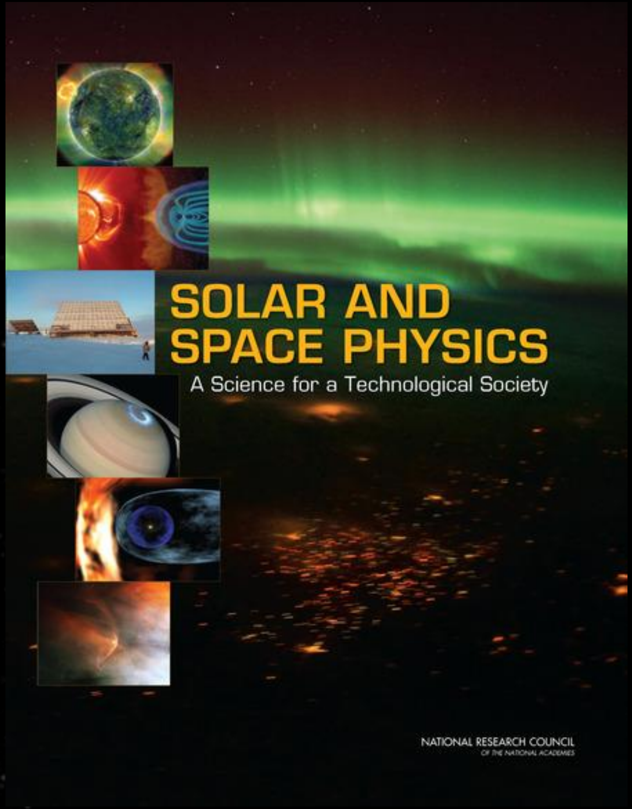
Image courtesy of Dr. Pekka Janhunen

Why An Electric Sail?

- 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).
- Propulsion system is scalable to small spacecraft
- Readily meets the requirements for relatively near-term interstellar precursor missions out to 500 AU

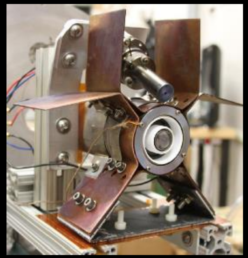
What Comes After Voyager?

- Voyager:
  - Took 36 years to reach the Interstellar Medium (ISM).
  - Escape Velocity (V∞) is 3.6 AU/yr.
  - Used gravity assists: Jupiter, Saturn, Uranus and Neptune.
  - Is 38 years old and going.
- Interstellar Probe:
  - Get there sooner: 100+ AU in 10 years.
  - Travel faster: 5x – 10x Voyager speed.
  - Survive longer: 50 – 100 years.

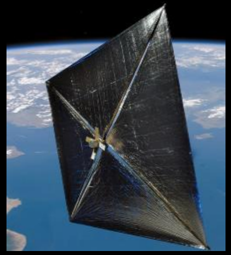


Interstellar Probe In-Space Propulsion Options

- 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/m2; Characteristic Acceleration = 0.43 mm/sec2
    - @ 3 g/m2; Characteristic Acceleration = 0.66 mm/sec2
  - Electric sail
    - Characteristic Acceleration = 2mm/sec2
    - Characteristic Acceleration = 1mm/sec2

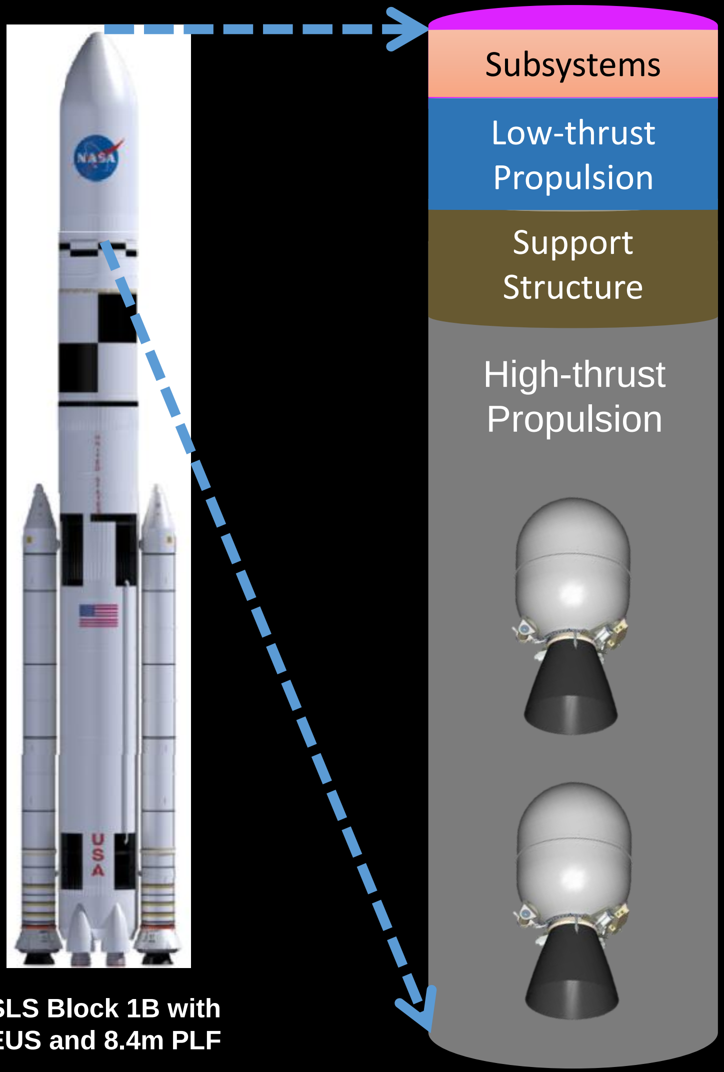


MaSMi Hall thruster



Solar sail

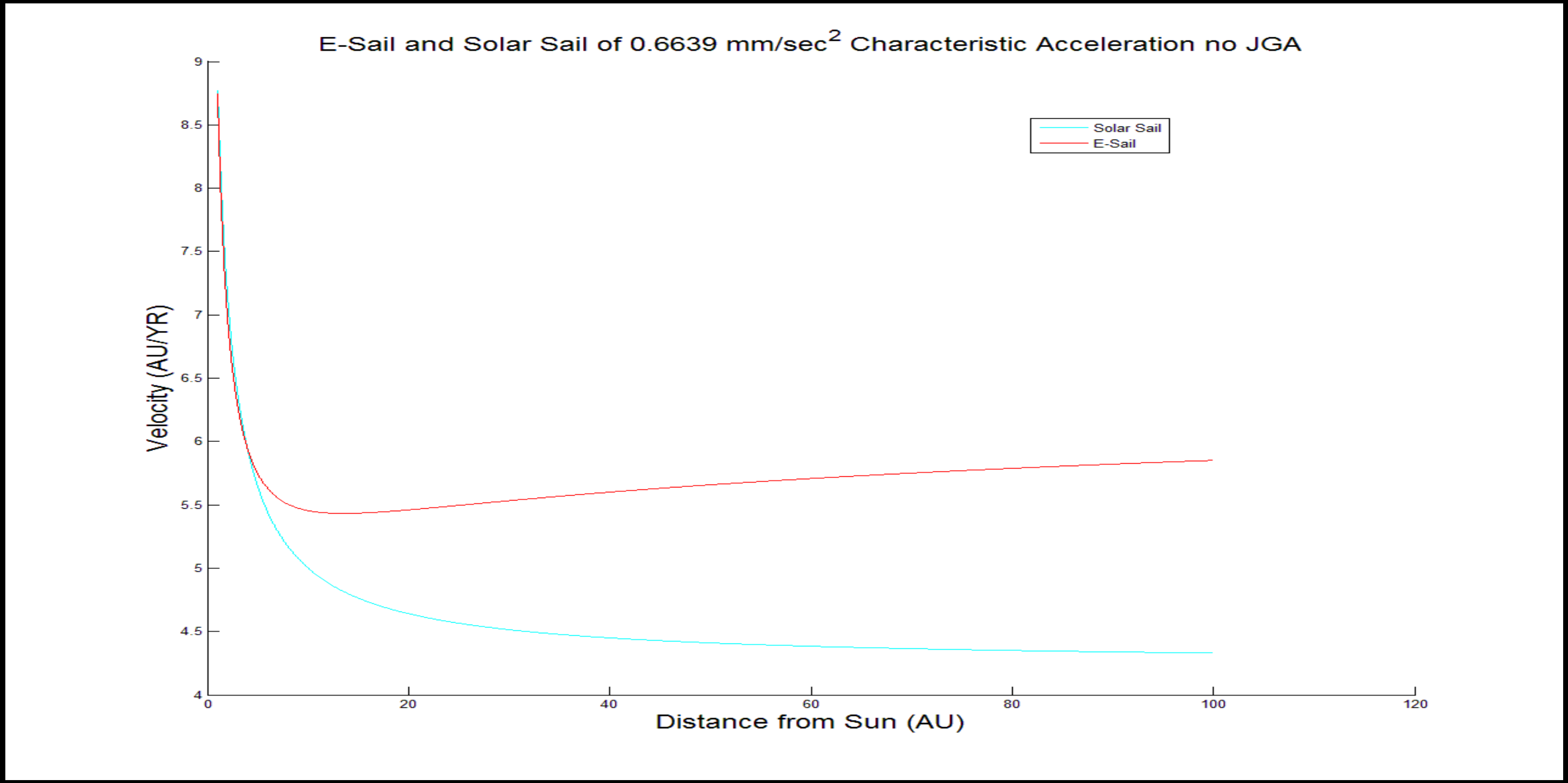
Electric sail



SLS Block 1B with EUS and 8.4m PLF

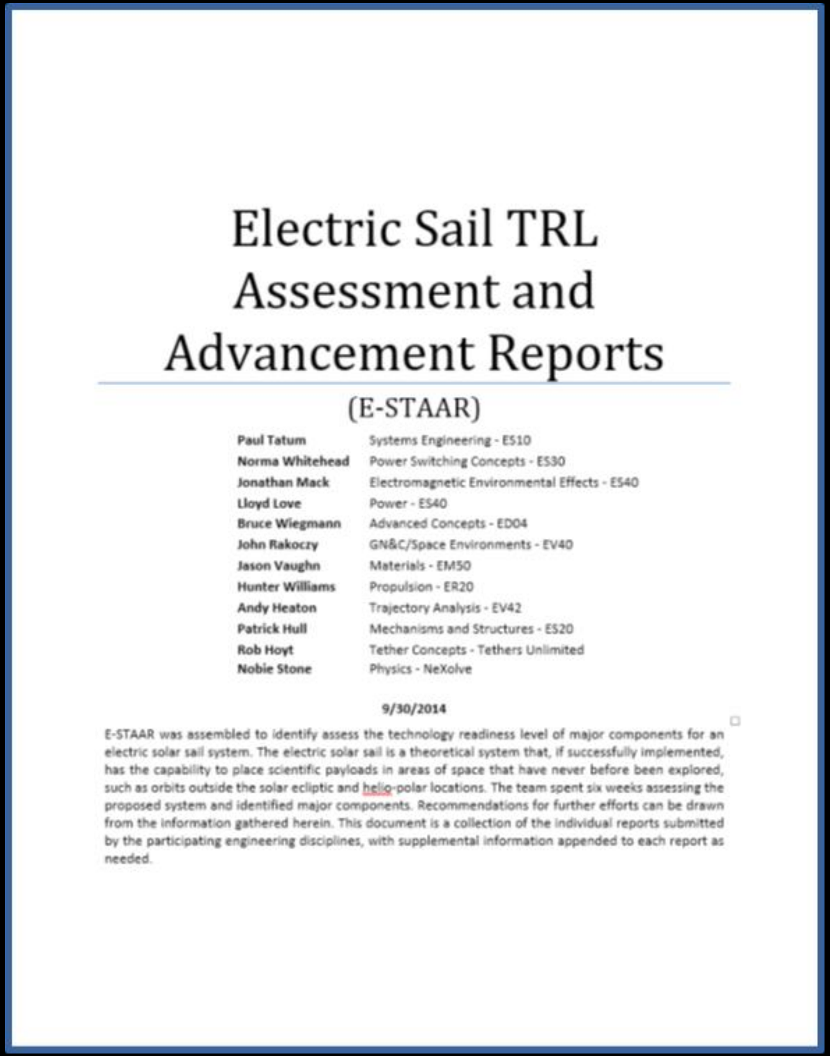
Velocity Comparison Between E-Sail and Solar Sail

- E-sail velocities are 25% greater than solar sail option because of the rate of acceleration decline (1/r7/6) vs solar sail acceleration decline (1/r2)
- E-Sail and Solar Sail propulsion options exceed the 2012 Heliophysics Decadal Survey speed goal of 3.8 AU/yr



Electric Sail Technology Readiness Level (TRL) Assessment and Advancement (E-STAAR)

- MSFC conducted a 2-month TRL assessment of E-Sail systems and components
- Most components are at relatively high TRL, but three elements significantly reduce the system-level TRL
  - Uncertainty of plasma physics model (used to determine current collection, hence, thrust)
  - Wire deployment
  - Guidance, Navigation and Control



Electric Sail TRL Assessment and Advancement Reports

(E-STAAR)

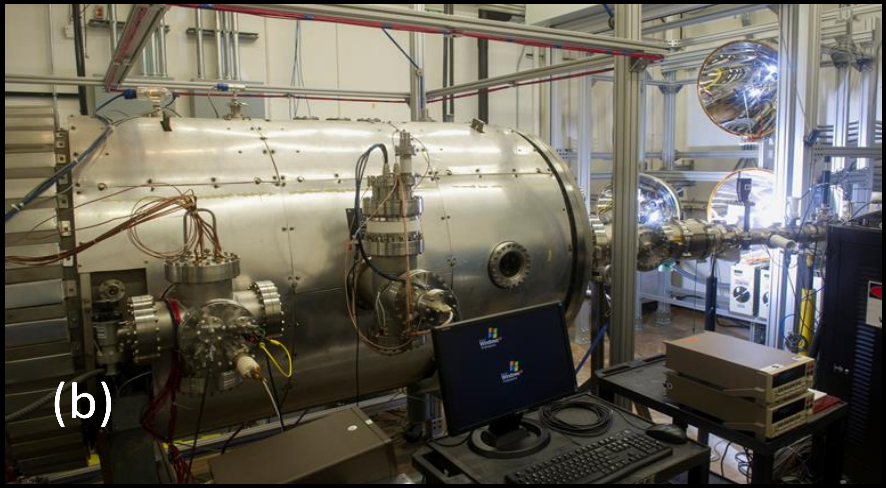
Paul Tatum	Systems Engineering - ES10
Norma Whitehead	Power Switching Concepts - ES30
Jonathan Mack	Electromagnetic Environmental Effects - ES40
Lloyd Love	Power - ES40
Bruce Wiegmann	Advanced Concepts - ED04
John Rakoczy	GN&C/Space Environments - EV40
Jason Vaughn	Materials - EM50
Hunter Williams	Propulsion - ER20
Andy Heaton	Trajectory Analysis - EV42
Patrick Hull	Mechanisms and Structures - ES20
Rob Hoyt	Tether Concepts - Tethers Unlimited
Nobie Stone	Physics - NeXolve

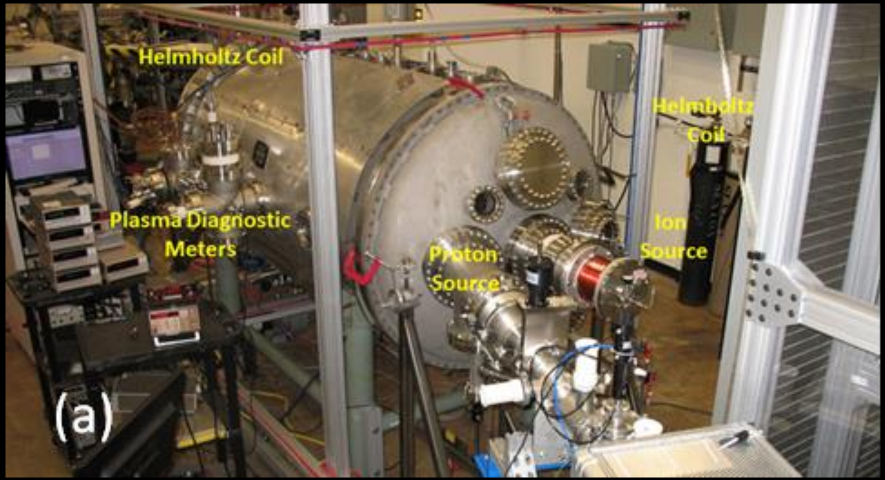
9/30/2014

E-STAAR was assembled to identify assess the technology readiness level of major components for an electric solar sail system. The electric solar sail is a theoretical system that, if successfully implemented, has the capability to place scientific payloads in areas of space that have never before been explored, such as orbits outside the solar ecliptic and helio-polar locations. The team spent six weeks assessing the proposed system and identified major components. Recommendations for further efforts can be drawn from the information gathered herein. This document is a collection of the individual reports submitted by the participating engineering disciplines, with supplemental information appended to each report as needed.

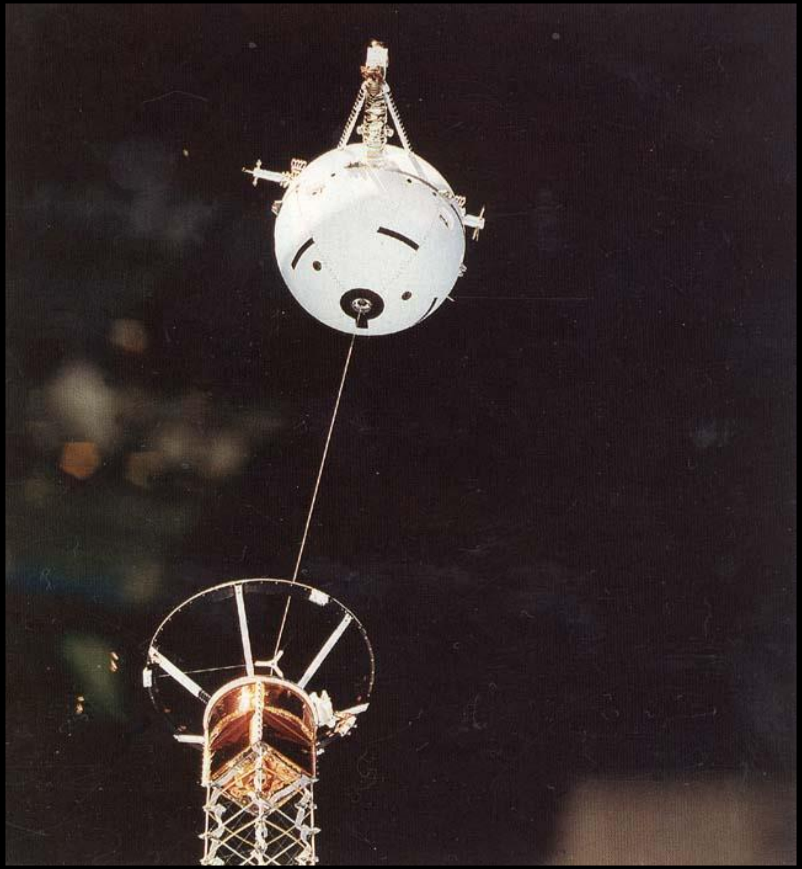
E-Sail Plasma Physics Measurements and Modeling

- Competing models exist for understanding the physics of long-thin charged wires in the solar wind
  - Langmuir-Mott Smith (LMS)
  - Orbit Motion Limited (OML)
- Models predict 10X different electron current collection, hence onboard power system requirements.
- Measurements in MSFC Space Environmental Effects test chambers will determine which model is correct and allow system sizing.





E-Sail Wire Deployment



- Deploying and maintaining stable, multi-km wires in deep space is complicated.
- Spin deployment requires unobtainable spacecraft rotational velocity for long tethers but may be practical for large number of short tethers.
- Propulsive deployment may be mass prohibitive.
- Electrodynamic deployment via solar wind interaction appears to be too slow, but doable.
- MSFC is exploring these and other options in more detail to determine the ‘best’ approach.

E-Sail Guidance, Navigation and Control

- Reflecting the solar wind for thrust and selectively reflecting it for attitude control and navigation is a complex challenge
- Large rotational inertia must be managed to produce desired headings / vehicle direction
- Variable tether voltage biasing will be modeled and control strategies explored to determine viable GN&C approaches

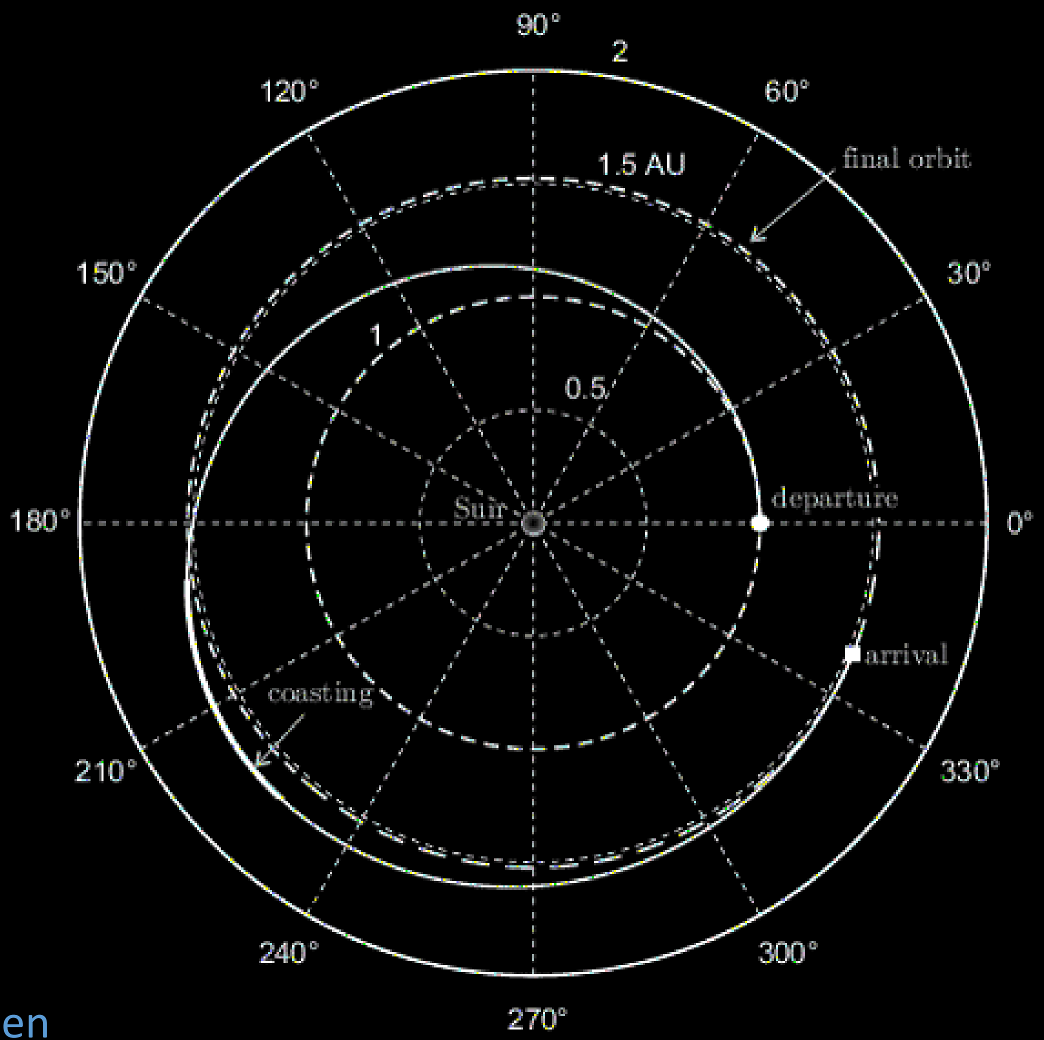


Image courtesy of Dr. Pekka Janhunen

We have a plan.

Roadmap

Wire 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)
Wire Configuration	How many? What length?	End-mass size and configuration		
Wire Material	Develop wire property requirements	Trade of wire materials	Test of structural performance	Test of electrical performance in ion chamber
Wire Dynamics	Analysis of E-Sail wire dynamics	Ground test of subscale wire dynamics		
High Voltage Subsystem	Analysis of optimal wire 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 wire 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

The Necessary Next Steps to a Heliopause Mission in 2025

2014 Phase I NIAC

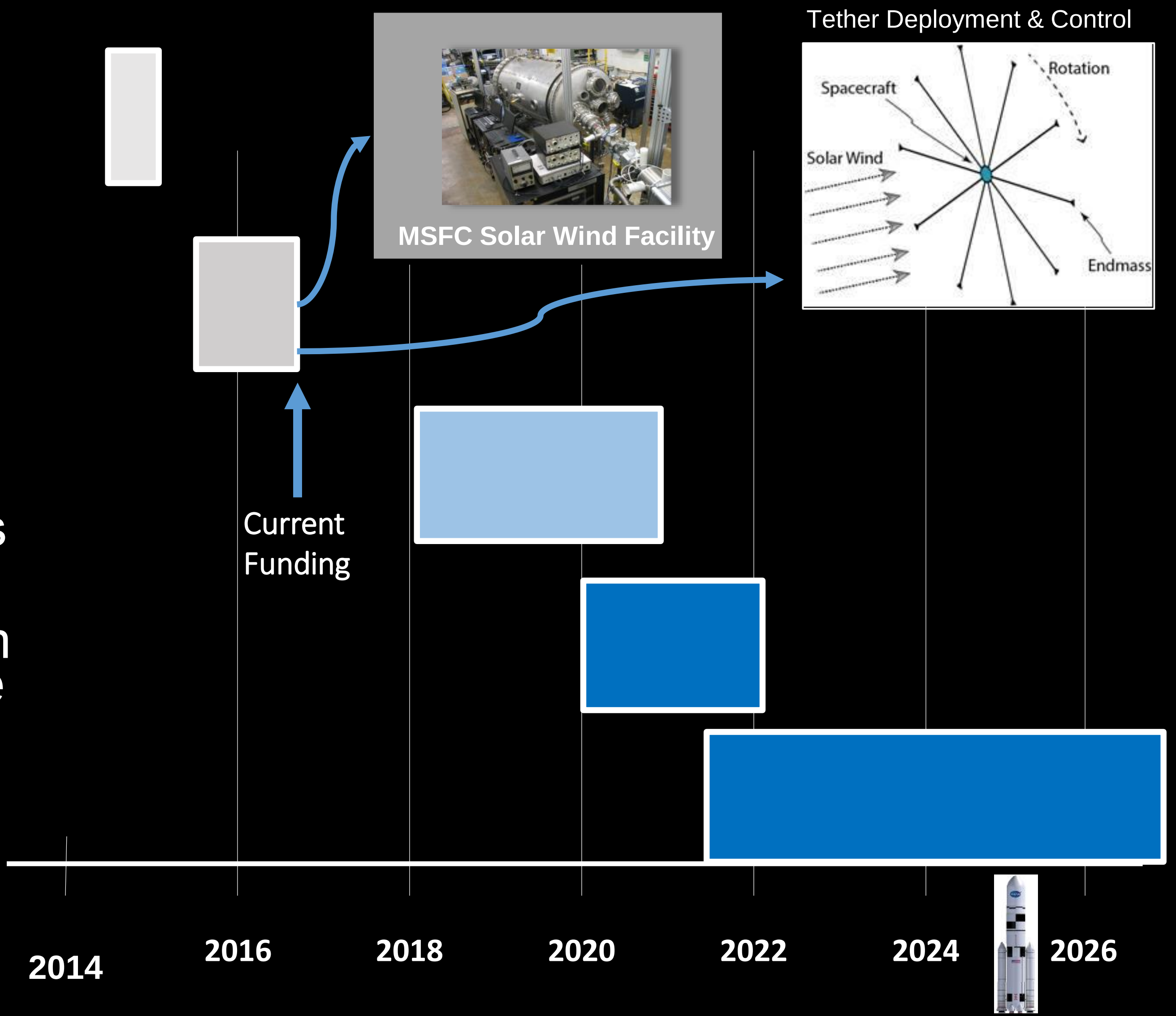
2015 Phase II NIAC

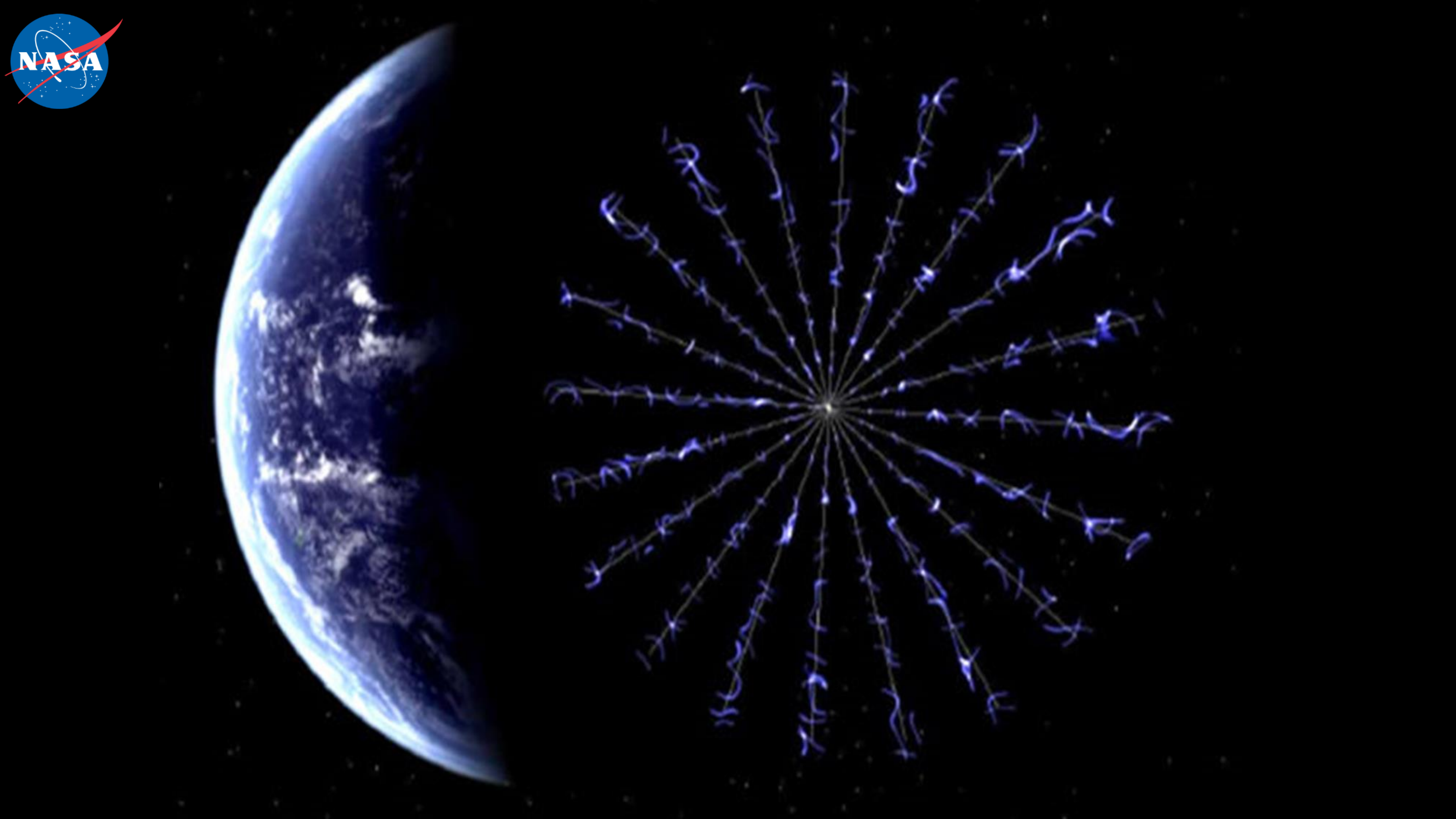
- Develop enhanced numerical modeling
- Perform ground tests to benchmark enhanced numerical codes
- Prototype tether & tether deployers

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

Incorporate design changes req'd from demo flight for build up of Deep Space flight hardware

Fabricate hardware for Heliophysics Mission (notional 2025 launch)




NASA