Electric Sail Propulsion to Enable Quick Heliopause and Beyond Missions of Scientific Discovery

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- Technology Assessment
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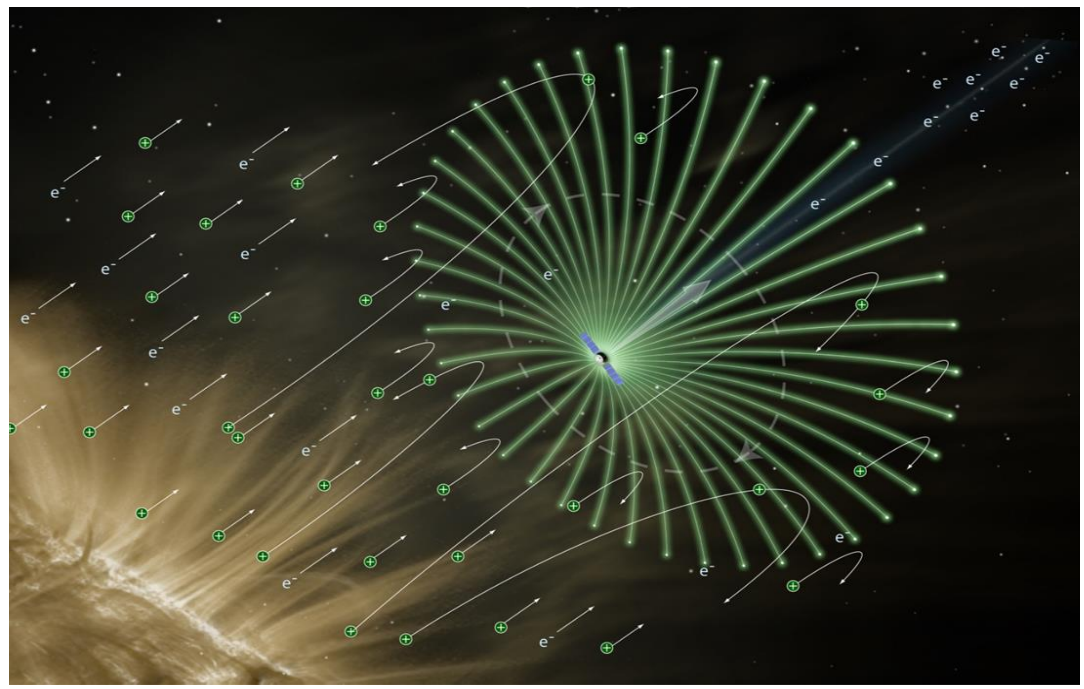
- Next Steps



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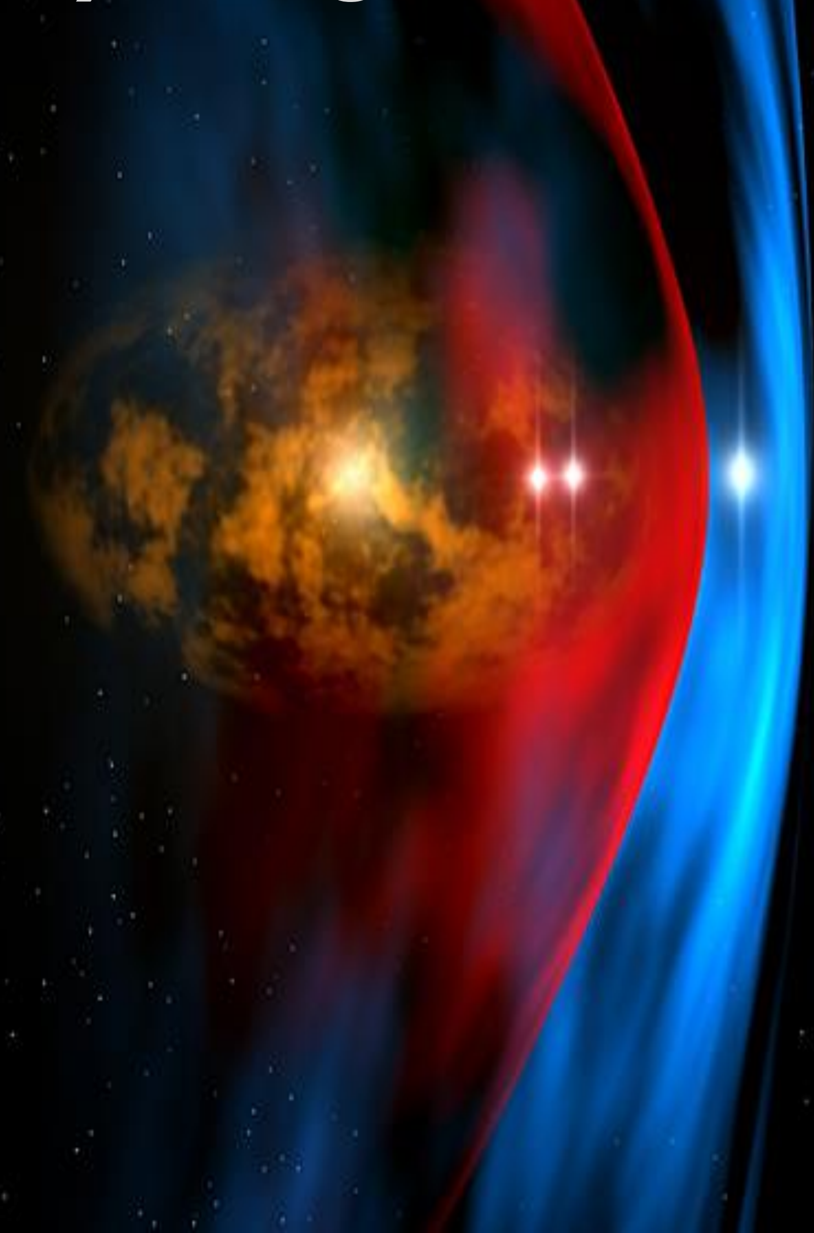
The NASA Innovative Advanced Concepts (NIAC) Program



The 9 Programs of NASA STMD

- **CENTENNIAL CHALLENGES**
  The NASA Centennial Challenges were initiated in 2005 to directly engage the public in the process of advanced technology development.The program offers incentive prizes to generate revolutionary solutions to problems of interest to NASA and the nation.The program seeks innovations from diverse and non-traditional sources.Competitors are not supported by government funding and awards are only made to successful teams when the challenges are met.
- **CENTER INNOVATION FUND**
  The purpose of the Center Innovation Fund is to stimulate and encourage creativity and innovation within the NASA Centers in addressing the technology needs of NASA and the nation.
- **FLIGHT OPPORTUNITIES**
  The Flight Opportunities program develops and provides opportunities for space technologies to be demonstrated and validated in relevant environments.It fosters the development of the commercial reusable suborbital transportation industry.
- **GAME CHANGING DEVELOPMENT (GCD)**
  This program seeks to identify and rapidly mature innovative/high impact capabilities and technologies, and to investigate novel ideas and approaches that have the potential to revolutionize future space missions.
- **NASA INNOVATIVE ADVANCED CONCEPTS (NIAC)**
  The NASA Innovative Advanced Concepts (NIAC) program nurtures visionary ideas that could transform future NASA missions with the creation of breakthroughs—radically better or entirely new aerospace architectures, systems, or missions—while engaging America's innovators and entrepreneurs as partners in the journey.NIAC projects study early, innovative, technically credible, advanced concepts that could one day change the possible in aerospace.The intended scope is for Technology Readiness Levels 1-2 or early 3.
- **THE SMALL BUSINESS INNOVATION RESEARCH (SBIR) AND SMALL BUSINESS TECHNOLOGY TRANSFER (STTR)**
  The SBIR/STTR programs programs provide an opportunity for small, high technology companies and research institutions to participate in government-sponsored research and development (R&D) efforts in key technology areas.
- **SMALL SPACECRAFT TECHNOLOGY PROGRAM**
  The Small Spacecraft Technology program's primary objective is to identify and support the development of new subsystem technologies to enhance or expand the capabilities of small spacecraft, while also supporting flight demonstrations of new technologies, capabilities, and applications for small spacecraft.The Program also seeks to use small spacecraft as platforms for testing and demonstrating technologies and capabilities that might have applications in spacecraft and systems of any size.
- **SPACE TECHNOLOGY RESEARCH GRANTS**
  The Space Technology Research Grants program will accelerate the development of "push" technologies to support the future space science and exploration needs of NASA, other government agencies and the commercial space sector.Innovative efforts with high risk and high payoff will be encouraged.The program is composed of two competitively awarded components: Fellowships and Grants.
- **TECHNOLOGY DEMONSTRATION MISSIONS (TDM)**
  The mission of NASA's Technology Demonstration Missions is to bridge the gap between need and means, between scientific and engineering challenges and the technological innovations needed to overcome them, between laboratory development and demonstration in space.Charged with proving revolutionary, crosscutting technologies—ones that could radically advance NASA's mission in space and reap untold benefits for science and industry here on Earth—the Technology Demonstration Missions program seeks to mature laboratory-proven technologies to flight-ready status.

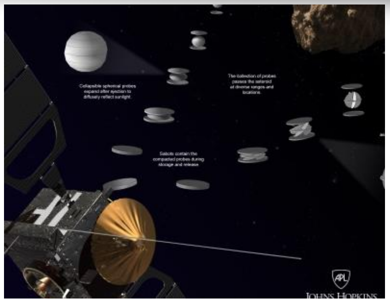
The NASA Innovative Advanced Concepts Program (NIAC)

- The NASA Innovative Advanced Concepts (NIAC) Program nurtures visionary ideas that could transform future NASA missions with the creation of breakthroughs — radically better or entirely new aerospace concepts — while engaging America's innovators and entrepreneurs as partners in the journey.

https://www.youtube.com/watch?v=1cXrpSdcTEg&feature=youtu.be

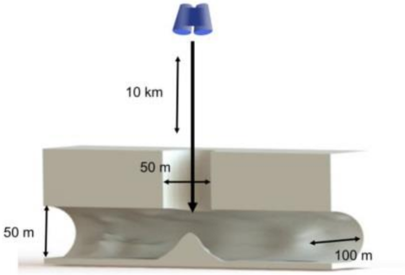
- The program seeks innovations from diverse and non-traditional sources and NIAC projects study innovative, technically credible, advanced concepts that could one day "change the possible" in aerospace. If you're interested in submitting a proposal to NIAC, please see our "Solicitations" link for information about the status of our current NASA Research Announcement (NRA). For descriptions of current NIAC funded projects, please refer to our "Funded Studies" link.

2015 NIAC Phase II Fellows

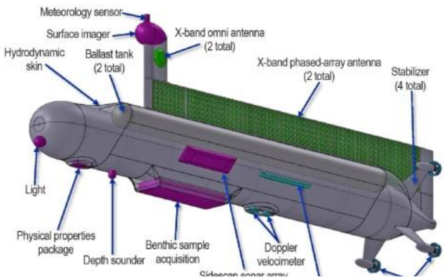


Swarm Flyby Gravimetry, Justin Atchison, Johns Hopkins University

3D Photocatalytic Air Processor for Dramatic Reduction of Life Support Mass and Complexity, Bin Chen, University of California Santa Cruz

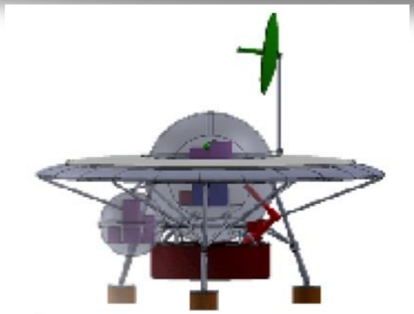


PERISCOPE: PERIapsis Subsurface Cave Optical Explorer, Jeffrey Nosanov, Nosanov Consulting, LLC

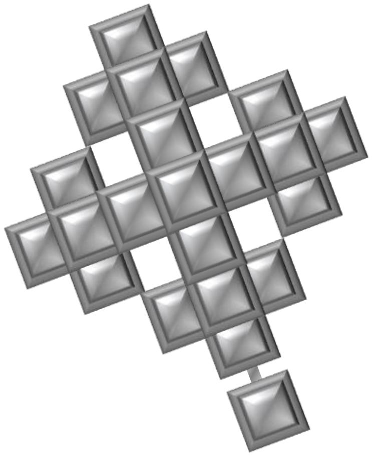


Titan Submarine: Exploring the Depths of Kraken Mare, Steven Oleson, NASA Glenn Research Center

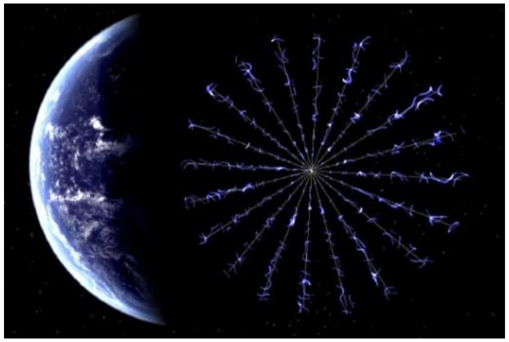
2015 NIAC Phase II Fellows



SCEPS in Space - Non-Radioisotope Power Systems for Sunless Solar System Exploration Missions, Michael Paul, Pennsylvania State University

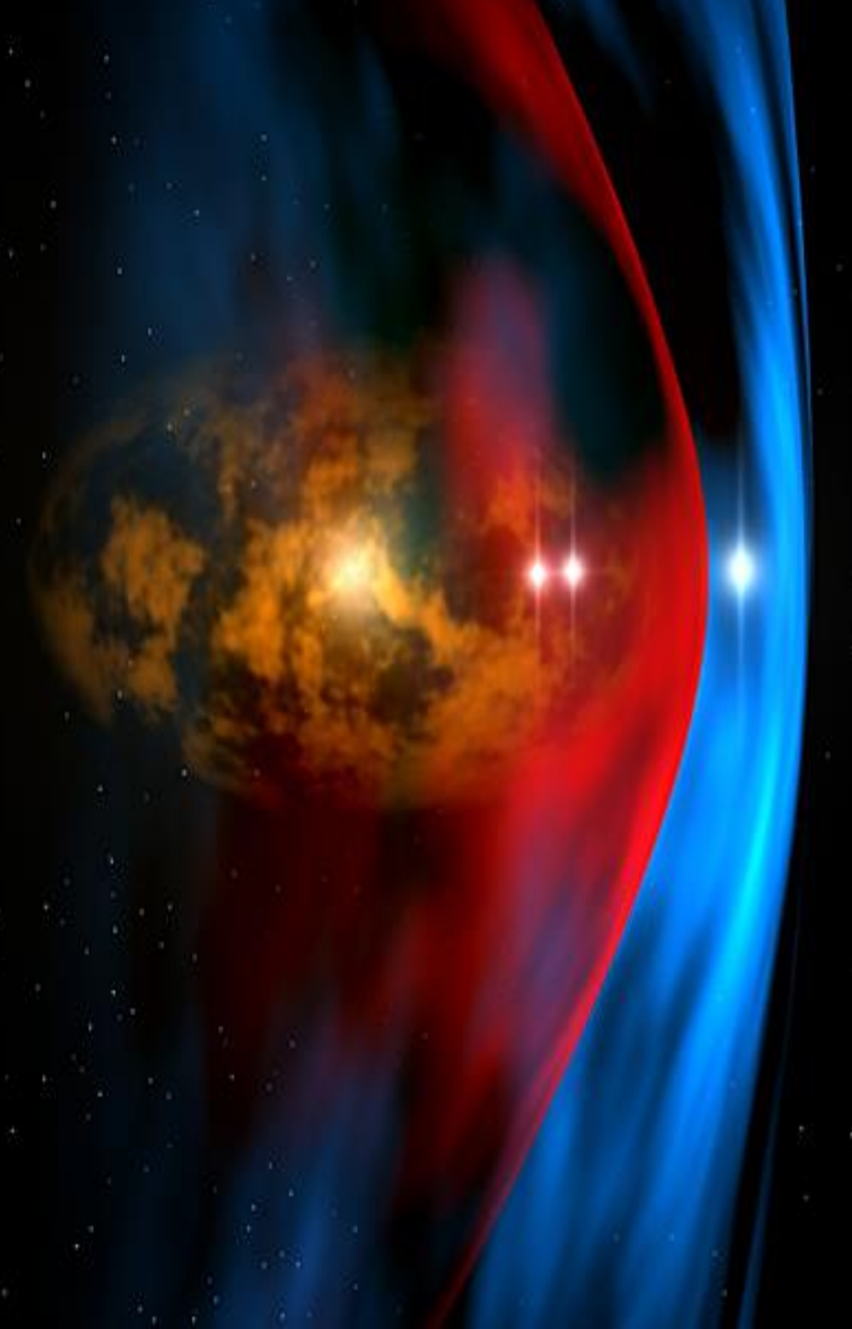


Trans-Formers for Lunar Extreme Environments: Ensuring Long-Term Operations in Regions of Darkness and Low Temperatures, Adrian Stoica, NASA Jet Propulsion Laboratory

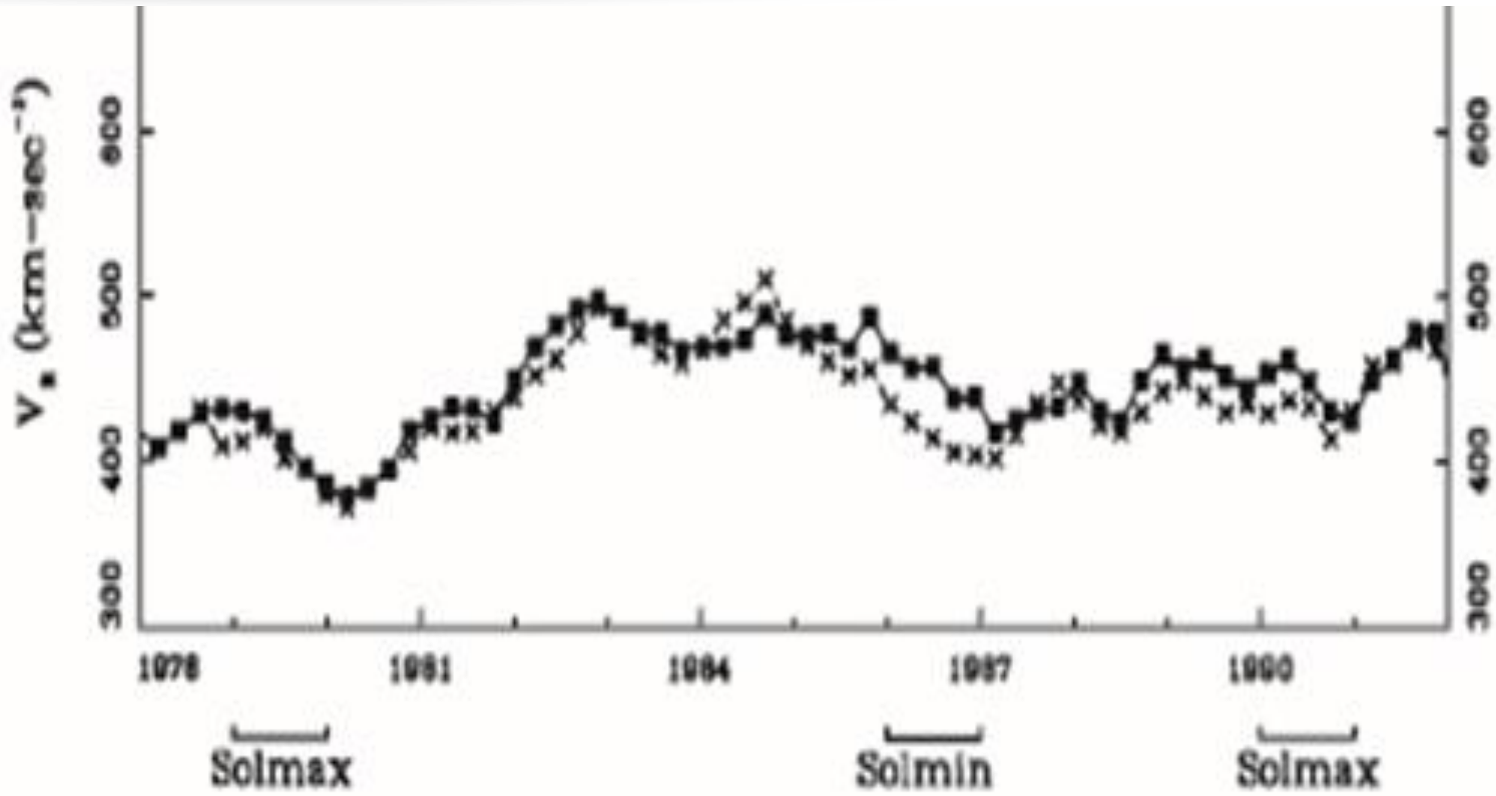


Heliopause Electrostatic Rapid Transit System (HERTS), Bruce Wiegmann, NASA Marshall Space Flight Center

The Solar Wind and Earth’s Magnetic Field

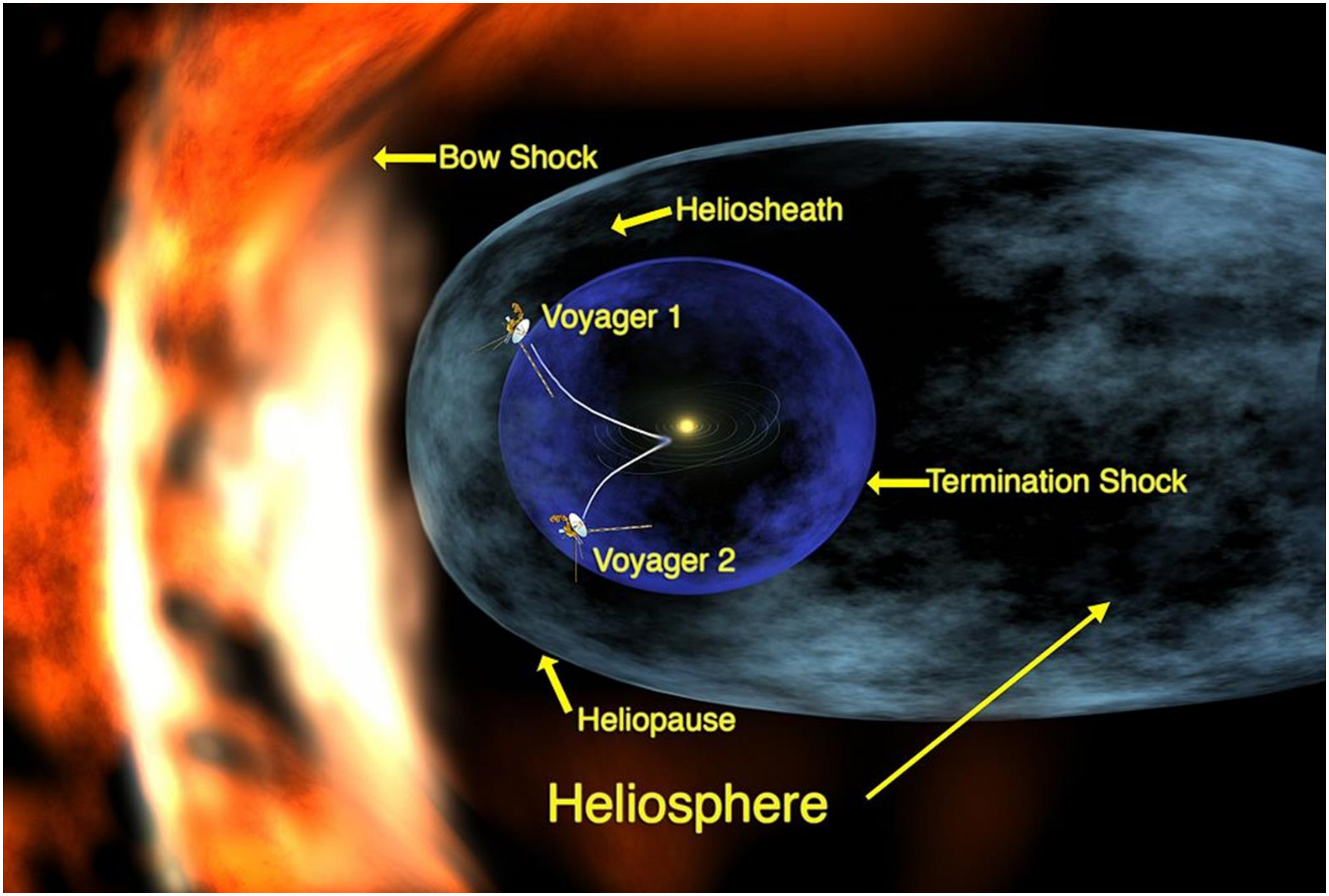


The Naturally Occurring Solar Wind

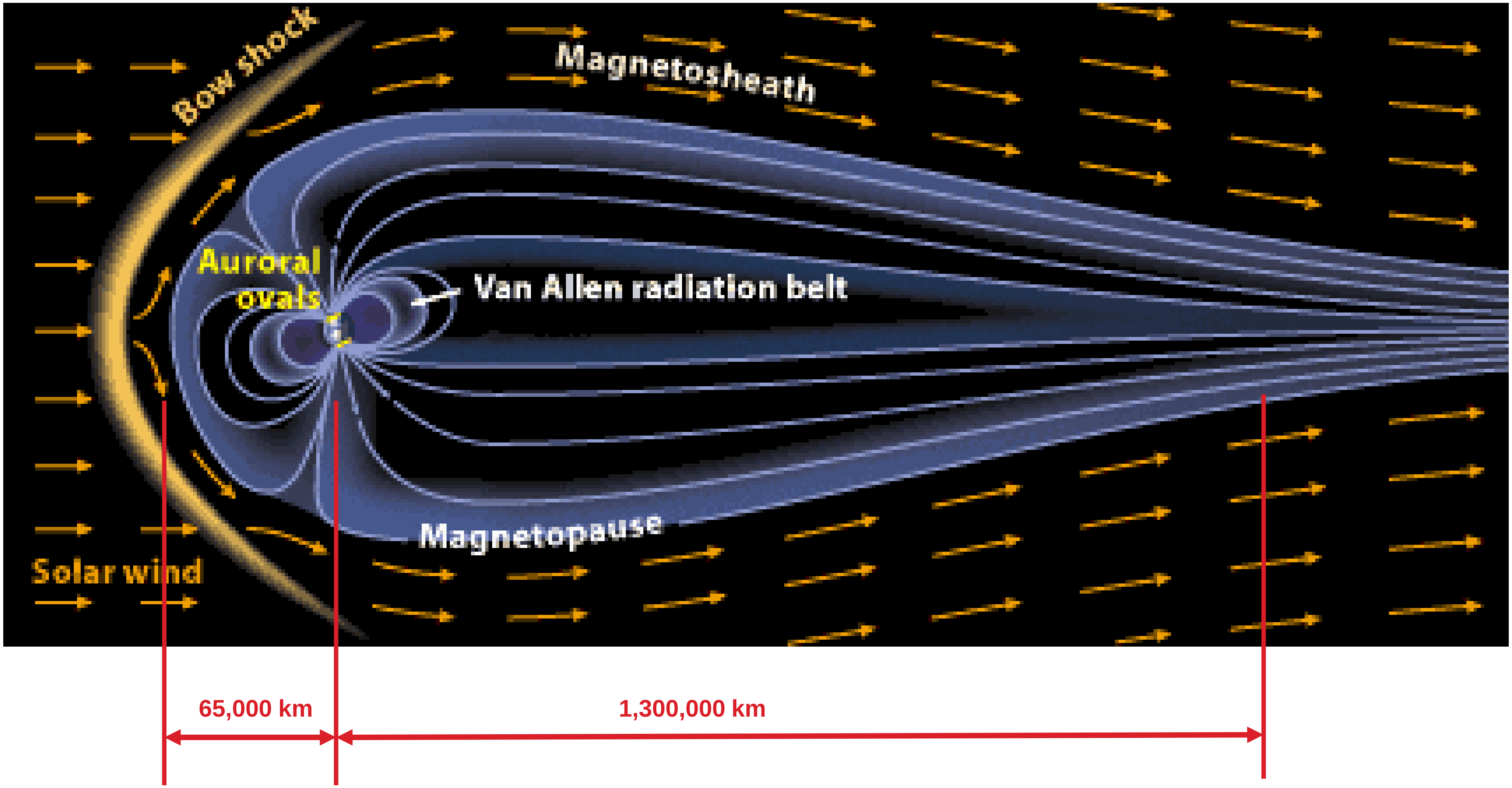


◆ **The relative velocity of the Solar Wind through the decades**

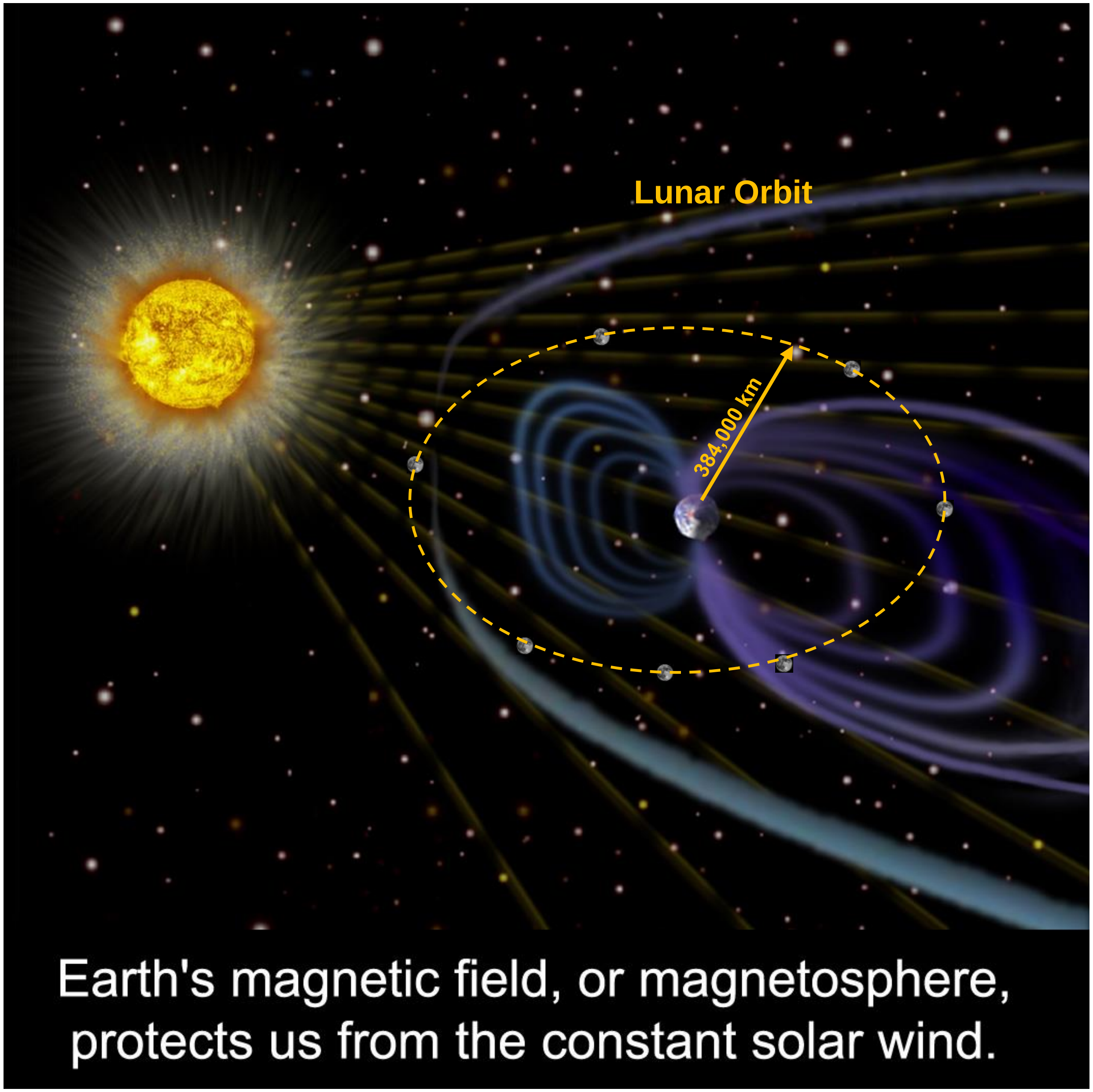
Our Solar Systems Solar Wind Relative to the Universe



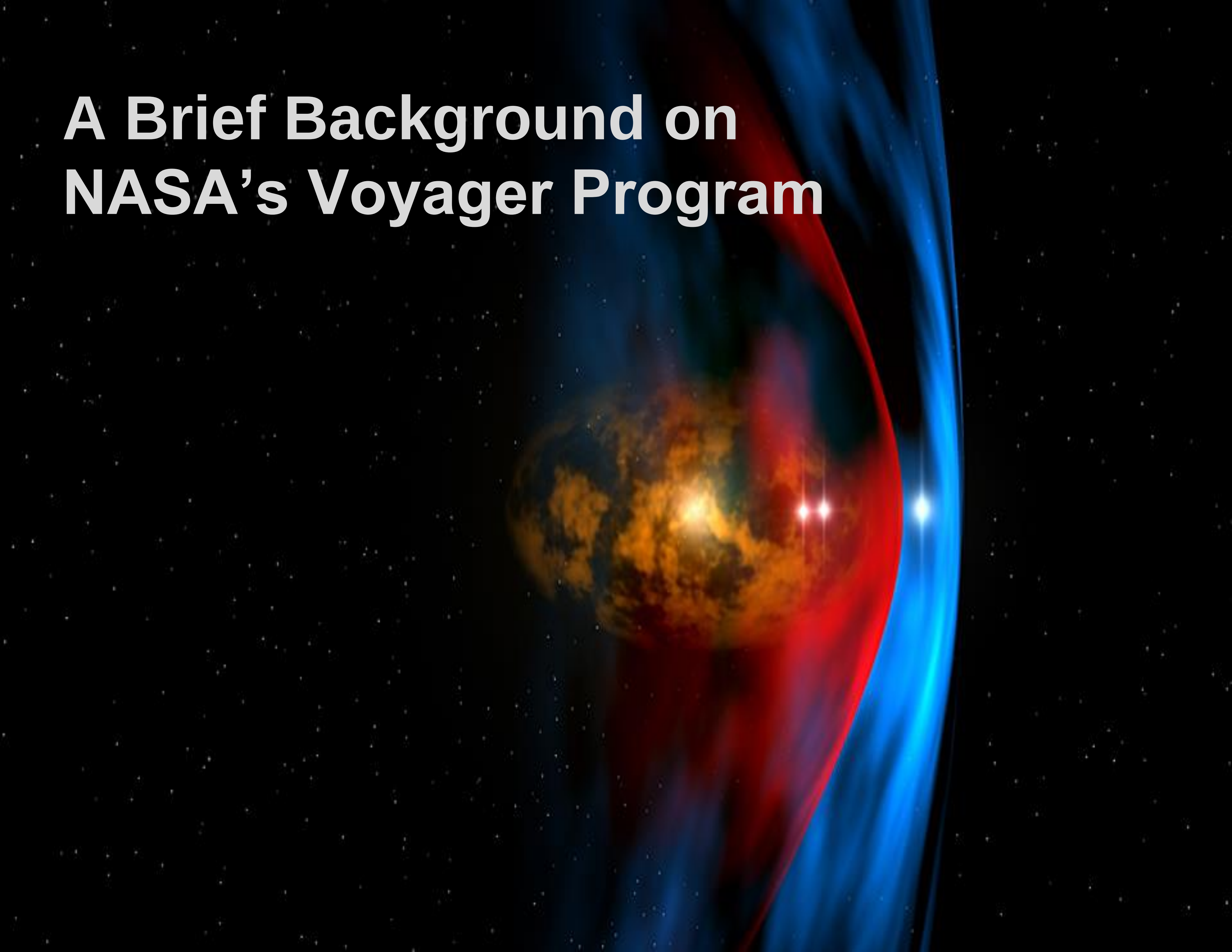
The Earth's Magnetic Field



The Earth’s Magnetic Field & Imposed Lunar Orbit

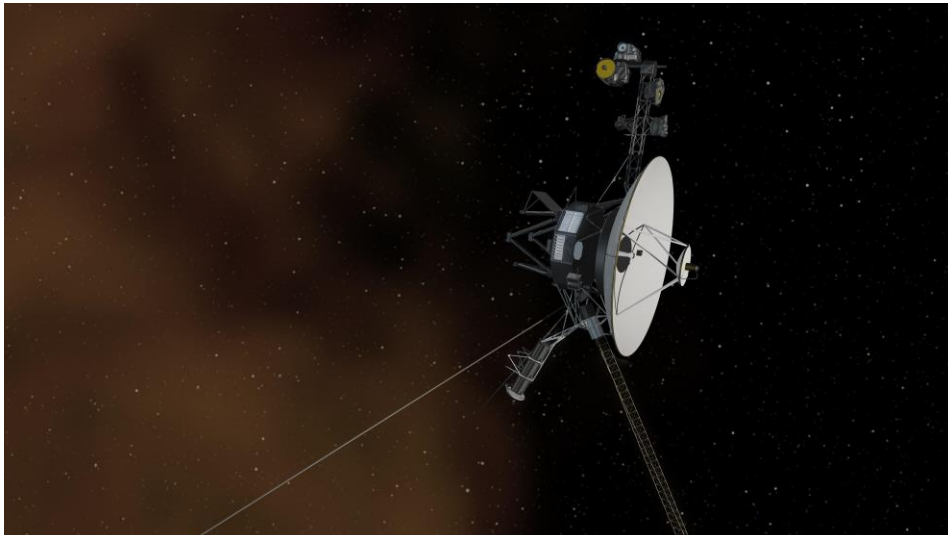


A Brief Background on NASA’s Voyager Program



The Voyager Spacecraft

- The Voyager Program was developed and managed by JPL in the early 1970's and it costed $865 million (1980 $) thru the Neptune encounter
  - That's ~$2.5 Billion today
- Originally envisioned to examine the outer planets except for Pluto, then travel to interstellar space
- Voyagers will be dead in 2025 due to declining power from the on-board RTGs



Voyager Milestones

- The Voyager Spacecrafts were launched in 1977
  - 1977 -- Voyagers are launched
  - 1979 – Went past Jupiter (5.2 AU distance)
  - 1980 – Went past Saturn (9.6 AU distance)
  - 1986 – Voyager 2 went past Uranus (30 AU distance)
  - 2004 – Voyager 1 crossed the Solar System termination shock (94 AU)
  - 2007 -- Voyager 2 crossed the Solar System termination shock (84 AU)
  - 2012 – Voyager 1 enters Interstellar Space (121 AU)
  - Today – Voyager 1 is 133 AU away; Voyager 2 is 110 AU away

Reflection Moment

- When Voyagers were launched in 1977
  - These were some key events:
    - Apple Computer incorporated & the Apple 2 computer is introduced
    - The MRI machine is invented
    - The Commodore PET was introduced as well
- When the Voyagers passed Jupiter in 1979
  - The cell phone was invented
  - Walkman invented
  - Roller blades invented
- When the Voyagers passed Uranus in 1986
  - USSR space station MIR was launched
  - Disposable cameras were marketed by Fuji Film
  - IPO of Microsoft Corp

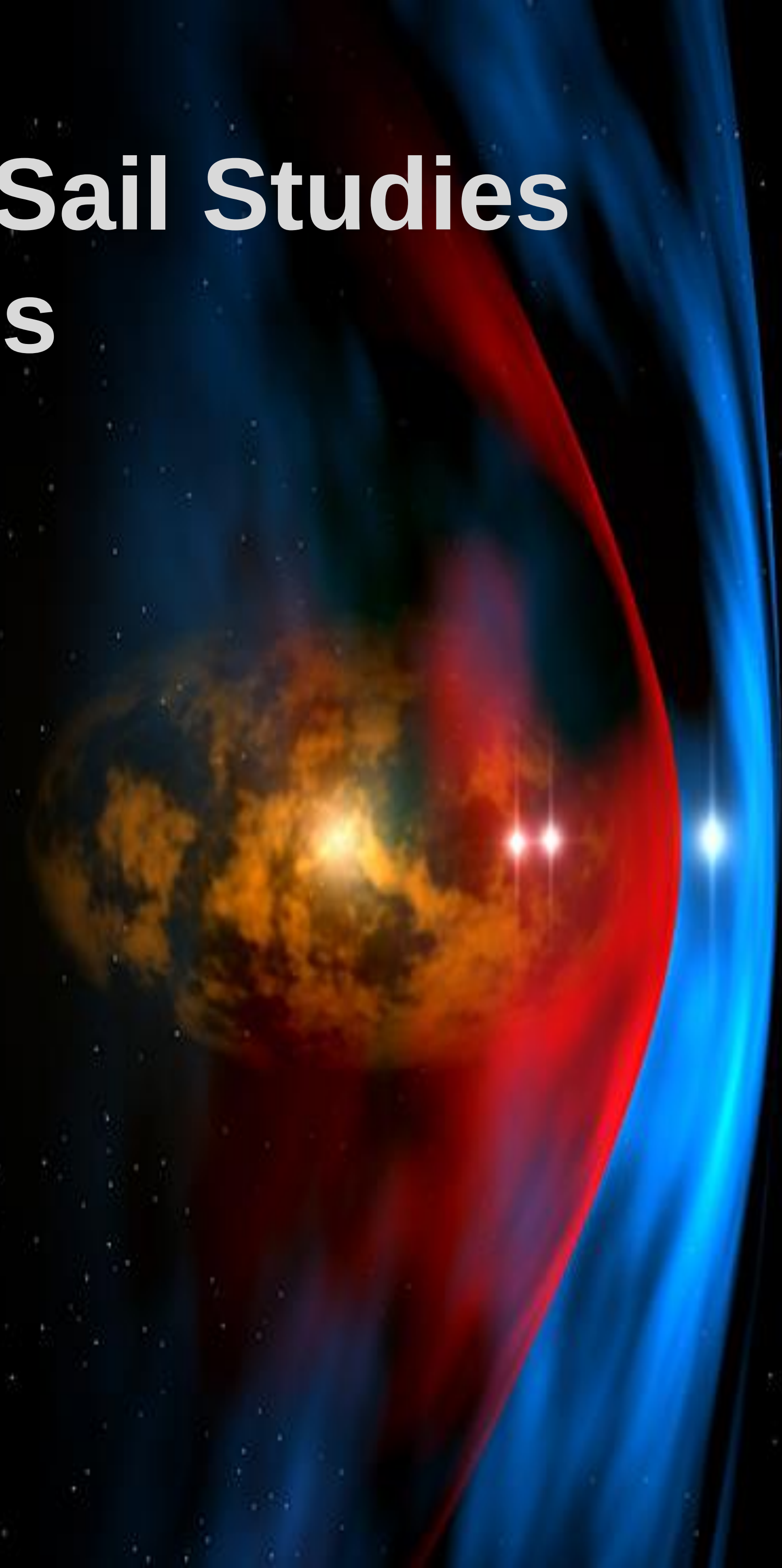
Reflection Moment (con't)

- When the Voyagers passed Neptune in 1989
  - Doppler Radar had just been invented in 1988
  - HDTV was invented in 1989

- When the Voyager 1 entered Interstellar Space in 2012
  - Viagra had been invented in 1998
  - iPods were invented in 2001
  - YouTube invented in 2005

During the life of the Voyager Missions, technology in nearly all areas progressed, but the propulsion systems for Deep Space Travel have stayed the same with the exception of Hall thrusters (NASA Dawn mission),
Our Phase II effort NIAC is setting the foundation to change that paradigm!

Initial Electric Sail Studies and the Results



Why Revolutionary Propulsion is 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 ($V_{mssn\ avg}$: 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."*

Why MSFC is Investigating

- Dr. Pekka Janhunen's of the Finnish Meteorological Institute is the inventor of the E-sail and this propulsion concept is intriguing,
  - But needed a more thorough investigation by NASA
- Systems and technologies required for a successful E-Sail development build upon past and present MSFC space flight hardware experience:
  - STS Tether Satellite System Missions (1980s- 1990s)
  - ProSEDs (Propulsive Small Expendable Deployer System)
    - (late 90s to early 2000s (cancelled))
  - Recent Electrodynamic Tether (EDT) work
    - TDM proposed mission
  - Solar Sail Missions
    - Nana Sail D
    - Lunar Flashlight and NEA Scout (AES funded mission) solar sail element
  - FastSat
  - Space Environments corporate knowledge
    - Solar wind physics and testing chambers

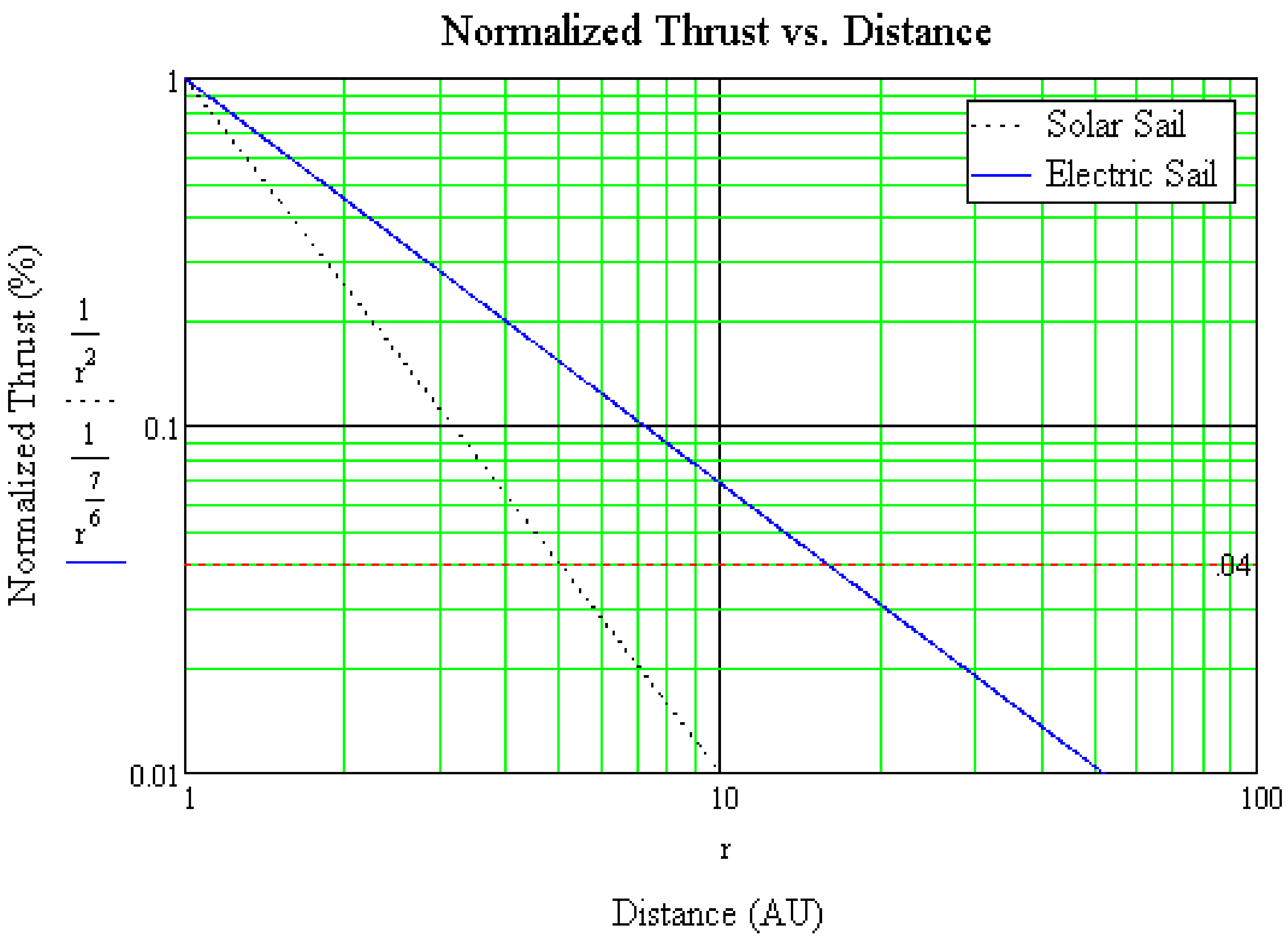
Benefits of E-Sail vs. Solar Sail

- 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
  - 3 times distance of applied acceleration to spacecraft

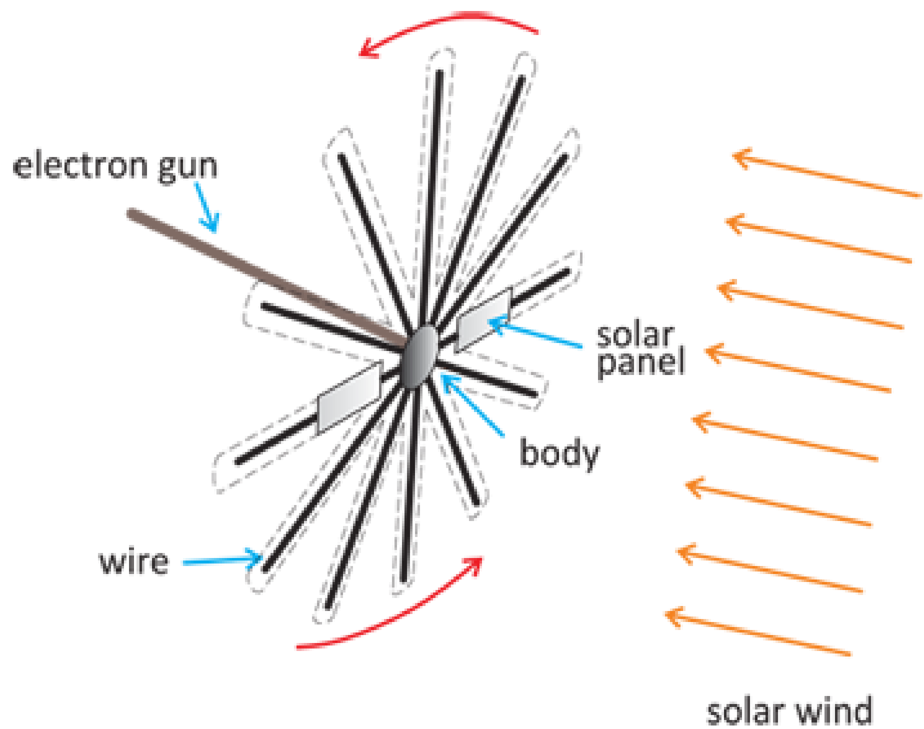
Normalized Thrust Decay Comparison



Electric Sail Physics

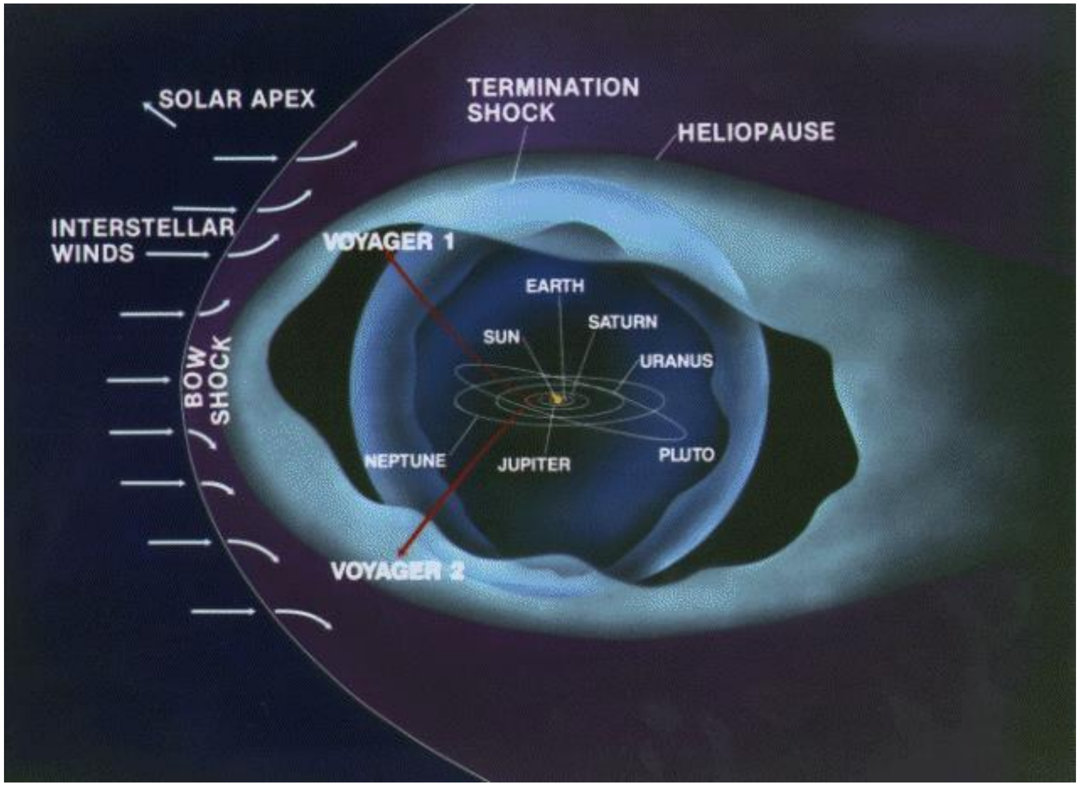
- Electric sail utilizes charged ‘Bare-Wires’ to *repel solar wind protons* to gain momentum

- Charged ‘Bare-Wires’ are centrifugally stretched and charged to a high voltage onboard electron gun
  - The centrifugal force is 5 times the estimated maximum thrust force produced to continually keep the long bare wires perpendicular to the sun
  - This enables the maximum exposed area to produce thrust



Electric Sail Concept

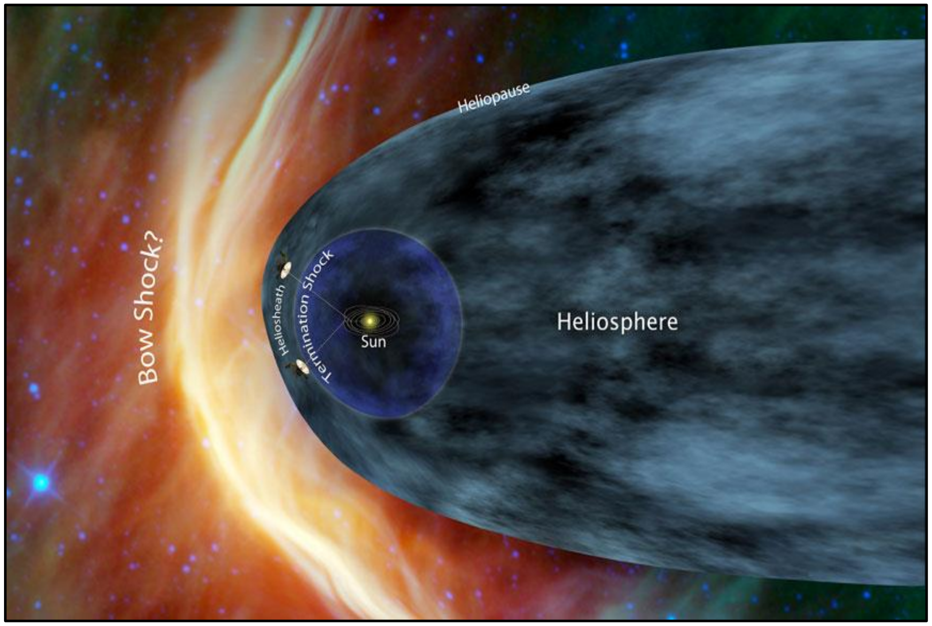
Mission Objectives

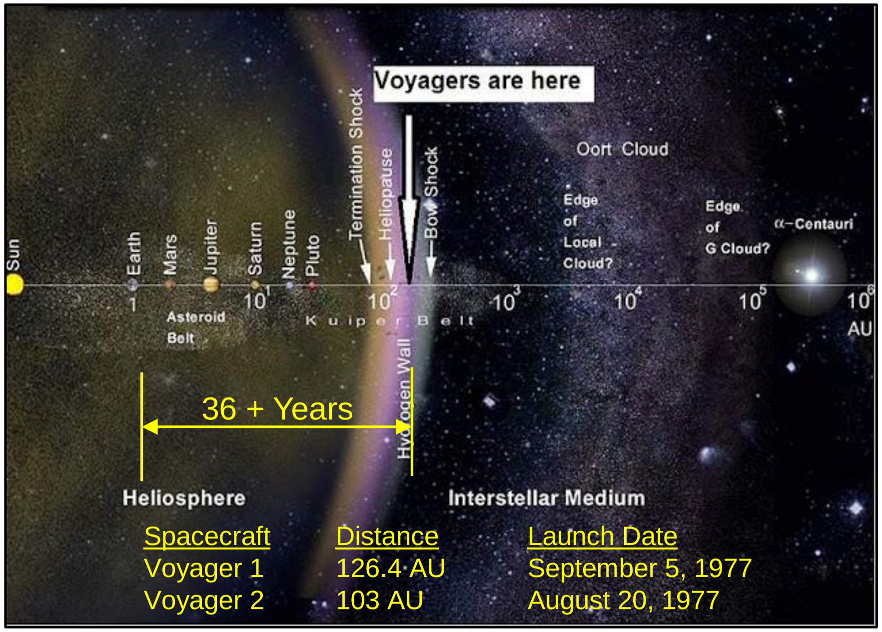


- No mission specifically designed to explore the outer solar system and investigate the interstellar medium
- Travel to ~100 AU and beyond as quickly as possible

Past 'extra' Solar System Spacecraft

- The need to send a craft to <u>the edge of the Solar System in a quick manner</u> is easy to understand, once you understand where Voyagers 1 and 2 are now and how long it took them to travel to these locations





Approach Used

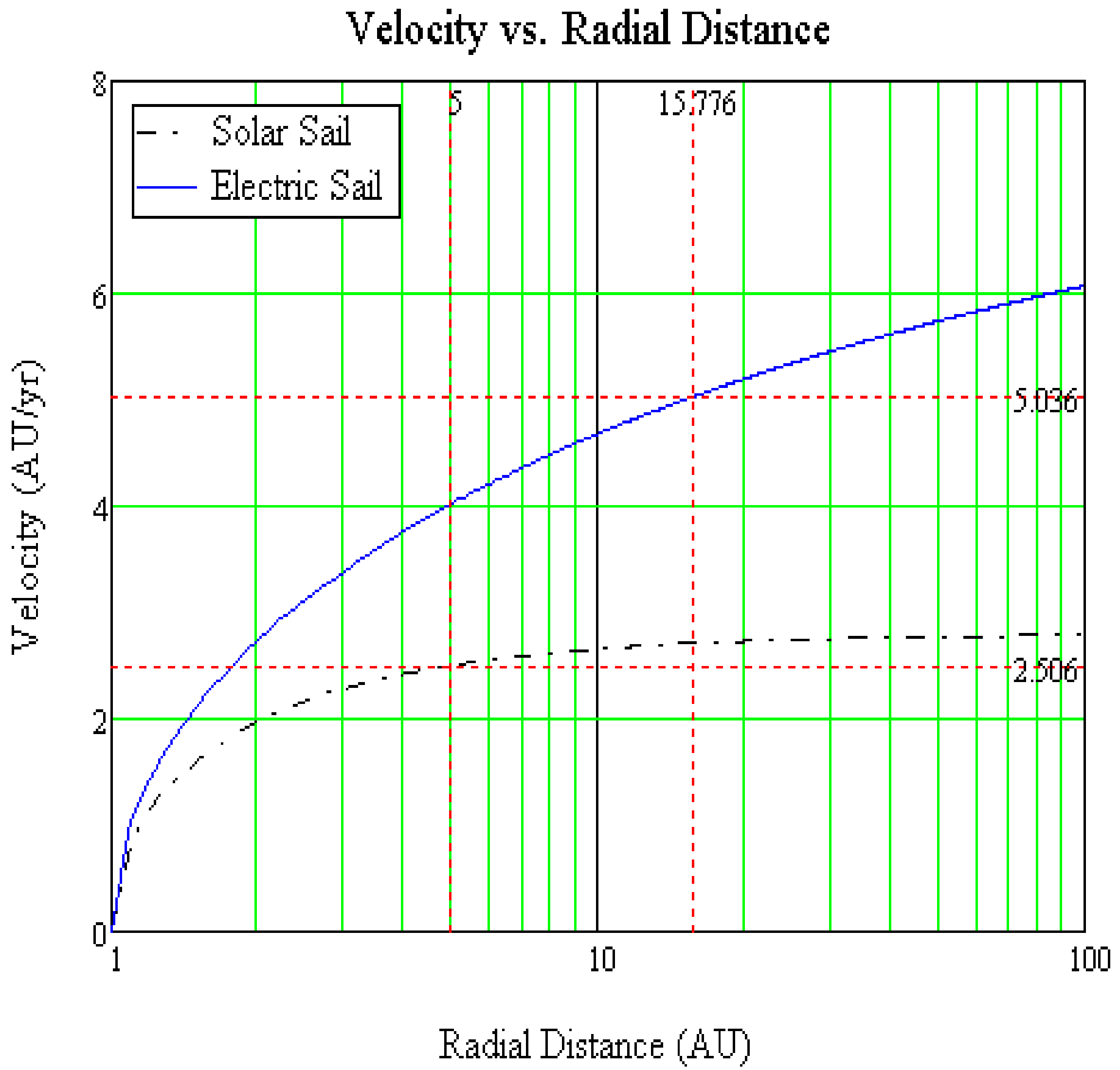
- Examined fundamental physics of the Electric Sail concept
  - Assessed previous work largely produced by P. Janhunen with others
  - Examined body of work, carried out at NASA/MSFC in the late 1970's to early 1980's w.r.t. spacecraft charging effects, to assess streaming proton interaction with charged conductors (impacts momentum exchange).
  - Examined work done by TRW in the 1960's to assess enhancement of electron collection as a result of plasma sheath focusing effects (impacts required electrical power).
  - Assessed environment (MSFC Dr. Gallagher & Dr. Seuss – Subject Matter Experts from NSSTC)
- Examined spacecraft concepts provided by various authors
- Compared Electric Sail concept to baseline Solar Sail concept

Comparison of Equal Thrust Concepts at 1 AU

- First cut utilized equal system thrust
- Early concepts assumed 200 kg payload
- E-sail
  - Janhunen baseline system (next slide)
  - 24 tethers totaling 192 km produce 482 mN
  - System mass of 558 kg
  - Acceleration of 0.864 mm/s^2
- Solar sail
  - Required sail area was 58,000 m^2 or 14.4 acres
    - This was recognized as unreasonable
    - SOA estimates a 100 m x 100 m or ~2.5 acre maximum area
  - Solar sail system mass of 815 kg
    - Adapted from McInnes with same payload
  - Acceleration of 0.591 mm/s^2

Velocity vs. Radial Distance from Sun (Equal Thrust @ 1AU)

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



E-Sail 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:

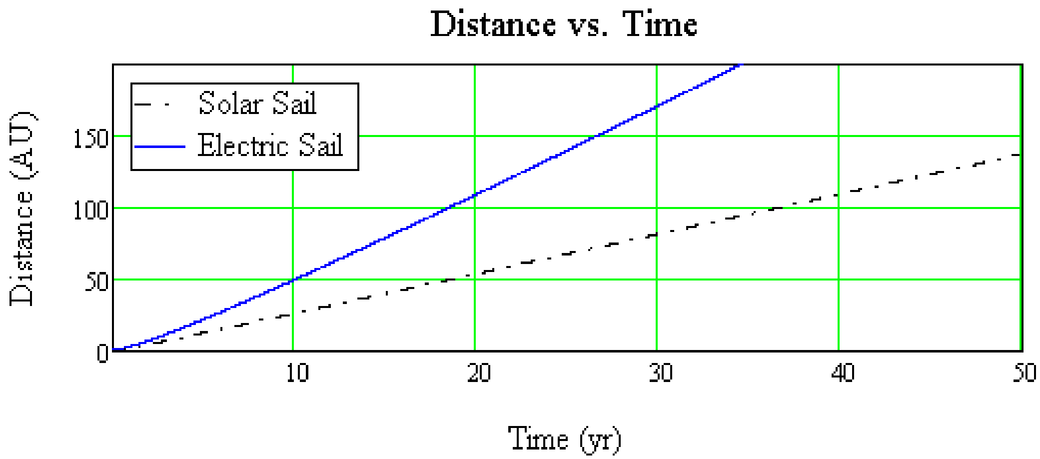
$$\frac{dF}{dz} = \frac{K m_P n_o v^2 \, 2\sqrt{\dfrac{\varepsilon_o T_e}{n_o e^2}}}{\sqrt{\exp\left[\dfrac{m_P v^2}{eV_o} \ln\left({r_o}/{r_w} \right)\right] - 1}}$$

- Removing the constants and exponent (small effect)

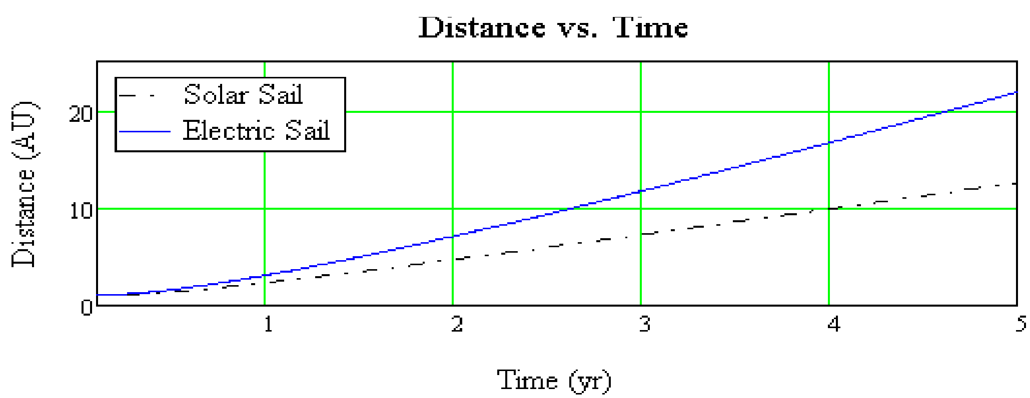
$$\frac{dF}{dz} \cong n_o \sqrt{\frac{T_e}{n_o}} \cong \sqrt{n_o T_e} \approx \sqrt{\frac{1}{r^2}\frac{1}{r^{1/3}}} \approx \left(\frac{1}{r}\right)^{7/6}$$

Simplified Distance vs. Elapsed Time

- Simplified straight line trajectory (drag race) away from the sun for comparison purposes
  - Ignores gravity assists, positive C3, proper orbit, and gravity
- Although thrusts are equal, system mass and thrust cutoff are different.
- 50 year

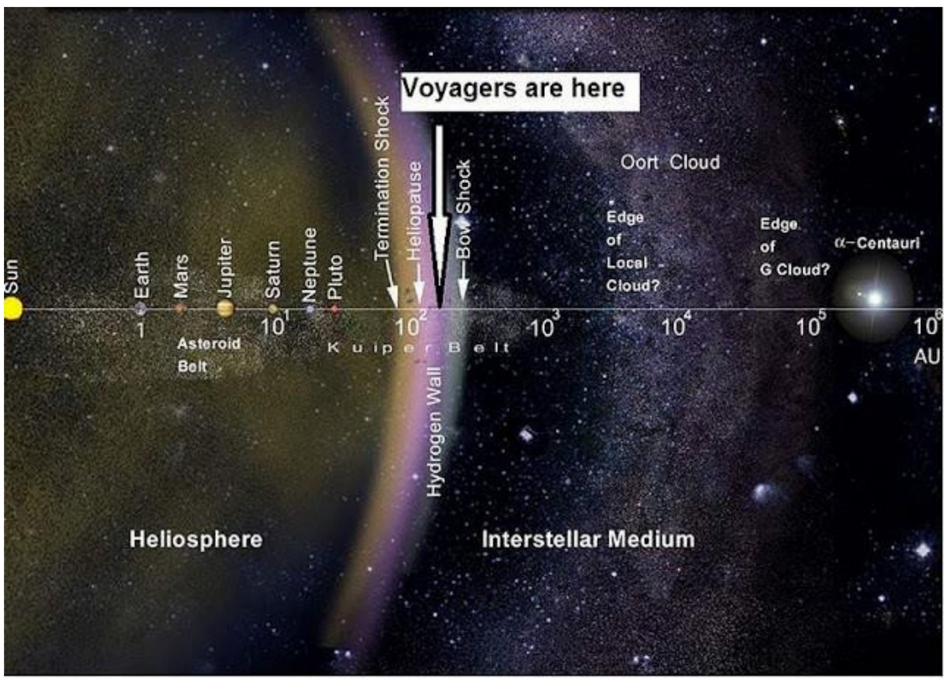


- 5 year



Trip Time Comparison: Equal Thrust Concepts at 1 AU

- Spacecraft accelerated until thrust dropped to 4% of initial thrust at 1 AU
  - Point in thrust decay where solar sails would be jettisoned
  - ~5 AU for Solar Sail, obtains ~2.5 AU/yr
  - ~15.8 AU for Electric Sail, obtains ~5.0 AU/yr



Planet	Electric (yr)	Solar (yr)
Mars (1.52 AU)	0.45	0.56
Jupiter (5.46 AU)	1.61	2.30
Saturn (9.58 AU)	2.55	3.94
Uranus (19.2 AU)	4.51	7.79
Neptune (30.1 AU)	6.69	12.15
Pluto (39.5 AU)	8.57	15.91
Heliopause (125 AU)	25.67	50.11

Note that this is a “drag race” comparison. Does not account for orbit trajectories, orientation, gravity assists, positive C3 etc…

Spacecraft Sizing Trades

- Based upon previous analysis, Decision to make mass of E-Sail S/C and Solar Sail S/C the same for next trade study
  - Reduced number of ‘Bare Wires’ to reflect practical experience and lower development risk
- Reviewed proposed spacecraft configurations from Janhunen and others
  - Most concepts used very large number of “Bare Wires’ (> 20) and very small diameter conductors
- Thrust was calculated using empirical data previously collected at MSFC (N. Stone), this increased thrust produced

Refined Trade Space: Spacecraft with Equal System Masses

- Spacecraft system mass was set equal
  - 200 kg payload was reduced to 20 kg
- Limited to maximum near-term deployable solar sail size (10000 m^2 or 2.47 acre) used to determine solar sail system mass
  - Same sizing references as previous

Electric Sail	
Tether	39.1
Main Tether reels	25.1
Electron Gun	0.6
Voltage Source	4.1
Sail Camera & Computer	17.8
Remote Units	10.0
Auxtether Mass	59.5
Propulsion Total	*156.2*
Structure & Payload	
ASRG:RTG	64.0
Telemetry System	5.0
Thermal Control System	7.2
Attitude Control System	12.7
Structure	45.2
Science Payload	20.0
20%Margin	*62.1*
Total System Mass	**372.3**

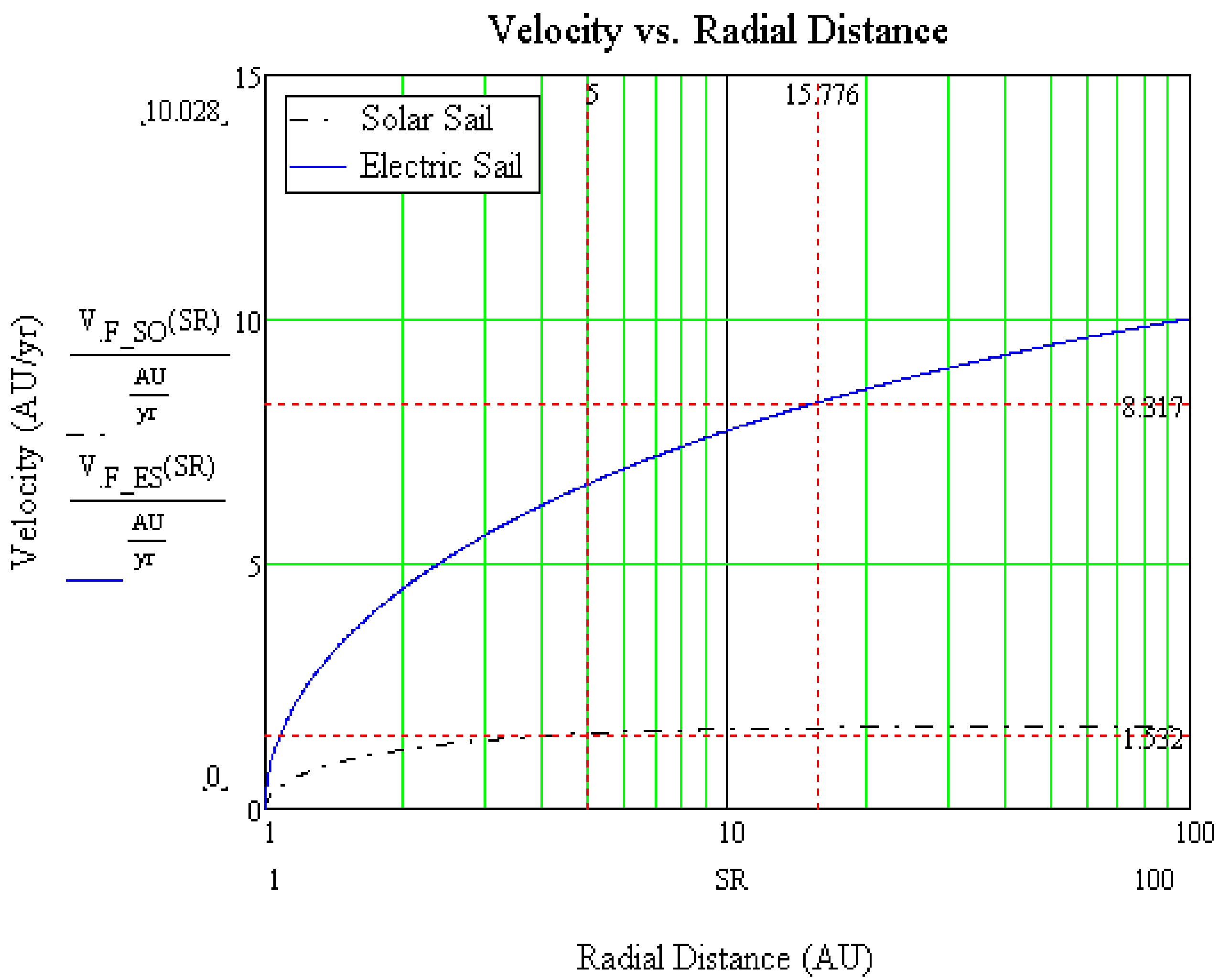
Solar Sail	
Solar Sail Film	75.0
Support Boom	50.0
Sail Coating	6.3
Bonding	9.8
Mechanisms	42.3
Propulsion Total	183.4
Structure & Payload	
ASRG:RTG	32.0
Telemetry System	5.0
Thermal Control System	7.9
Attitude Control System	18.5
Structure	44.5
Science Payload	20.0
20%Margin	*62.3*
Total System Mass	**373.5**

Difference in Thrust @ 1 AU between HERTS and Solar Sail

- Electric sail thrust per unit length calculated by Stone
  - $2.51 \cdot 10^3$ nN/m
- Electric sail S/C mass allocation allowed for 350 km of 'Bare-Wires'
  - 877 mN
- Acceleration of 2.356 mm/s^2
  - Smaller payload
- Solar sail thrust per unit area
  - $8.25 \cdot 10^3$ nN/m^2
- Resulting solar sail thrust (10000 m^2 sail)
  - 83 mN
- Acceleration of 0.221 mm/s^2
  - Smaller payload but much smaller sail

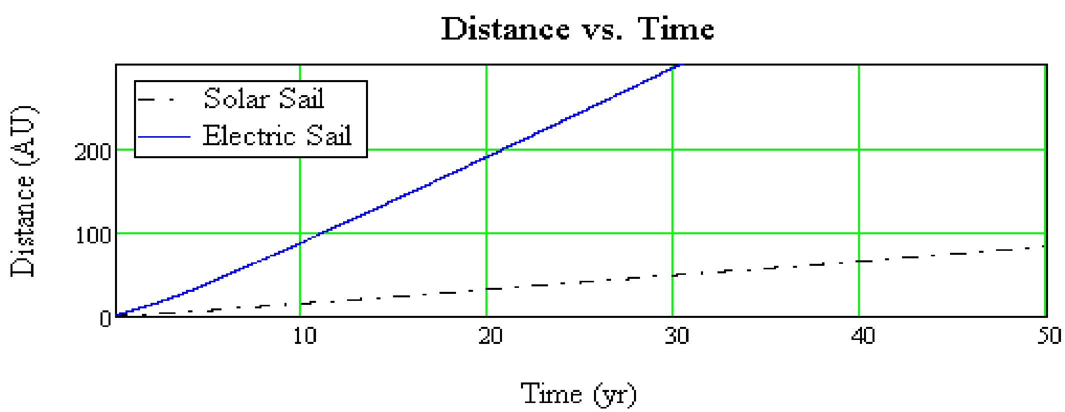
Velocity vs. Radial Distance Comparison for Equal Mass Spacecraft

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

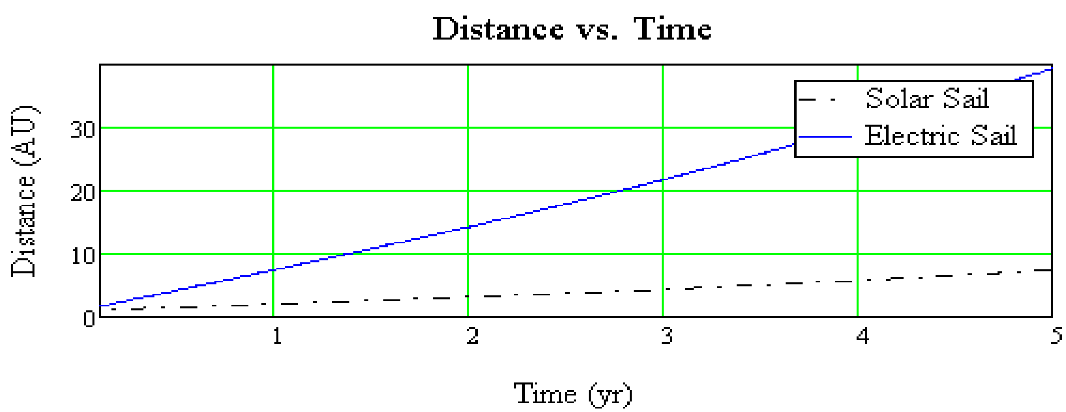


Comparison of Simplified Distance vs. Elapsed Time (for like mass S/C)

- Simplified straight line trajectory (drag race) away from the sun for comparison purposes
  - Ignores gravity assists, positive C3, proper orbit, and gravity
- Equal mass spacecraft with different thrust and cutoff.
- 50 year



- 5 year



Trip Time Comparison for Same Mass Spacecraft

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  - ~5 AU for Solar Sail, obtains ~1.53 AU/yr
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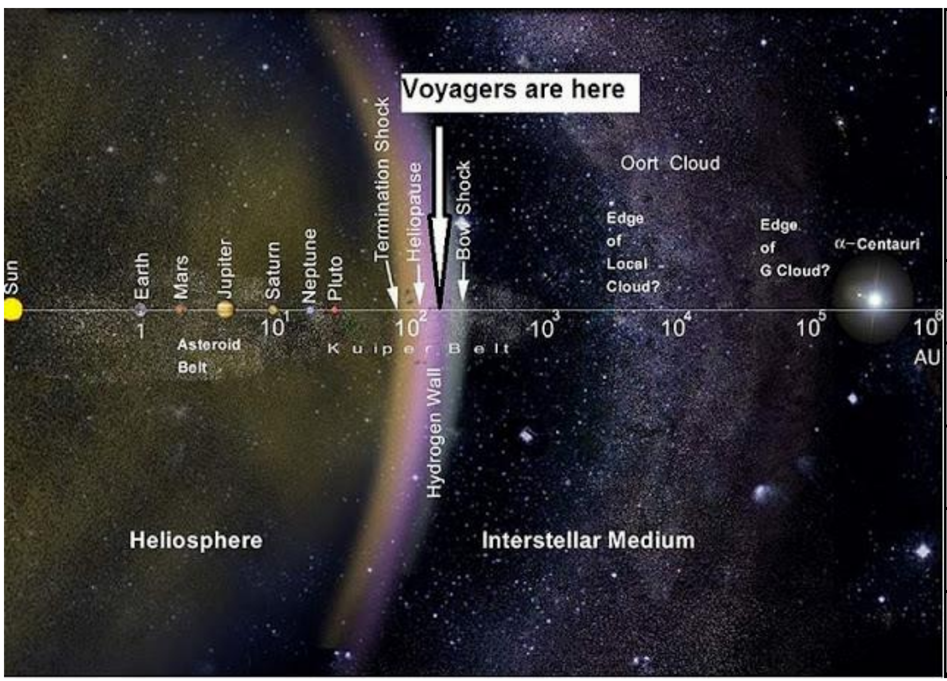

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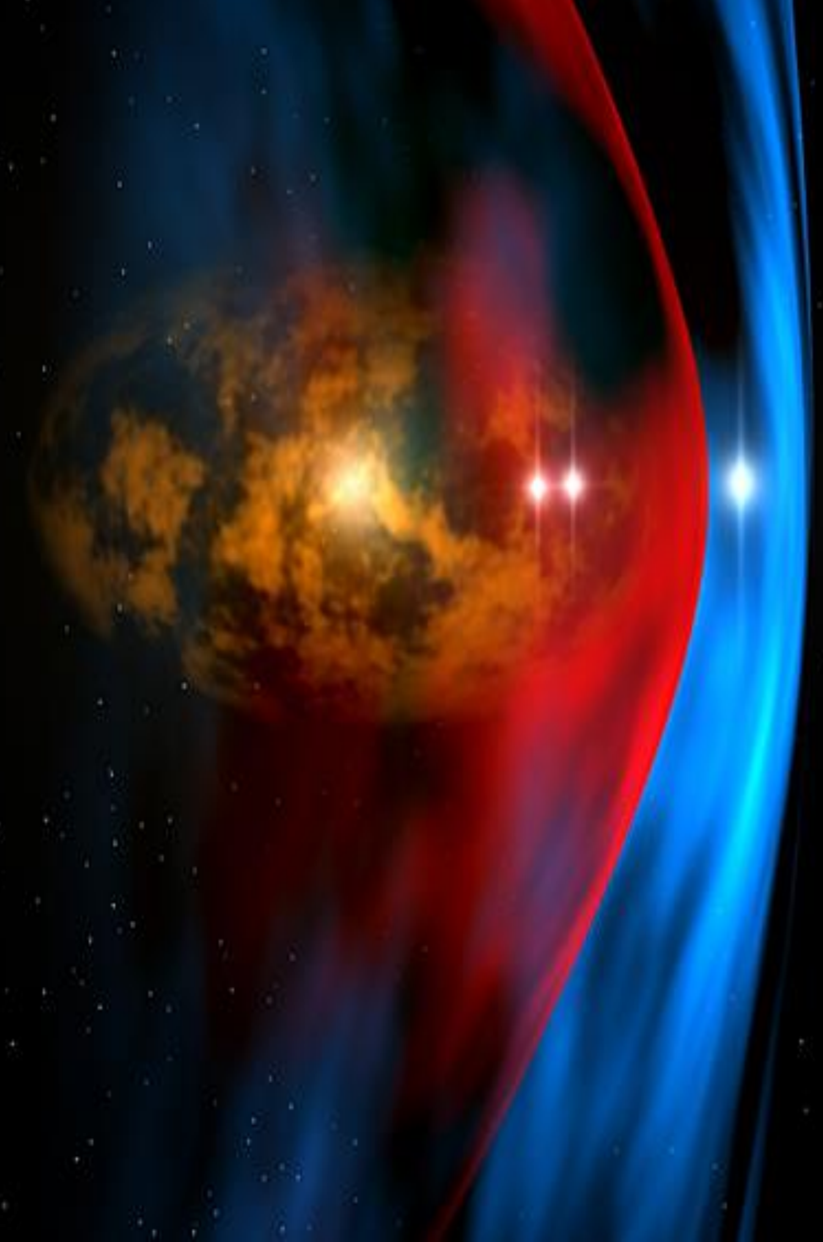
Jupiter (5.46 AU)	0.69	3.79
Saturn (9.58 AU)	1.32	6.33
Uranus (19.2 AU)	2.62	12.16
Neptune (30.1 AU)	3.93	18.65
Pluto (39.5 AU)	5.06	24.21
Heliopause (125 AU)	15.34	74.39

Note that this is a “drag race” comparison. Does not account for orbit trajectories, orientation, gravity assists, etc…

Electric Sail: Technical Justification

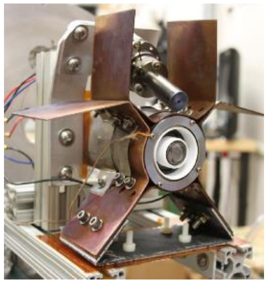
- Has the potential to fly payloads out of the ecliptic and into non-Keplerian orbits, place payloads in a retrograde solar orbit, flyby missions to terrestrial planets and asteroids and position instruments for off-Lagrange point space weather observation.
- Low mass, low cost propulsion system.
- Electric sail thrust extends deep into the solar system (further than a solar sail).
- Can be packaged in a small spacecraft bus

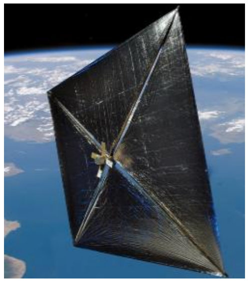
Comparison of Alternative Advanced Transportation Options

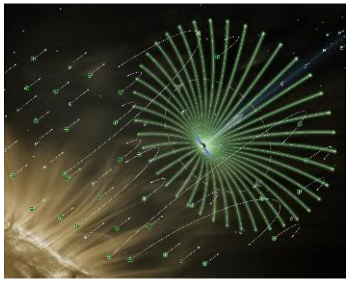


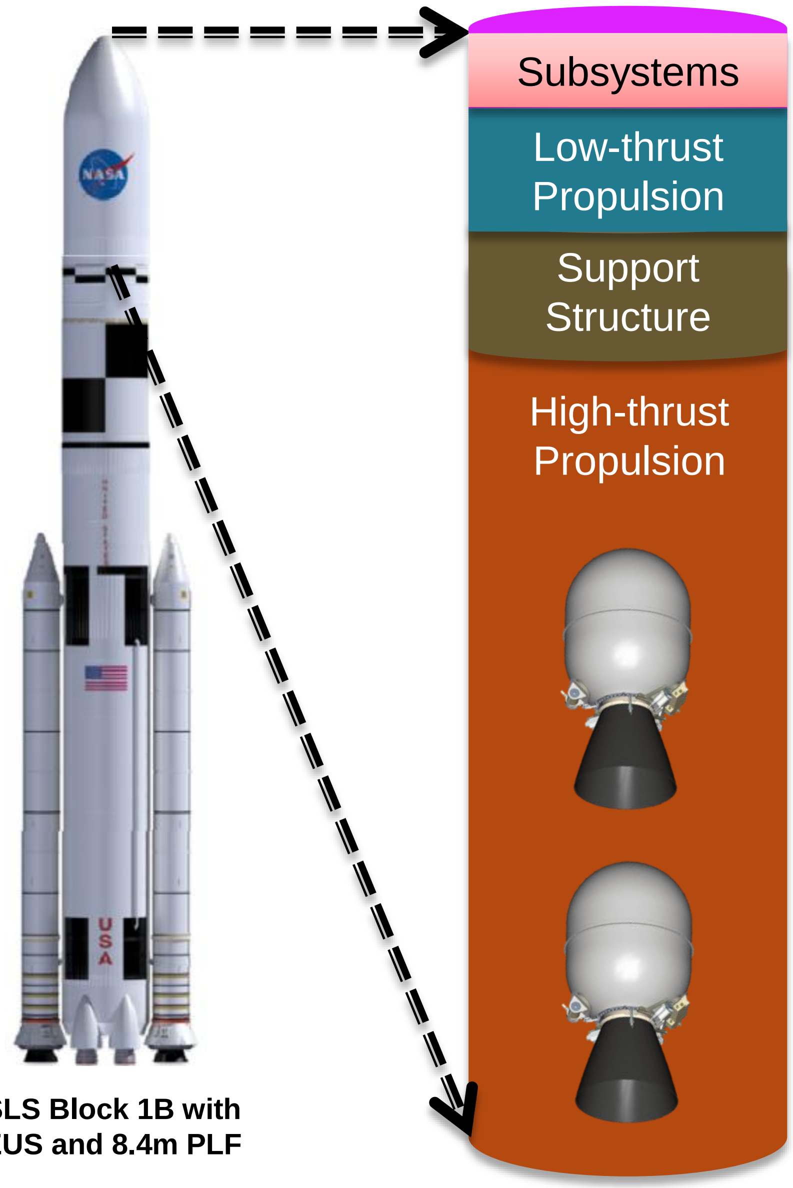
Investigated In-Space Propulsion Options

- **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

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	E-Sail could be launched on an Atlas V as well
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).

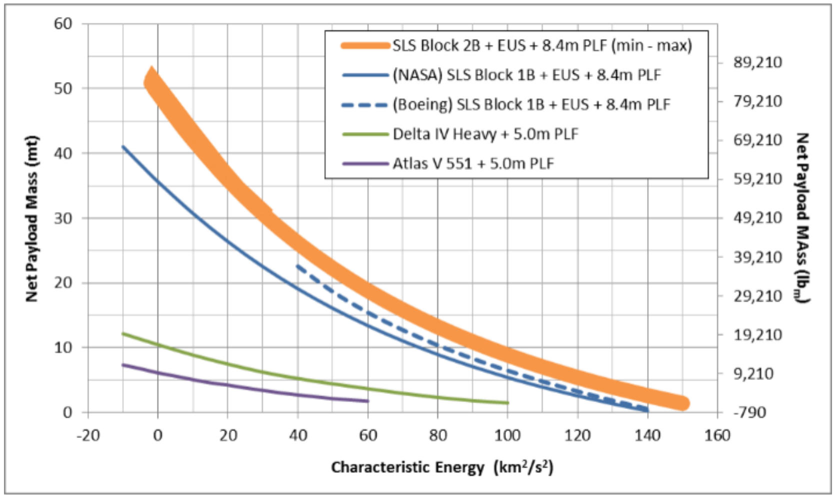


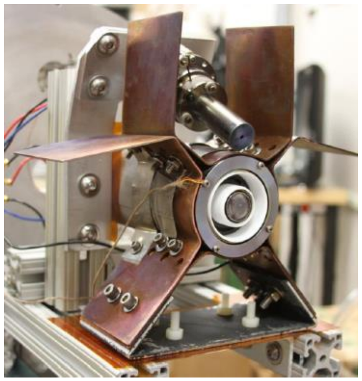
Figure 7. C3 Energies for SLS and other large launch vehicles. * †

* 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]

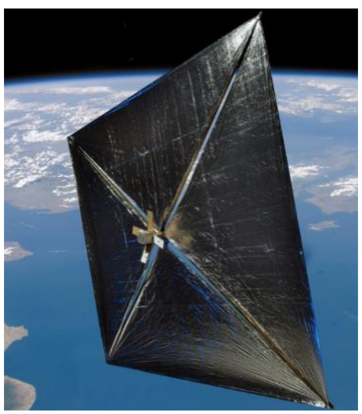
Ground Rules & Assumptions (GR&A)



MaSMi Hall thruster

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



Notional Solar Sail

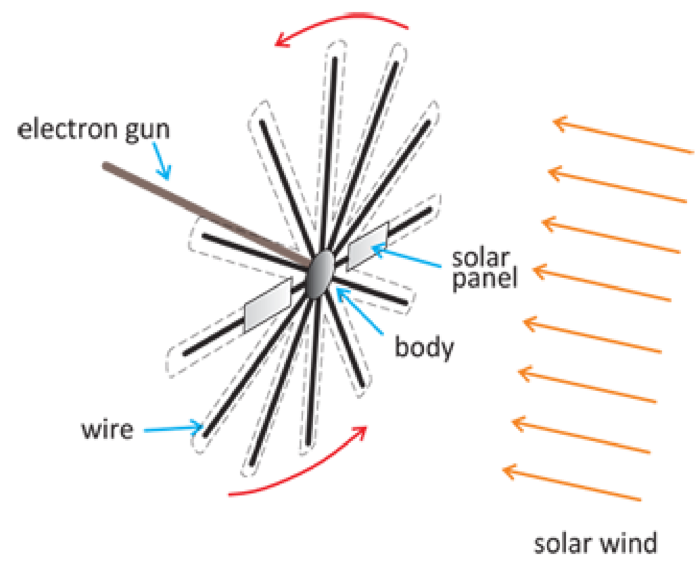
Solar sail GR&A.

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.

E-Sail Ground Rules & Assumptions

- 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 either to Deep Space or to the Inner Solar System and is scalable.



E-Sail propulsion system schematic

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)

In-Space Trajectories Investigated for Various Propulsion Options

MaSMi Hall thruster

---- and ----

E-Sail

Solar Sail

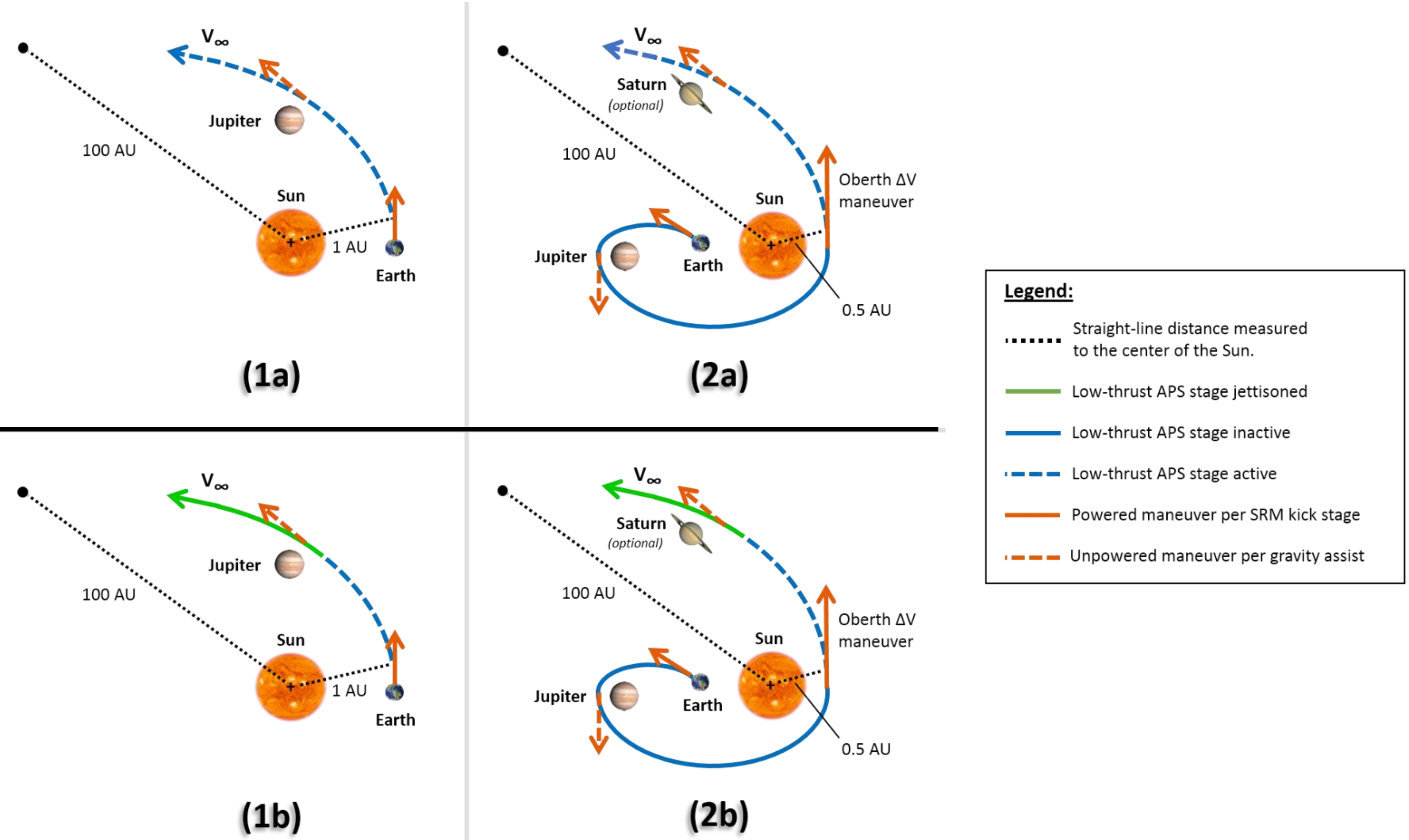


Figure 2. Mission trajectory profile options considered.

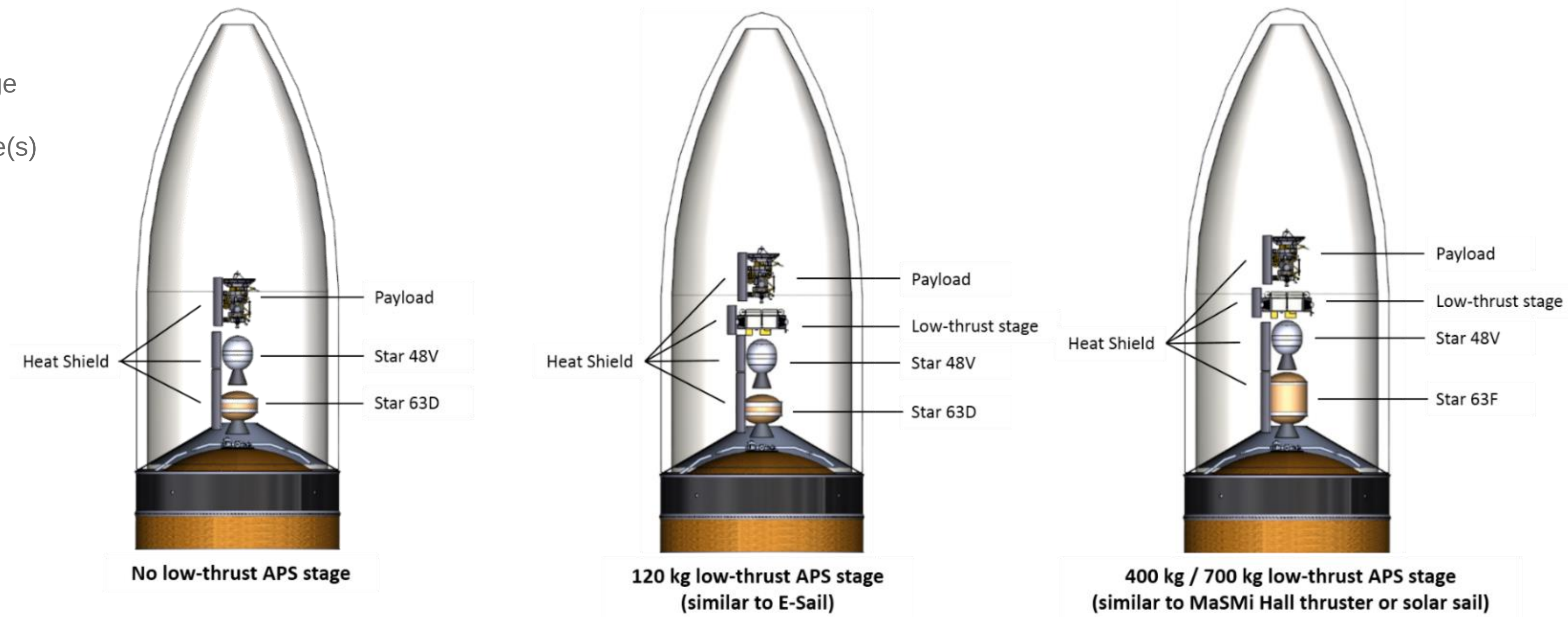
Payloads Packaged Within SLS Shroud

Total Payload Mass:

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$_m$)

Including:

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



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

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

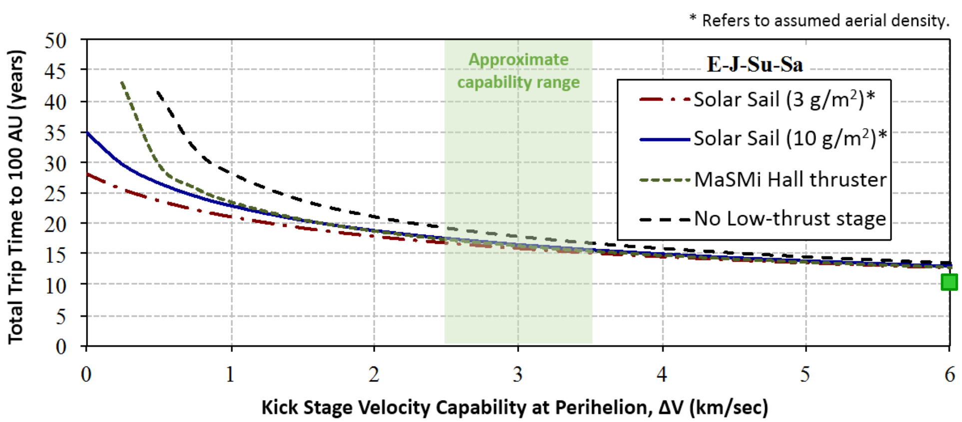
Low-thrust Stage Mass	Impulsive Burn 1 (Earth departure)	Impulsive Burn 2 (Perihelion)	Notes
0 kg (0 lb$_m$)	Star 63D	Star 48V	Star 63D – 20% of propellant offloaded.
120 kg (265 lb$_m$)	Star 63F	Star 48V	Star 48V– 5% of propellant offloaded.
400 kg (882 lb$_m$)	Star 63F	Star 48V	Star 48V– 20% of propellant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

Comparative Results

MSFC Advanced Concepts

◆ Earth-Jupiter-Sun-Saturn trajectory:

Figure 12



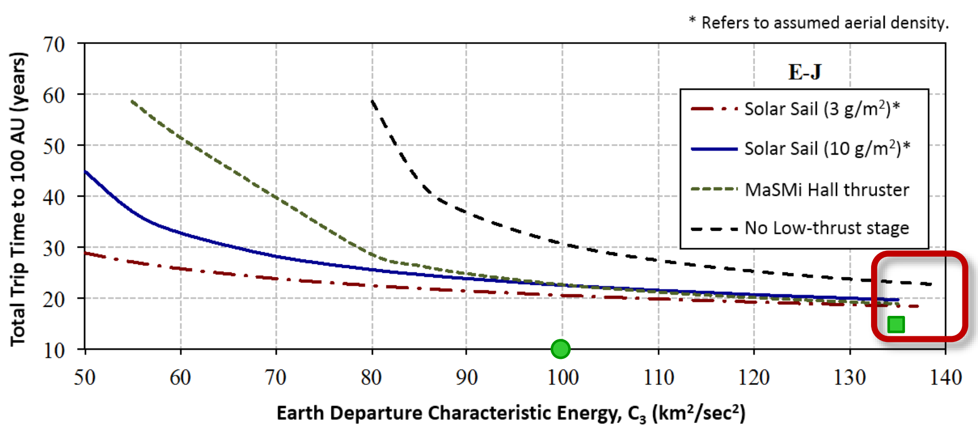
E-Sail Capability:

➢ 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:

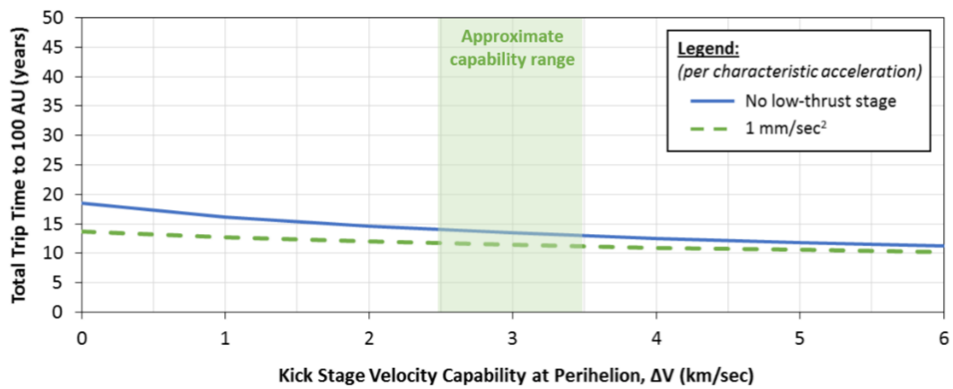
● 9.9 years
- $C_3 = 100$ km^2/s^2
- 2 mm/s^2

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

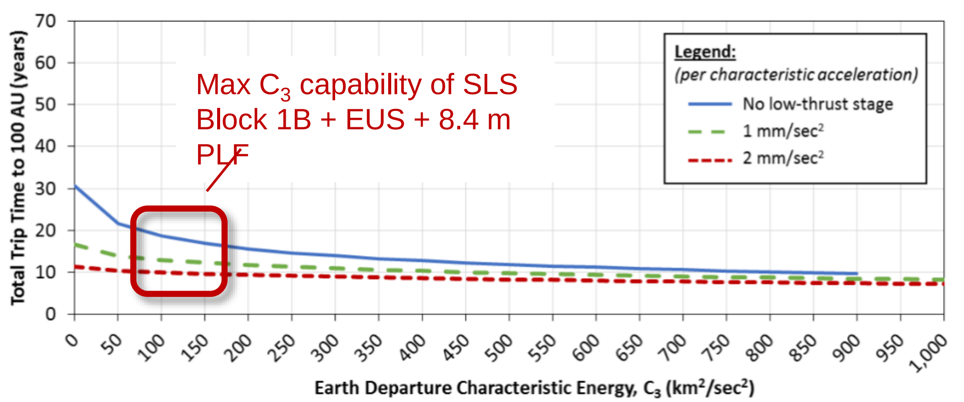
Max C_3 capability of SLS Block 1B + EUS + 8.4 m PLF

Comparative Results

- Earth-Jupiter-Sun-Saturn trajectory:

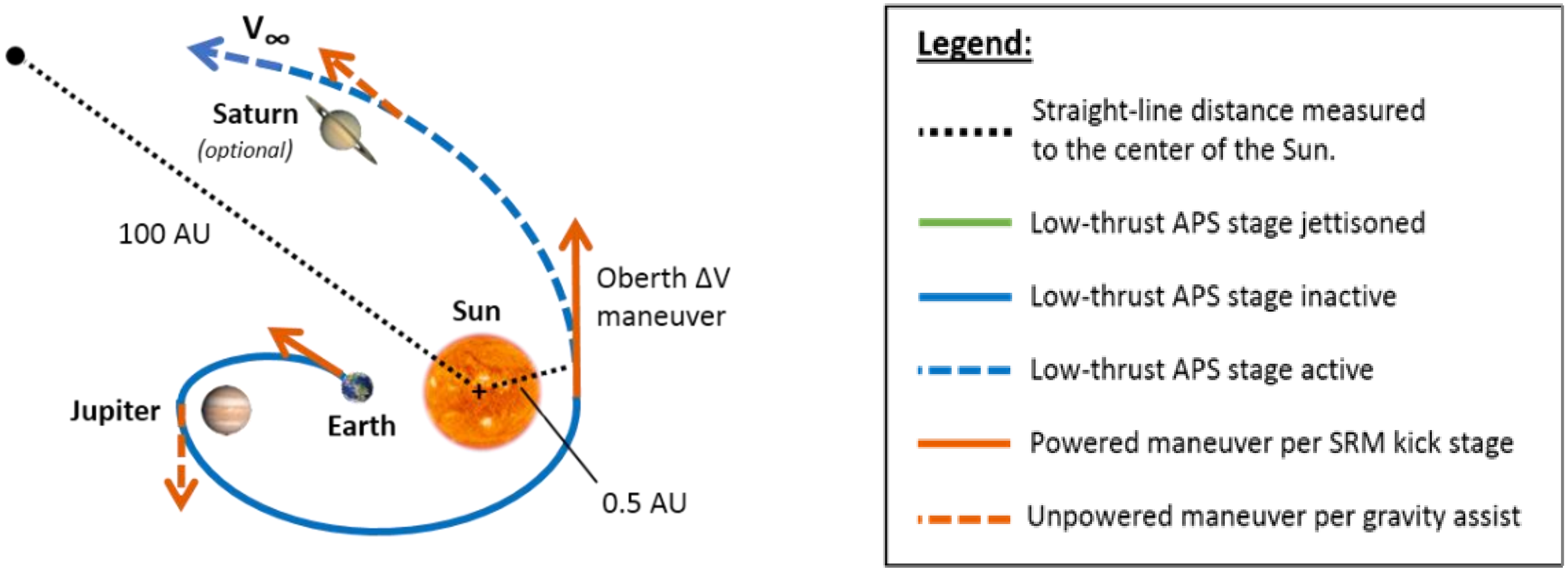


- Earth-Jupiter trajectory:

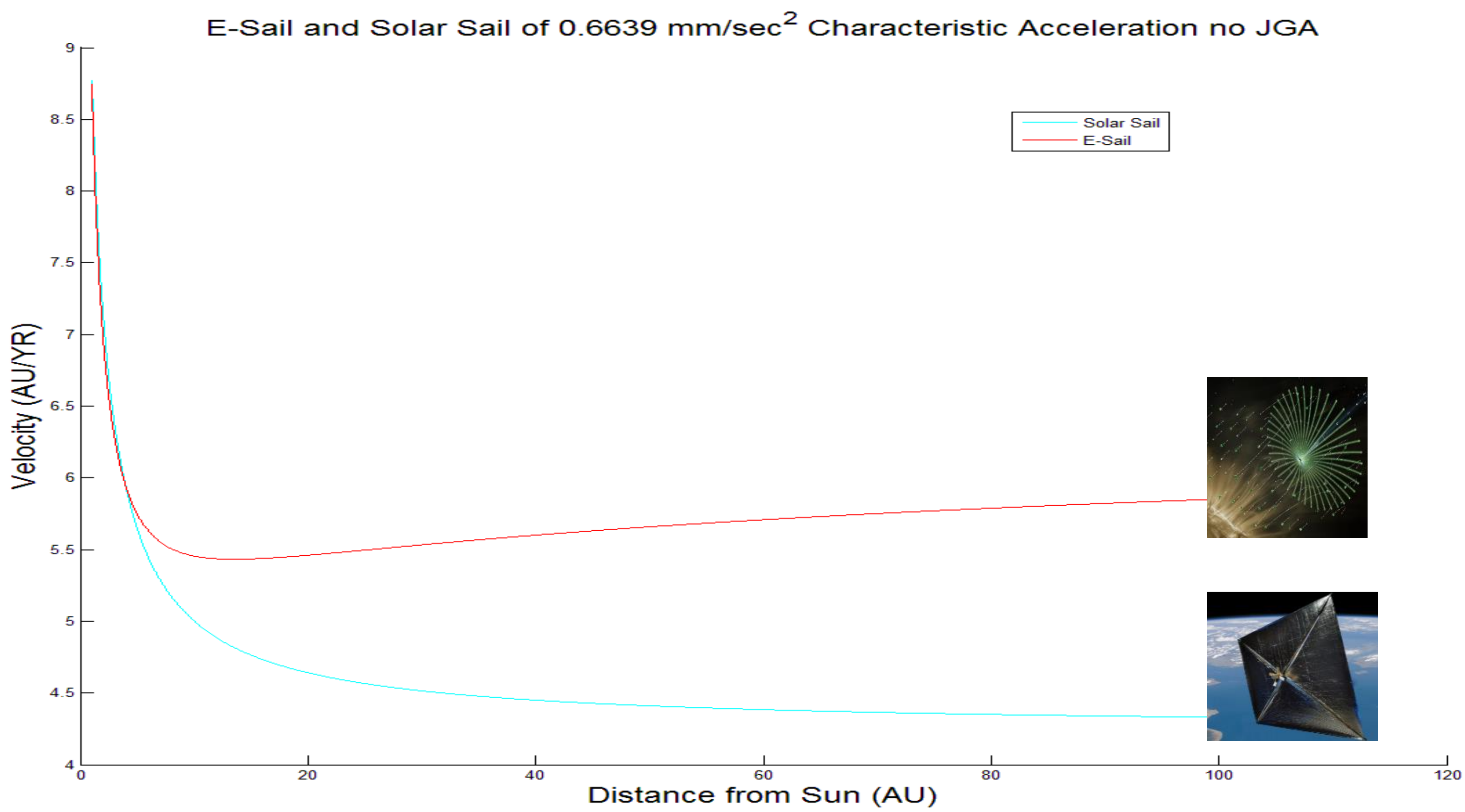


Trajectories Investigated for E-Sail

- 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

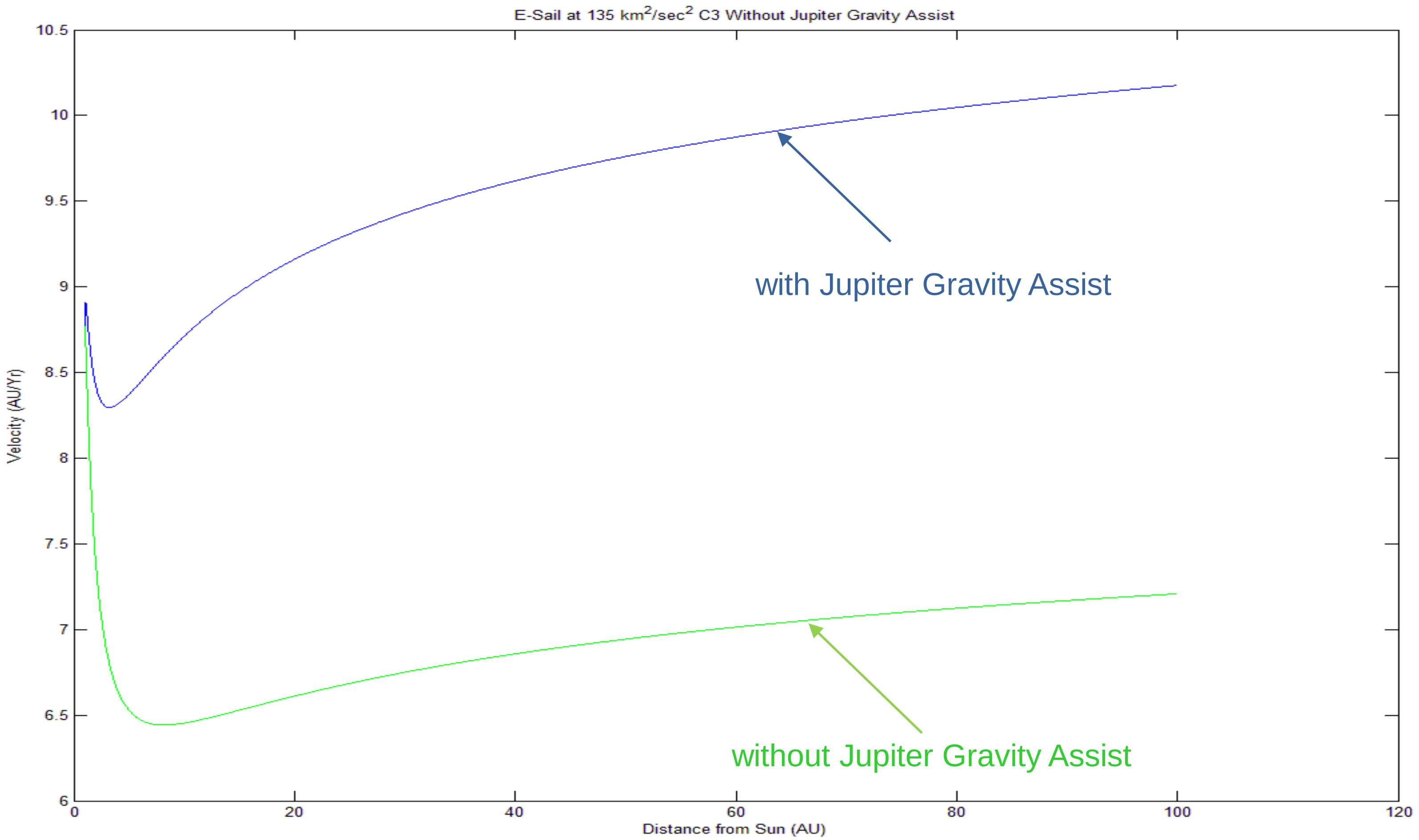


Velocity Comparison Between HERTS/E-Sail and Solar Sail



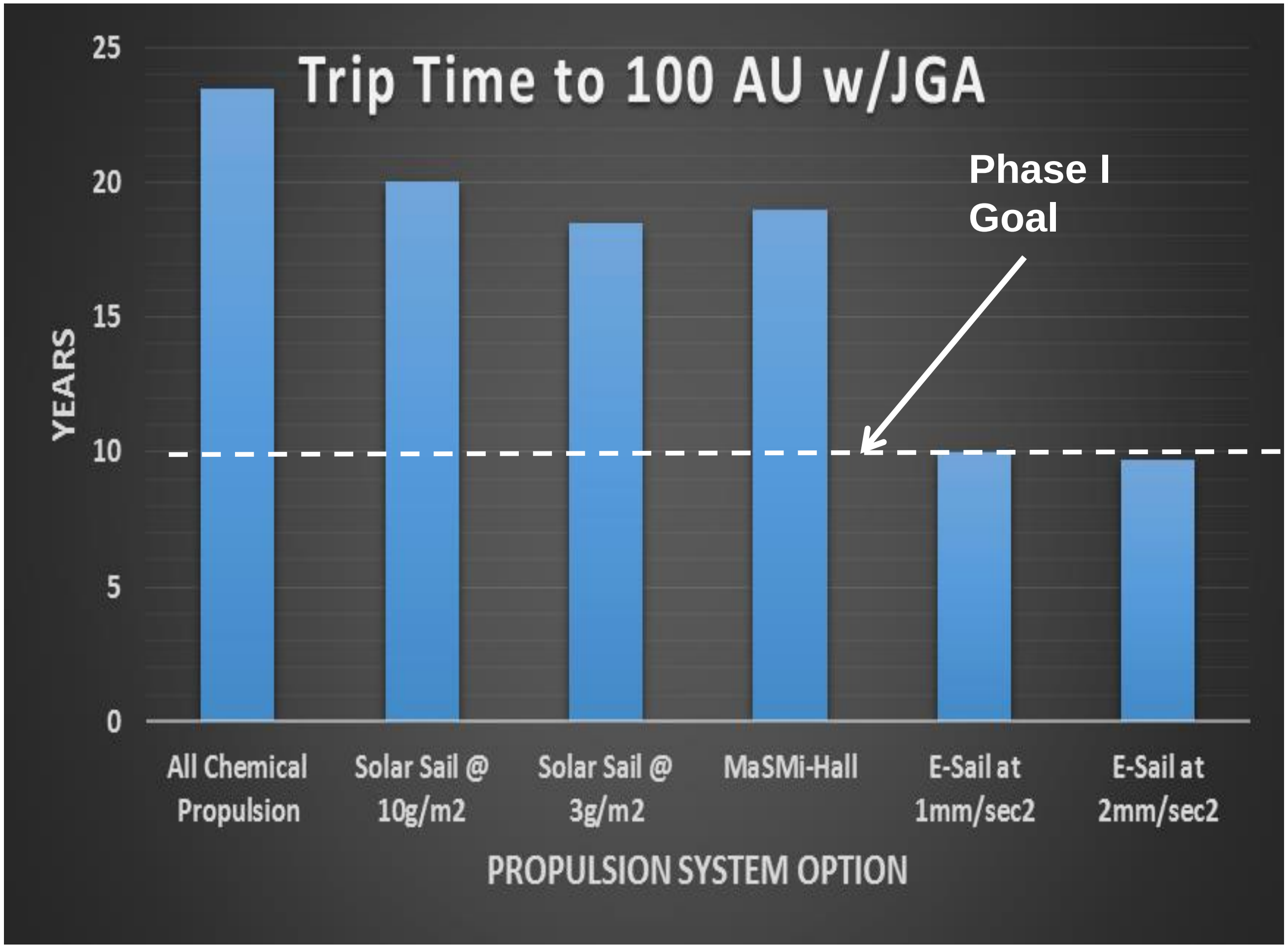
- **E-sail velocities are 25% greater than solar sail option because of the rate of acceleration decline ($1/r^{7/6}$) vs solar sail acceleration decline ($1/r^2$)**
- **E-Sail and Solar Sail propulsion options exceed the 2012 Heliophysics Decadal Survey speed goal of 3.8 AU/yr**

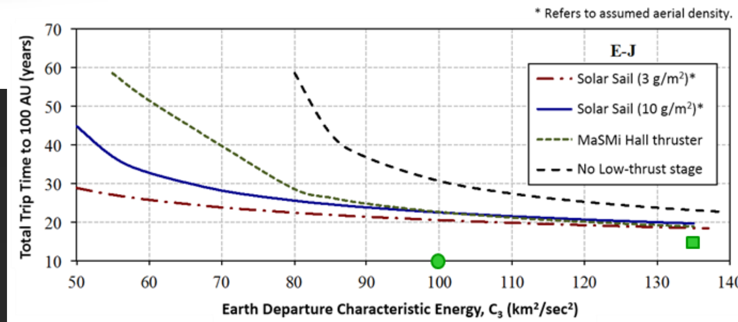
Effects of Jupiter Gravity Assist on E-Sail Option

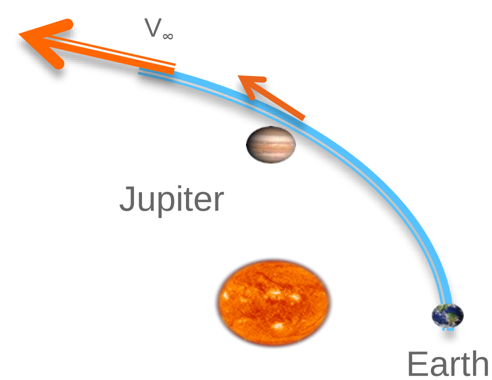


The Effects of a Jupiter Gravity Assist

Comparison of In-Space Propulsion Options



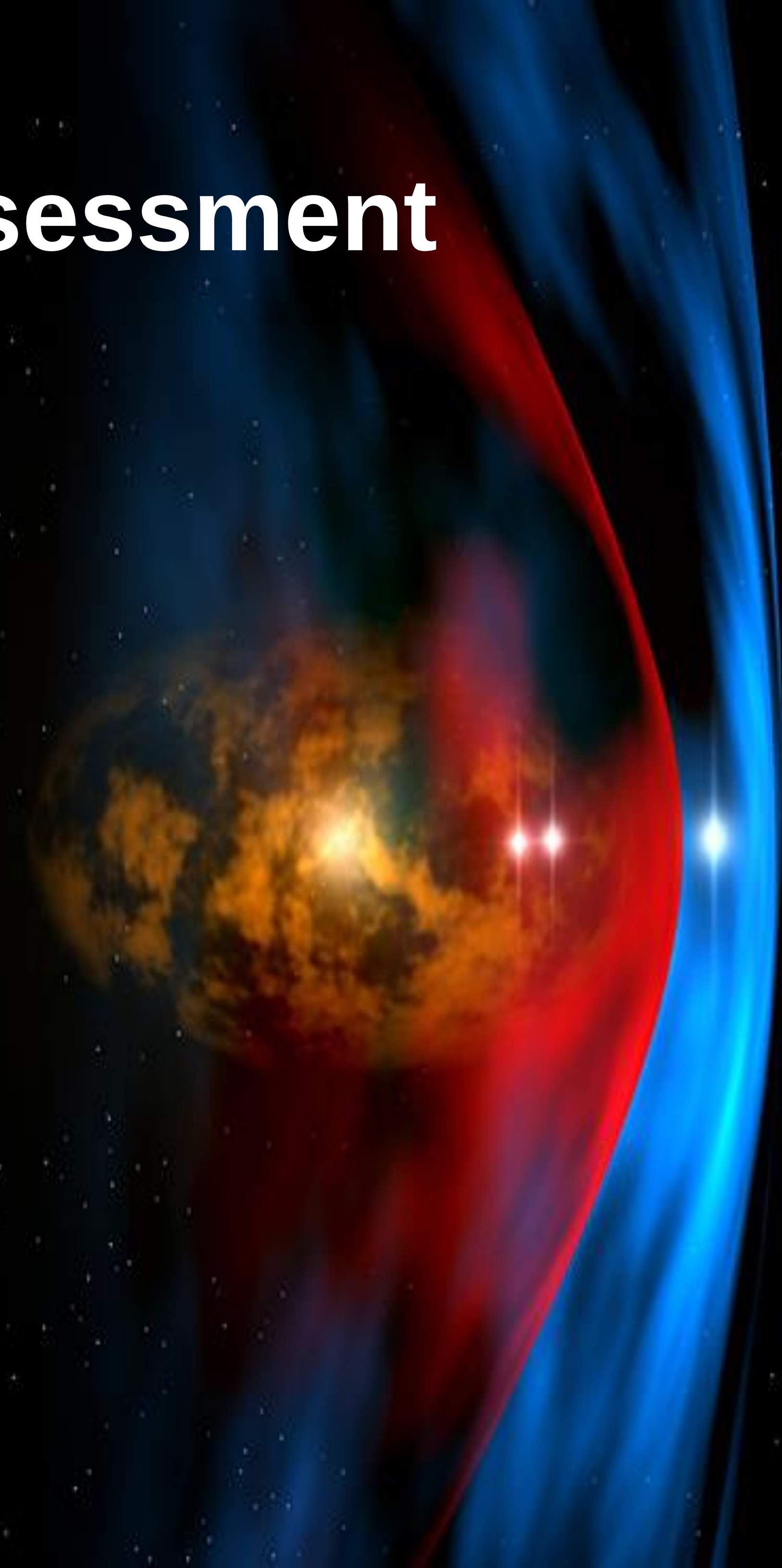




Direct escape using SLS, Jupiter Gravity Assist (JGA) and onboard in-space propulsion system.

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

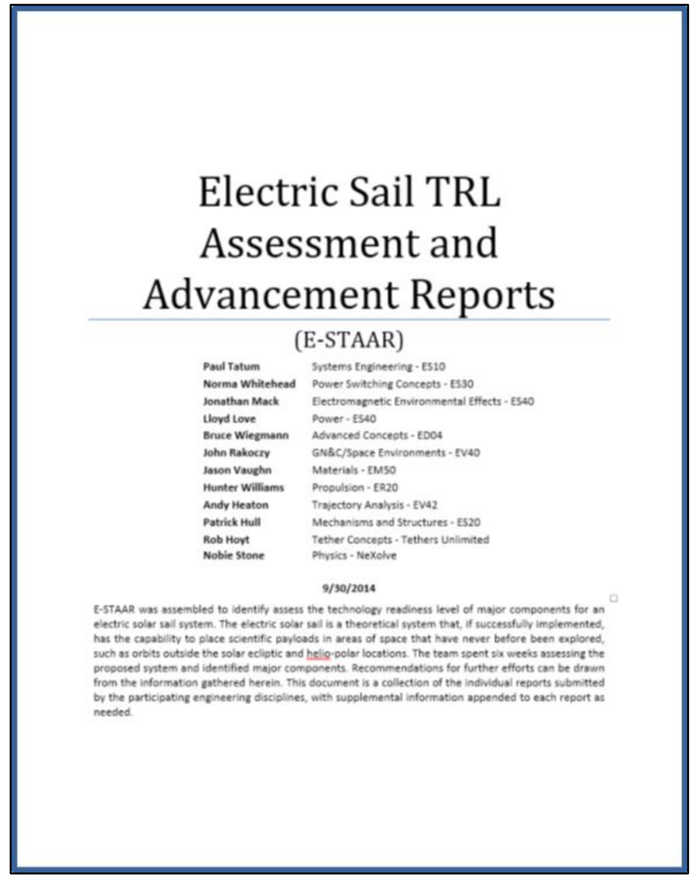
E-Sail TRL Assessment



HERTS Technology Readiness Level (TRL) Assessment

- MSFC conducted a 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
  - E-Sail spacecraft trajectory guidance & control via offsetting the applied S/C Cp through the voltage biasing of individual wires



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.

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

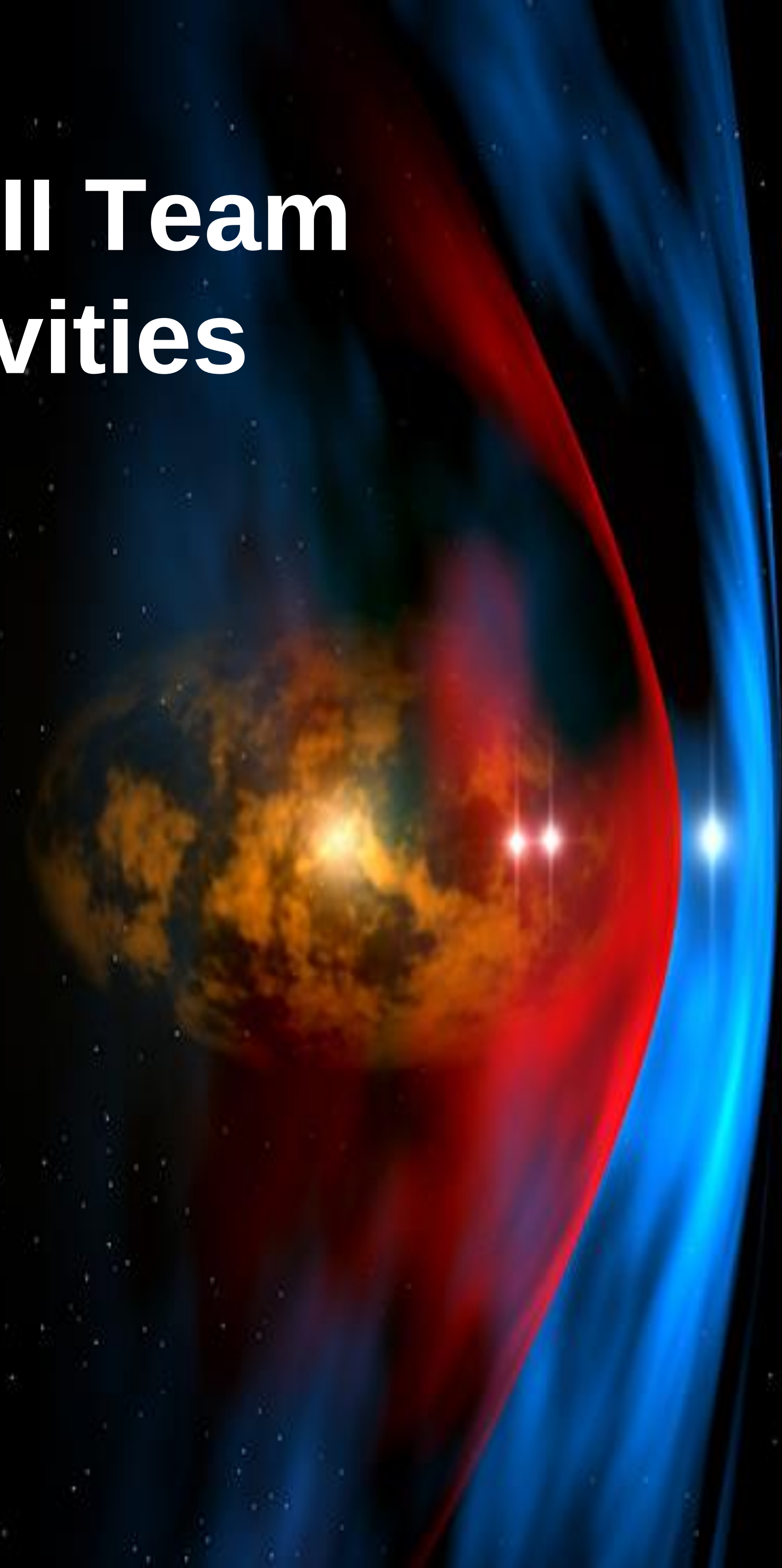
Roadmap	Level 1	Level 2	Level 3	Level 4
Tether Deployment	Trade between satellite propulsion spin up system and e-sail	Trade between multiple individual deployers and single deployer	Subscale ground deployment test	Full scale deployment test (maybe shorter length)
Tether Configuration	How many? What 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

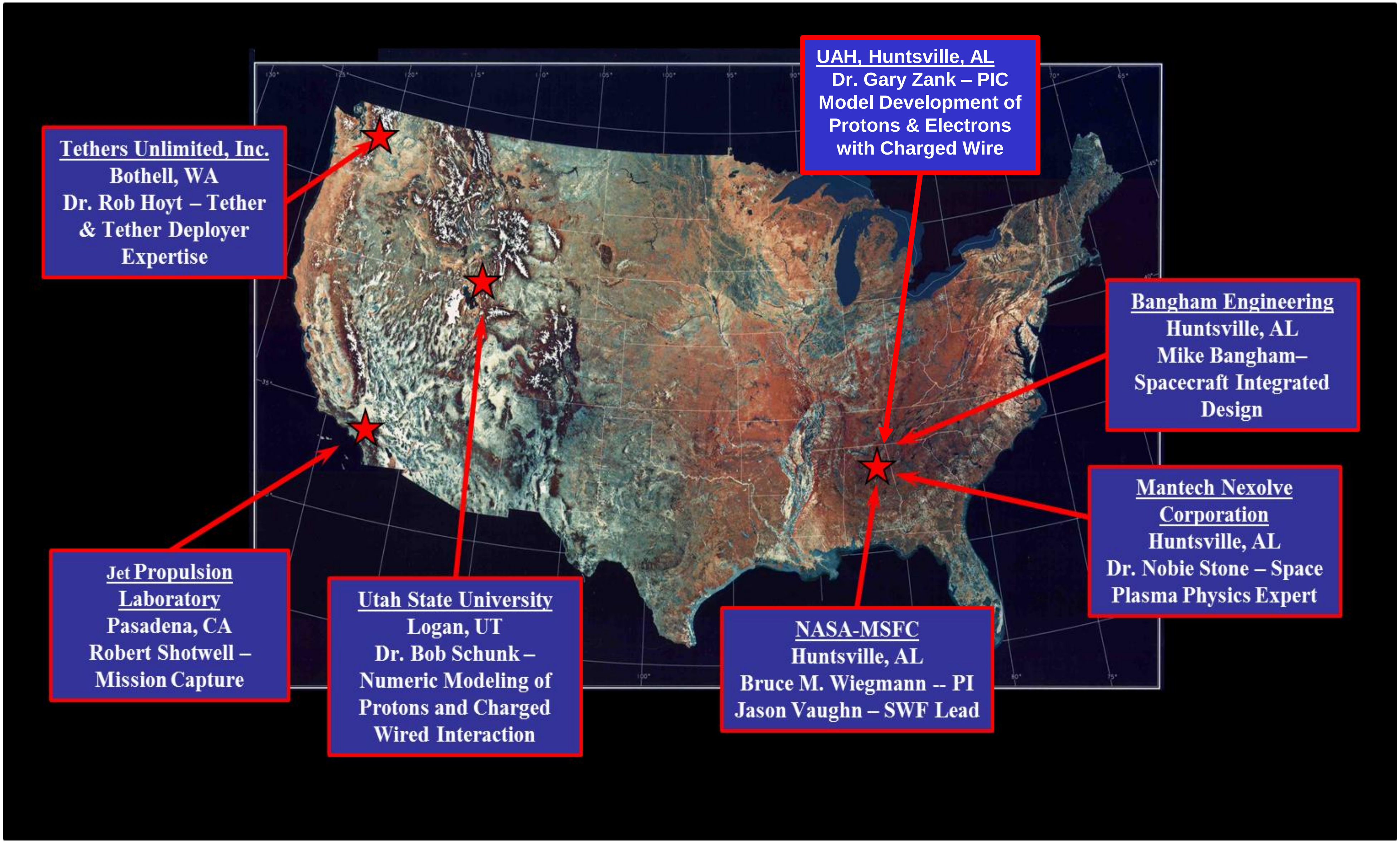
Areas of Emphasis under NAIC Phase I

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

HERTS Phase II Team & Funded Activities



The Phase II HERTS Team

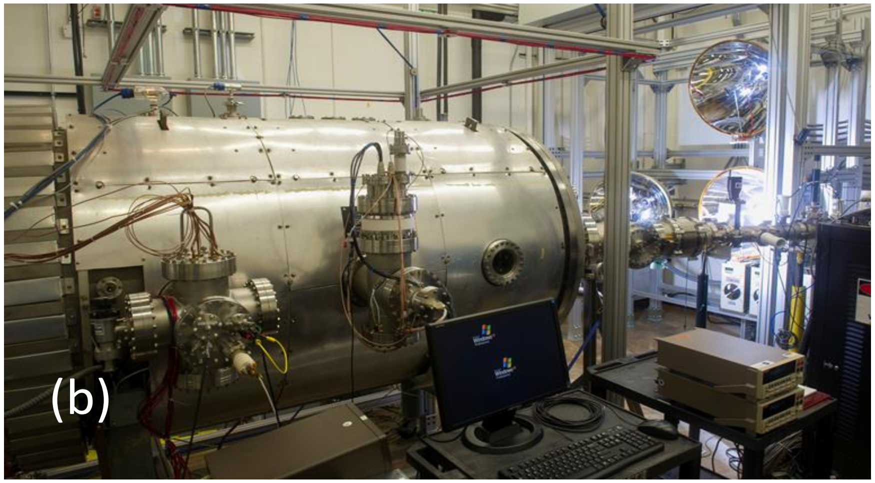


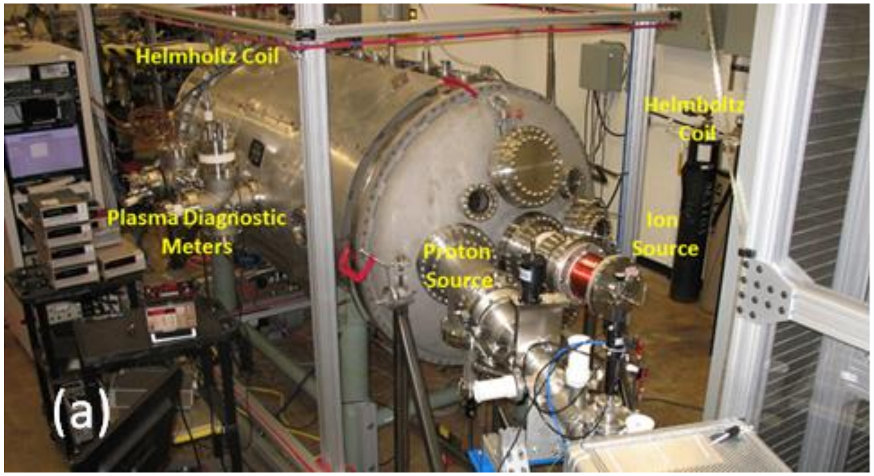
Phase II Activities

- Extensive experimental plasma chamber testing at MSFC’s Space Environmental Effects Facility of charged bare wire/s in a representative Solar Wind flux MSFC’s Space Environmental Effects Facility
- Development and bench-marking of a Particle-In-Cell (PIC) numeric model (UAH) validated from the experimental data
  - This model will output the effective resulting thrust force produced by a representative configuration as well as be used to size the electron gun and power system needs of the propulsion system
- Development of notional approaches to successfully deploy multiple 10-20 km length wires from the spacecraft
- Determination of best methods to actively control the rotating spacecraft to enable differing mission trajectories
- Based upon the realized thrust available from PIC model outputs, an identification of alternative missions will be produced (JPL)

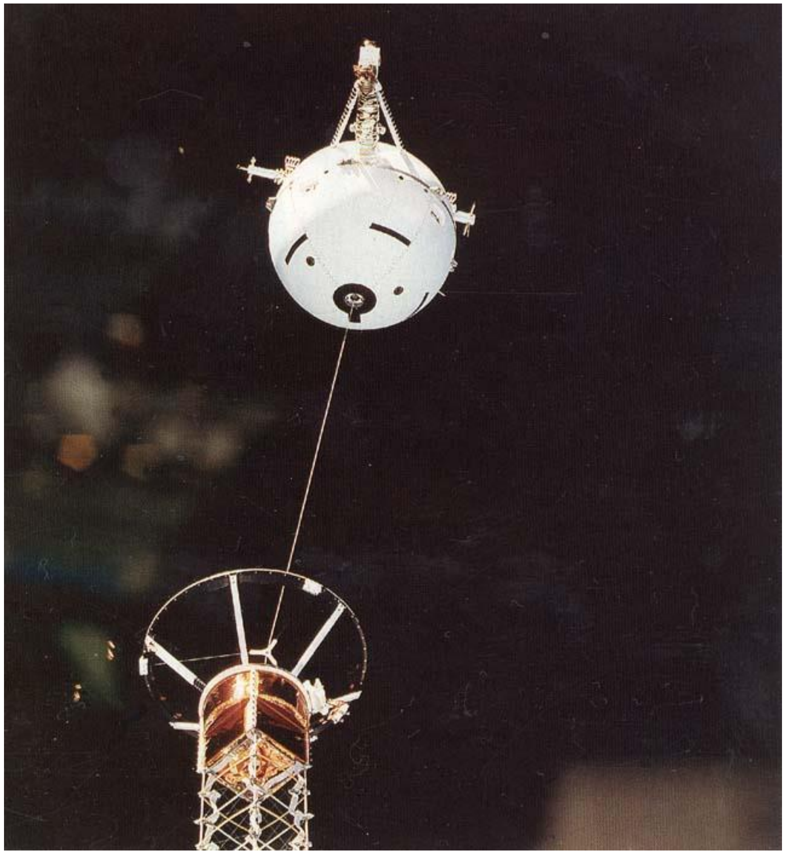
E-Sail Plasma Physics Measurements and Modeling

- 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, which translates into different onboard power system requirements
- Measurements in MSFC's Space Environmental Effects plasma chambers (beginning in mid Feb 2016) 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 challenging
- MSFC is exploring various options in more detail to determine the 'best' approach.
  - Spin deployment may be practical for large number of short tethers.
  - Propulsive deployment
  - Electrostatic deployment via solar wind interaction

E-Sail Guidance, Navigation and Control

- Deflecting the solar wind for thrust and selectively deflecting 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

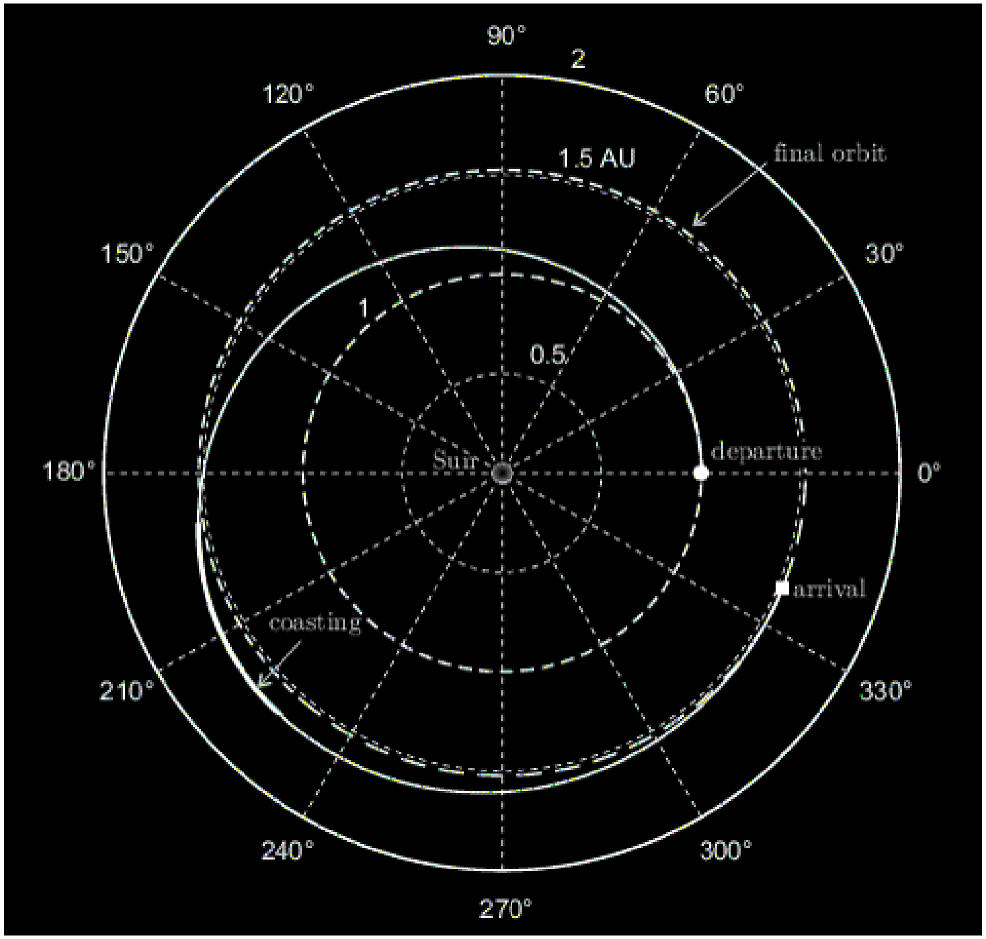


Image courtesy of Dr. Pekka Janhunen

Closing Summary and Critical Next Steps

HERTS Summary

- Mission Capture:
  - Scientific missions going outward into Deep Space at velocities exceeding the stated goal cited in the 2012 Decadal Survey
  - Final achieved speeds of spacecraft estimated at 40-60 km/sec
- Fuel-less Deep-Space, scientific, spacecraft propulsion system that enables mission trip times 3 times as fast as like mass solar sail concepts
  - Estimated 10 to 15 years to the Heliopause (Voyager took 36 years)
  - Enables Outer Planet scientific missions
- Can be fully matured by 2025 timeframe
- Scientists will be able to receive data from numerous missions within their working career

Next Steps

- Develop methods to test multiple - TBD km length tethers being deployed simultaneously
  - Via High altitude balloon test
  - Via, Sub-orbital test

- Conceptually design a small demonstration spacecraft that could deploy multiple TBD km length bare wire tethers and perform a mission of scientific discovery, as well

- Upon completion of NIAC Phase II, pursue other funding mechanisms (SBIR, Game Changing, TDM)
  - Demonstration vehicle

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)

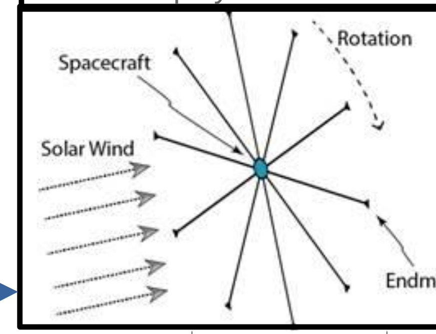
Incorporate design changes req'd from demo flight for build up of Deep Space flight hardware

Fabricate hardware for Heliophysics Mission (notional 2025 launch)

2014 2016 2018 2020 2022 2024 2026

MSFC Solar Wind Facility

Tether Deployment & Control



BACK UP SLIDES FOLLOW

Example Scientific Payload

Measurement objective	Instrument	Mass [kg]	Power [W]
Solar Wind	Plasma Analyzer (IPA)	2.0	1.3
Plasma and Radio Waves	Plasma Wave and Radio Experiment (IPWE)	4.5	4.0
Magnetic Field	Magnetometer (IMAG)	3.7	3.4
Neutral Atoms	Neutral Atom Detector Imager (INCADI)	0.5	1.8
Energetic Particles	Energetic Particle Detector (IEPD)	1.8	1.2
Interstellar Dust	Dust Analyzer (IDA)	1.0	1.0
UV-Emission	UV-Photometer (IUVP)	0.3	0.3
Solar Monitor	Solar Activity Monitoring	0.6	3.0
	Structures and Central Payload Power Supply	3.0	-
	Margin 20%	3.5	3.2
Total		**20.9**	**19.2**