National Aeronautics and Space Administration

Solar Sailing: Technology and Mission Opportunities

Keats Wilkie - Langley Research Center

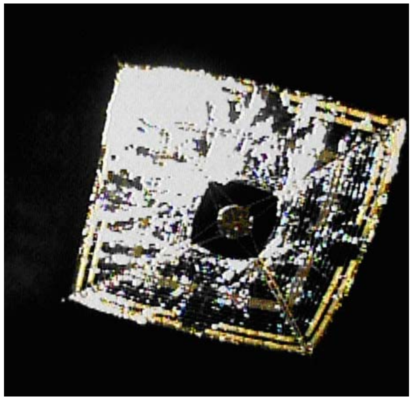
Les Johnson, Roy Young – Marshall Space Flight Center

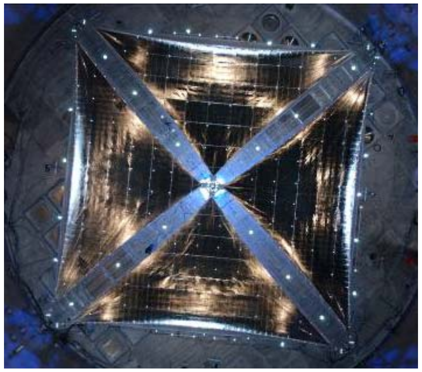
Tim Van Sant, Bruce Campbell – Goddard Space Flight Center

John West, Mark Thomson – Jet Propulsion Laboratory

Ben Diedrich - NOAA

Solar Sailing: Where are we now? (TA-02)



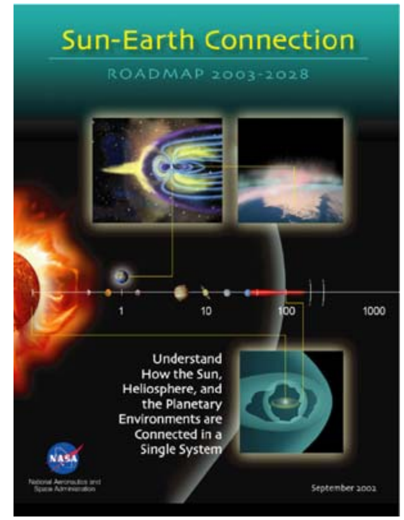


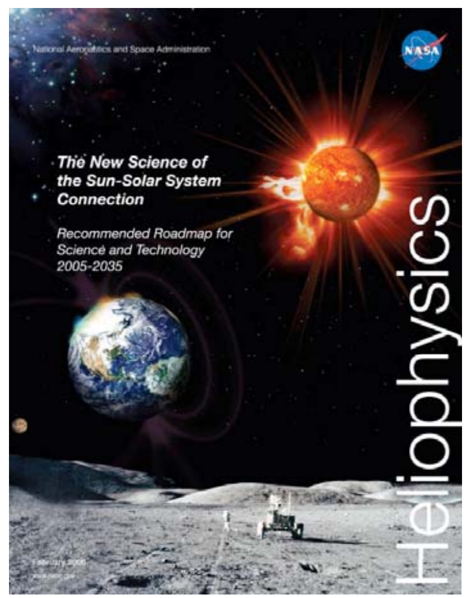
- Description:
  - Solar sails are large, lightweight reflective structures that produce thrust by reflecting solar photons and thus transferring much of their momentum to the sail.
- State of the Art:
  - The state-of-the-art solar sails were produced for the NASA In Space Propulsion 20 meter Ground System Demonstrations (GSD) in 2005.
  - The JAXA funded Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS), launched in May, 2010, deployed its sail in June and has since demonstrated both photon acceleration and attitude control.
    - IKAROS has a square sail that is approximately 14 meters long on each side, 7.5 micrometers thick and used a spin deployment method to deploy its sail.
- Technical Challenges:
  - System level integration and test of the component technologies for >1,000-m2 sail using existing materials and technologies are needed.
  - Gravity offload and deployment tests of the large sail are needed.
- Milestones to TRL 6
  - Due to the constraints of gravity, solar sail propulsion performance will not be totally demonstrated to TRL 6 on the ground.
  - *A space flight demonstration will be required to fully achieve TRL 6.*

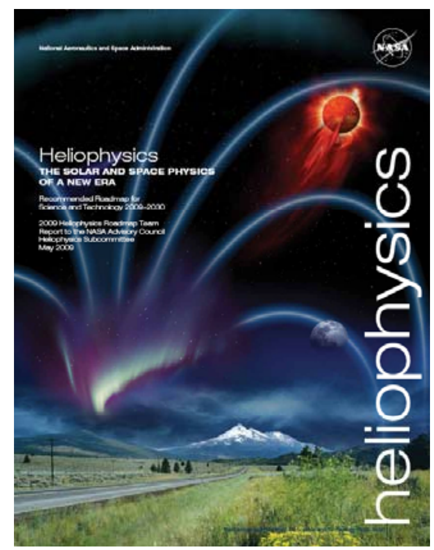
http://www.nasa.gov/pdf/501329main_TA02-InSpaceProp-DRAFT-Nov2010-A.pdf

The Solar Sail Is In Science Roadmaps

- Sails have been in Science Roadmaps since 1997.
  - They have remained because they enable science missions not possible with conventional means.
  - The science of feasible, *conventional* alternatives is much less compelling.
- A Sail Demo Mission *was* in the 2006 Heliophysics Roadmap.
  - *Dropped from 2009 roadmap mission list*
- The National Academy is preparing a new Decadal Survey, scheduled for publication in 2012.
- A Sail Demo is expected to reappear on the Heliophysics mission list



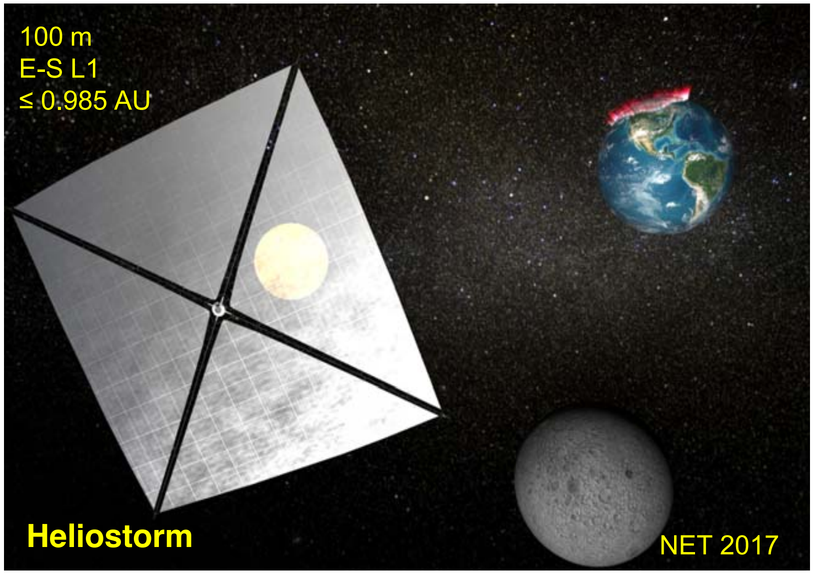


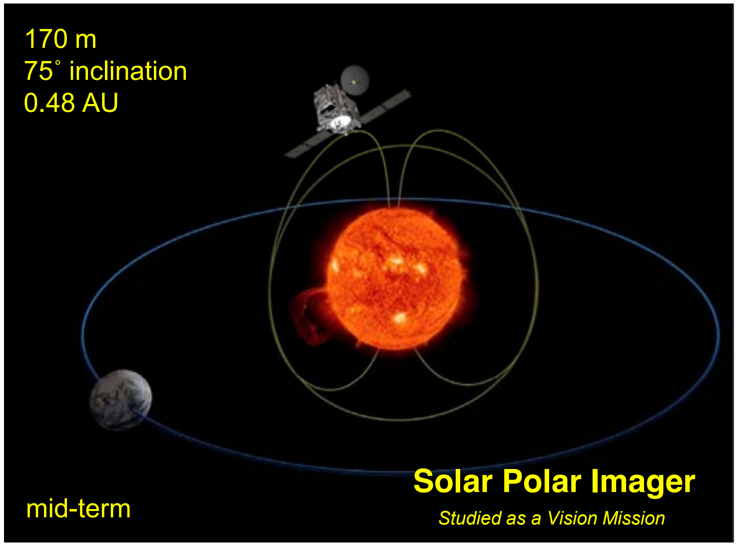


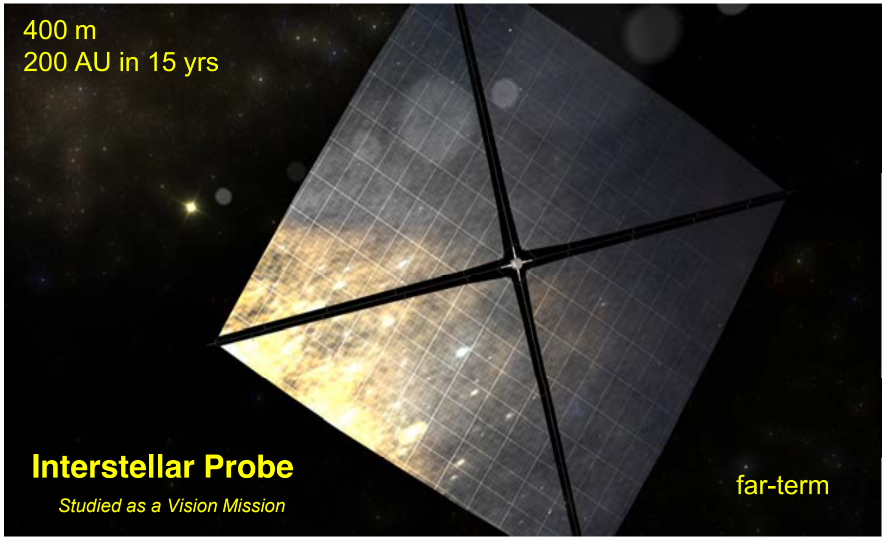
http://sec.gsfc.nasa.gov/sec_roadmap.htm

Strategic Missions and Technology Pulls

- Three canonical strategic missions in the Heliophysics Roadmaps:
  - *Heliostorm*
  - *Solar Polar Imager (SPI)*
  - *Interstellar Probe (ISP)*
- Heliostorm is significantly enhanced via solar sail technology
- Solar sails are *enabling* for SPI and ISP





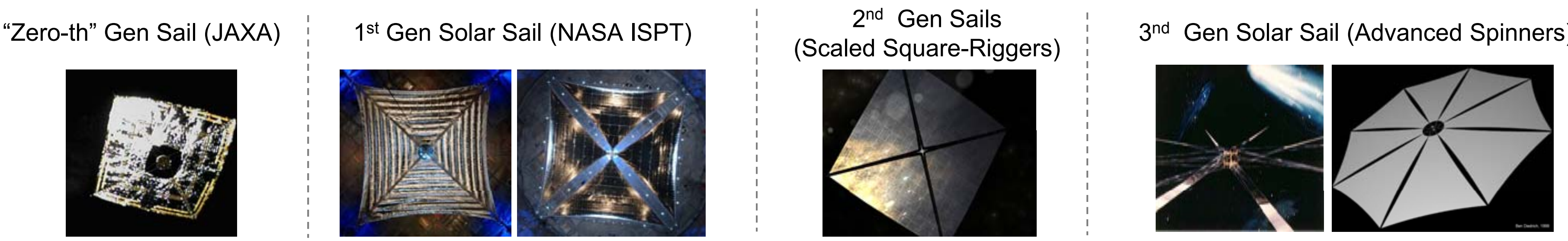


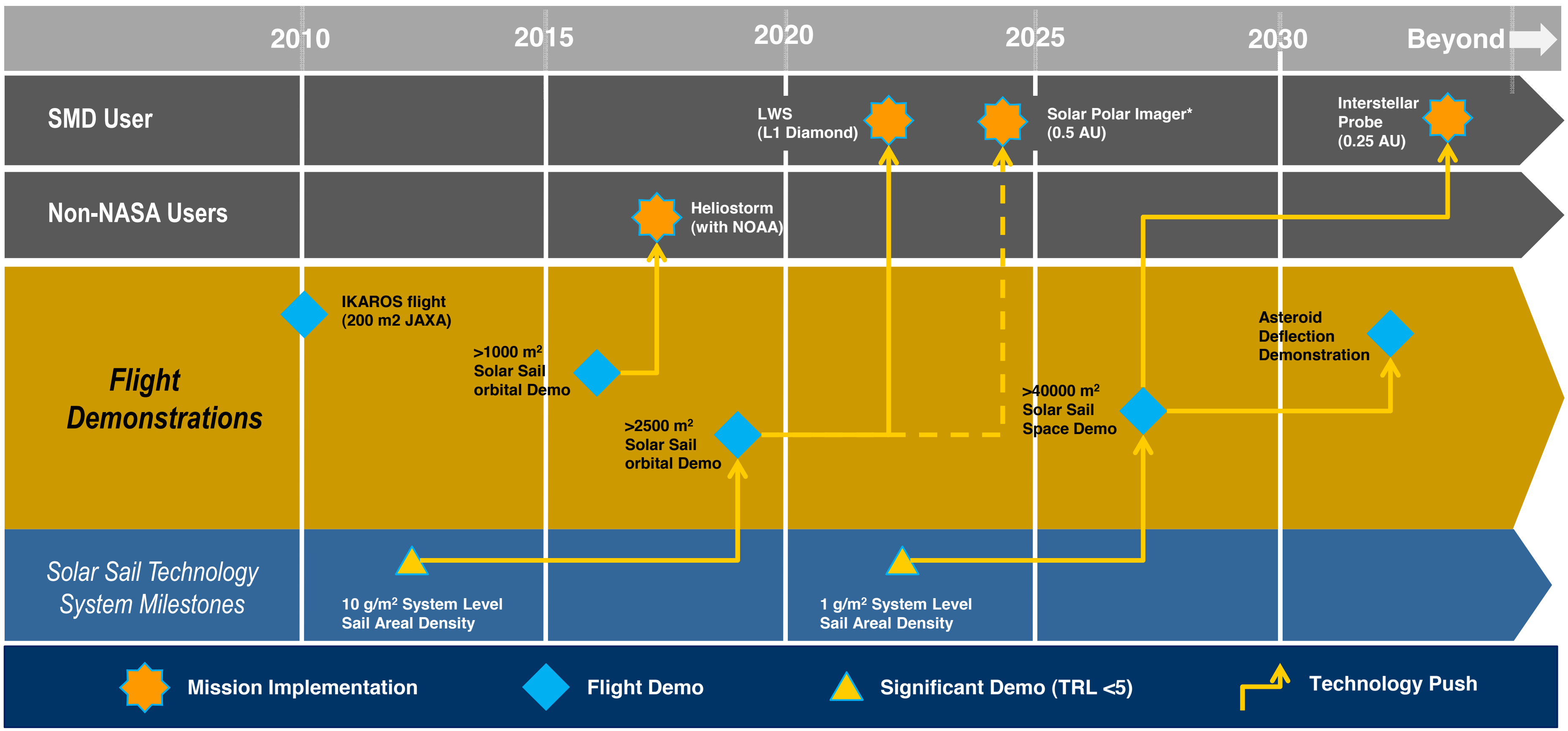
Relevance to SMD and Human Space Flight

Mission	Benefit to SMD	Benefit to Exploration
Heliostorm *Measures "upstream" solar wind*	Near-Earth heliospheric measurement is critical baseline for inner/outer heliospheric & geospace science*	Doubles warning time of space weather events; provides more actionable intelligence for astronauts and systems in cislunar space*
Solar Polar Imager *Supplies critical missing observations*	Answers fundamental solar physics questions such as the dynamo and CME release mechanisms†	Out-of-ecliptic orbit is ideal for forecasting space weather events throughout the solar system†
Interstellar Probe *First to sample the interstellar medium*	First measurement of the charged particle and magnetic fields of the interstellar medium‡	**True exploration!**

*Criticality of the L1 measurement is discussed in "Recommendations of the NASA Sun-Solar System Connection Radiation Working Group Report, NASA, July 2005.
†Solar Polar Imager: Observing The Sun From A New Perspective, Vision Mission Study Report, January 2006.
‡Interstellar Probe, STDT Report 1999; two Vision Mission Studies, 2004-2005.

A NASA Solar Sail Technology Roadmap

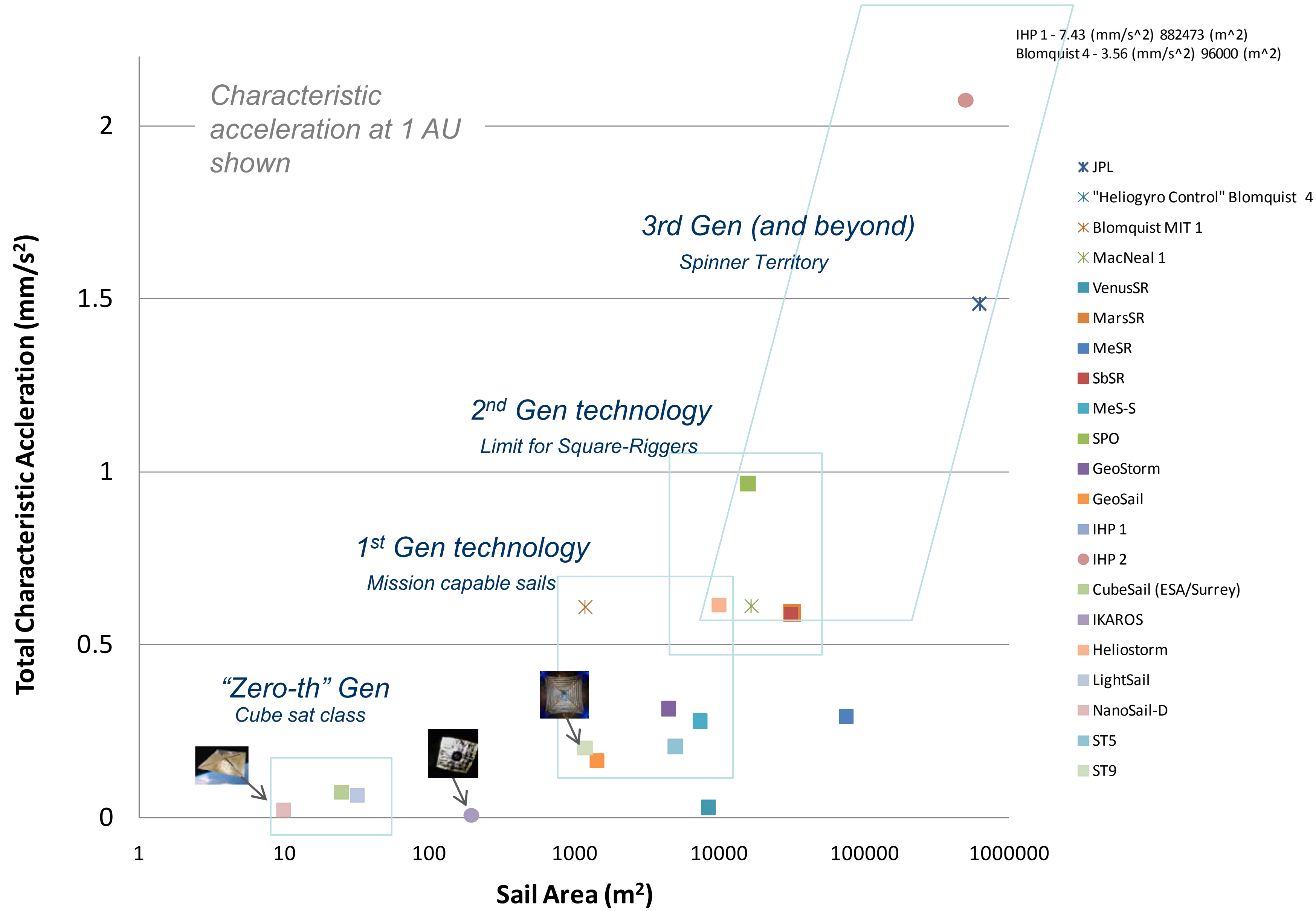




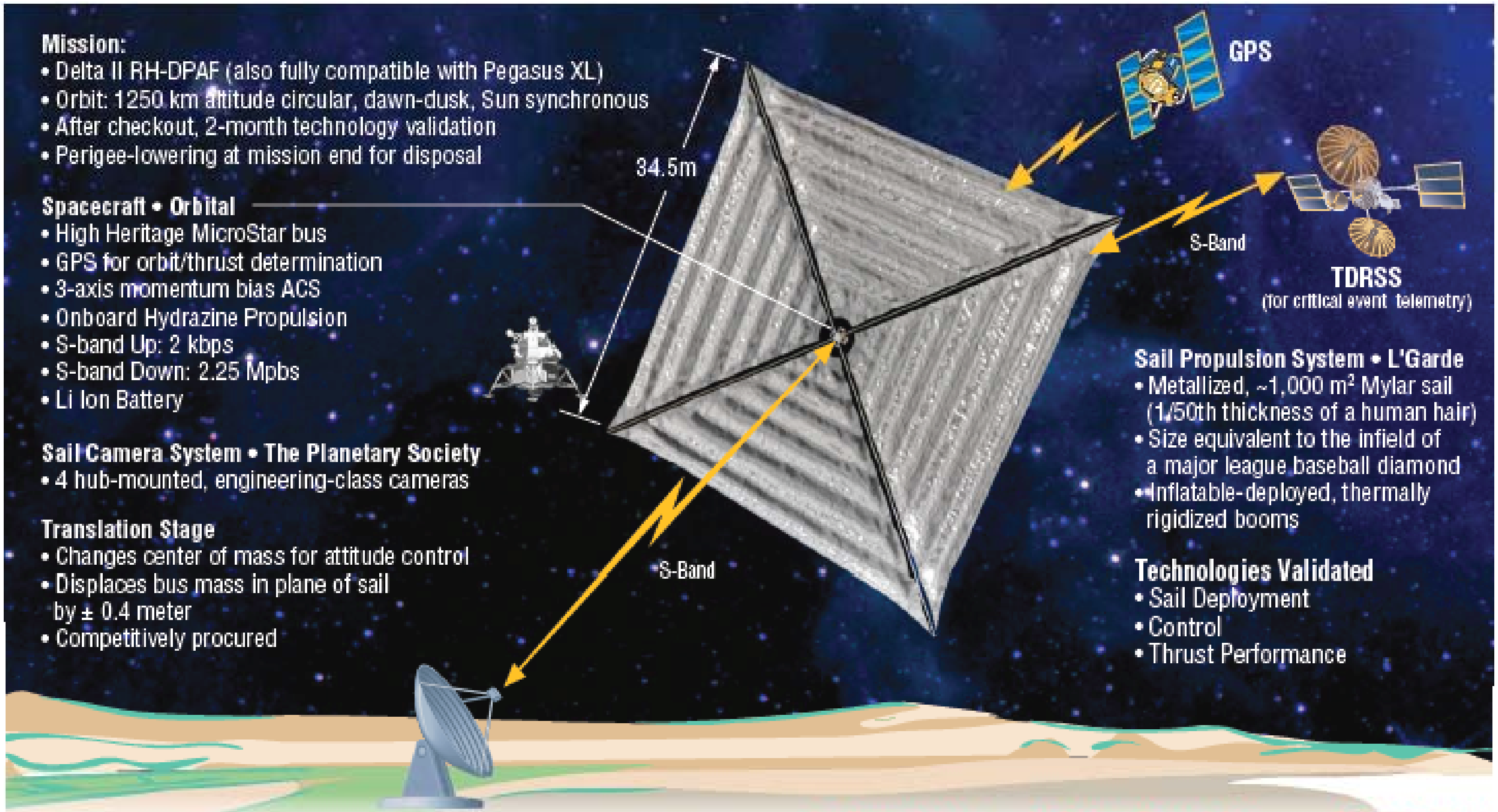
http://www.nasa.gov/pdf/501329main_TA02-InSpaceProp-DRAFT-Nov2010-A.pdf

* Additional mid-term mission candidate.

Lightweight and big? How hard could it be?



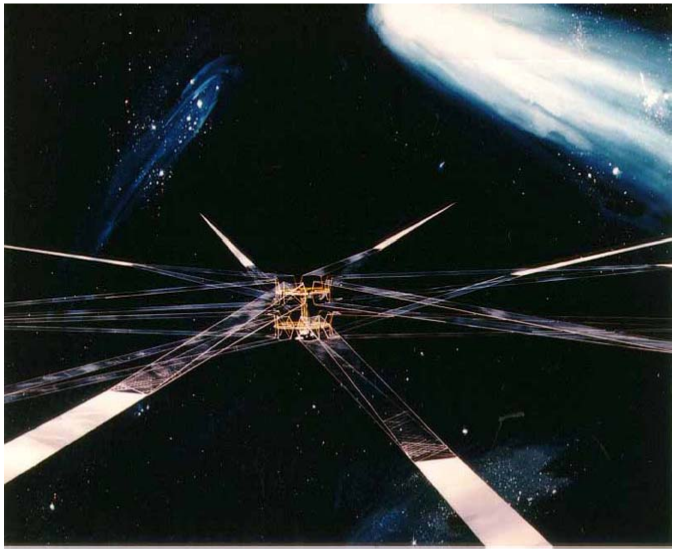
What now? … 1st Gen Flight Demo ("ST9 Reloaded")



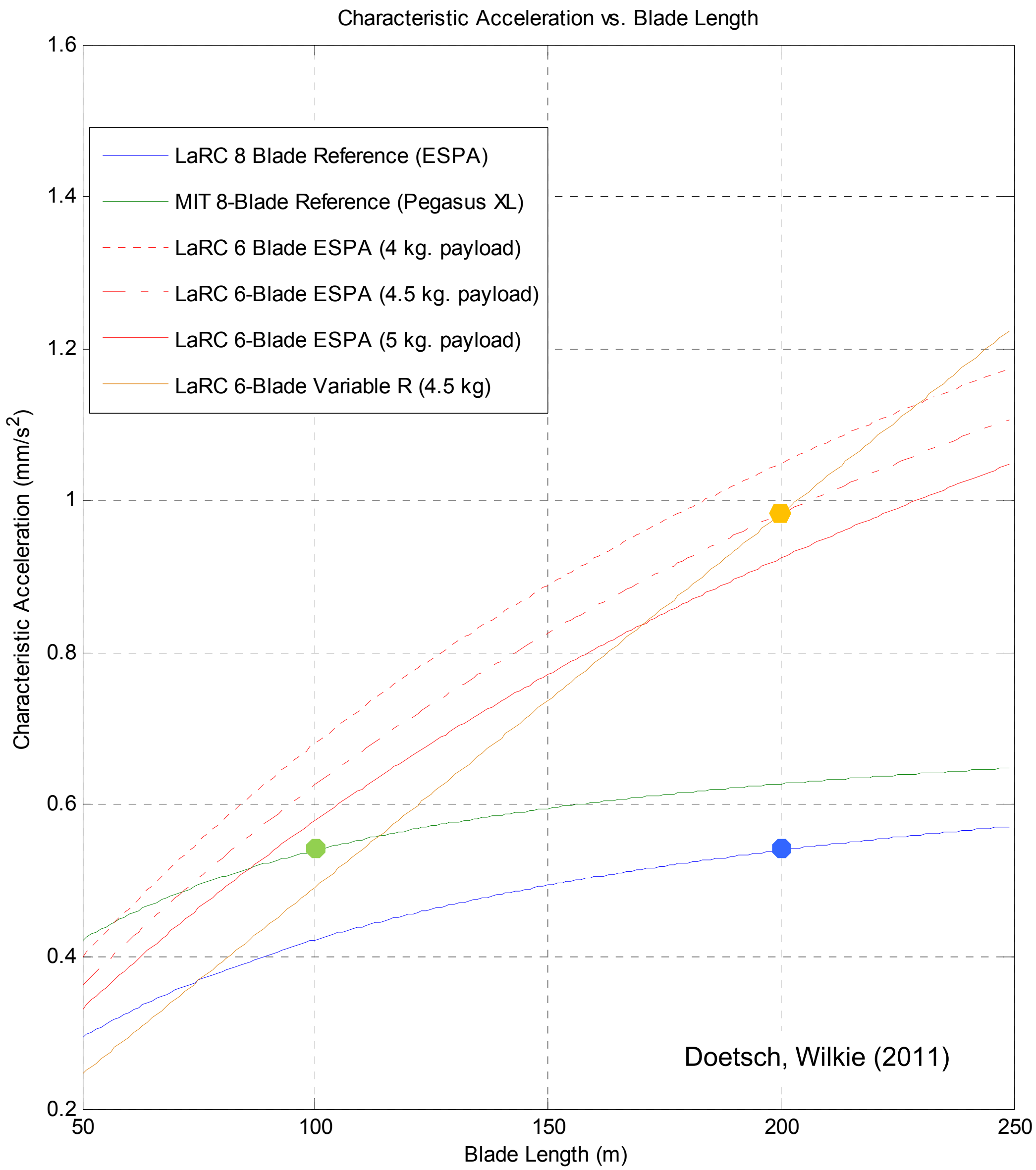
L'Garde	Orbital	Goddard Space Flight Center		Jet Propulsion Laboratory	In-Space Propulsion Technologies Project		The Planetary Society
Tustin, CA • Solar Sail • Sail Electronics and Structure	**OSC Mission Operations Center Dulles, VA** • Spacecraft Bus • System Integration and Test • Mission Operations	**NASA Ground Network** • 11 m Dishes - Alaska - Wallops	**Greenbelt, MD** • Project Management • Systems Engineering • Mission Assurance • Technology Validation • Education/Public Outreach	**Pasadena, CA** • Thrust Estimation • Inflation/ Deployment Modeling	**LaRC Hampton, VA** • Structural Modeling	**MSFC Huntsville, AL** • Control Modeling • Design Validation and Test • Space Environment Test	**Pasadena, CA** • Sail Camera System • Education/ Public Outreach

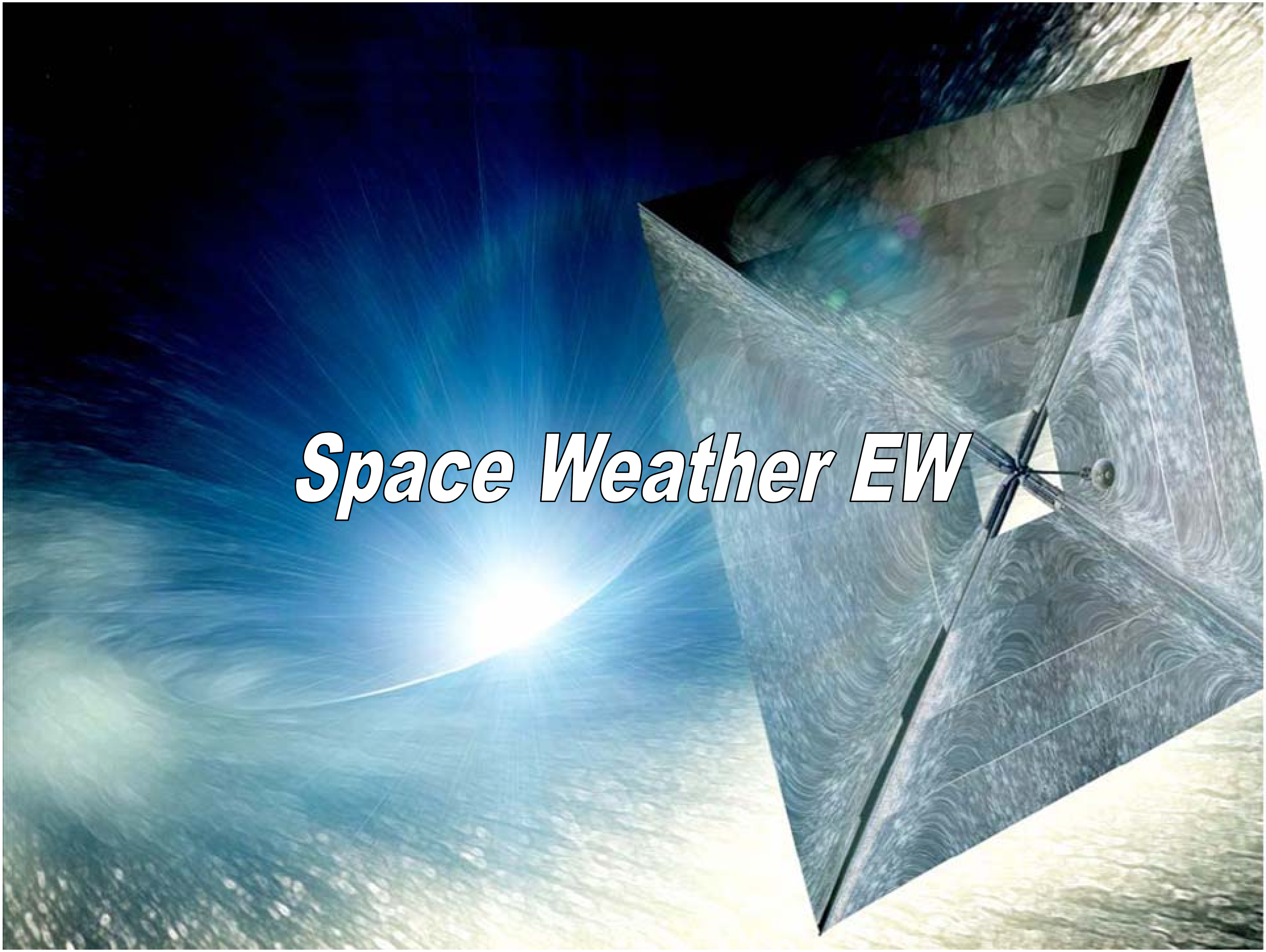
And next? … 2nd (3rd?) Gen Sail Technology Program

- Advanced "Heliogyro" spinner architectures being (re-)studied.
- Scalable to *extremely* large dimensions (R ~ km)
- Deployments and packaging simplified (no large acreage)
- Complete 6-axis control
- Flight demo validation required



JPL 16 km 'Heliogyro' Solar Sailcraft (ca. 1978)




Space Weather EW

Space Weather Detection and Warning

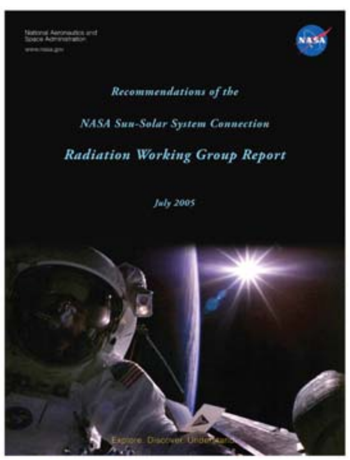
- Over the past 20 years, on average one to two satellites per year experience a partial or total mission loss directly attributed to radiation effects on electrical components.
- Low altitude orbits are protected by the earth's magnetic field, but higher earth orbits, or missions to the Moon or to Mars experience significant radiation environments.

- There were Apollo lunar landings in April 1972 and in December 1972. Had the great solar storm of August 4, 1972 happened earlier or later, astronauts in the lunar module would have been exposed to a radiation dose over a 12 hour period that would have caused acute radiation sickness and possibly even death.

- From "Radiation and the International Space Station: Recommendations to Reduce Risk (2000), Commission on Physical Sciences, Mathematics, and Applications"

Violent space weather

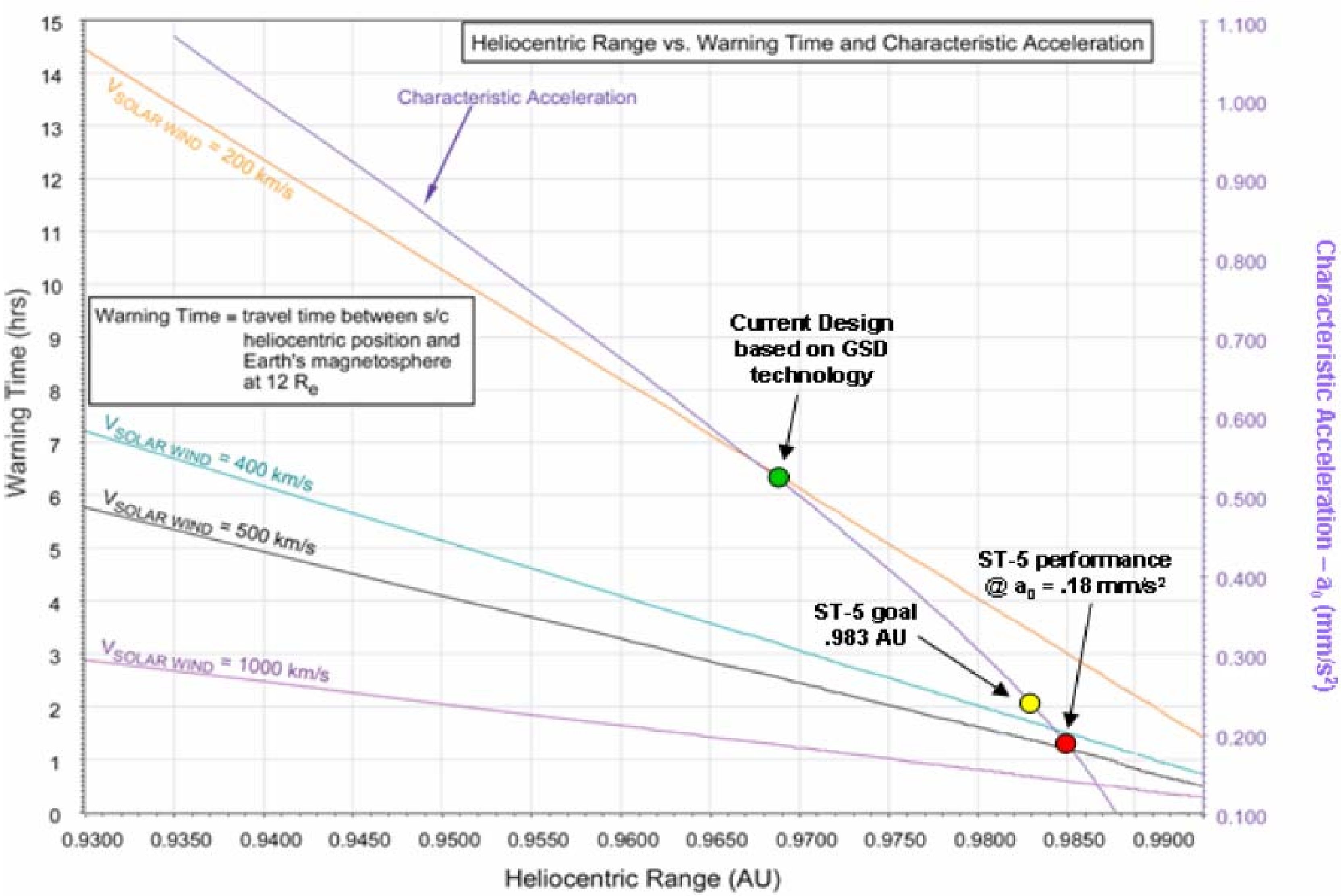
- High energy CMEs can produce “shocks” - particle fluences can increase by many orders of magnitude in a very short time.
- While some relativistic particles could reach the earth and moon within minutes, the highest intensity is expected at 4-6 hours after the flare.
- The Apollo plan was to move the astronauts off of the lunar surface and back to the command module, with its better shielding.
- Astronauts exposed directly risk lethal radiation doses.
- Spacecraft design must include “storm shelters” for protection during such events.
- A network of satellites and ground stations monitor the sun for signs of SPEs.
- Astronauts inside a spacecraft would probably be shielded enough to survive.
- The real risk is to astronauts outside of the spacecraft during a spacewalk or on the lunar or Martian surface.
- It has been estimated that the dose from a flare that occurred in July 1959 could have been between 40 – 360 rad. (1000X average annual dose on Earth)



To provide more advanced warning of solar wind disturbances as well as to warn of approaching co-rotating streams that could be missed by a single Sun-aligned probe, the committee recommends a Solar Wind Sentinels (SWS) mission as part of the future LWS program. Three spacecraft equipped with 100-m solar sails will surround the Earth-Sun line at 0.98 AU with separations in the 0.1-AU range. - *The Sun to the Earth -- and Beyond: A Decadal Research Strategy in Solar and Space Physics (2002), Space Studies Board*

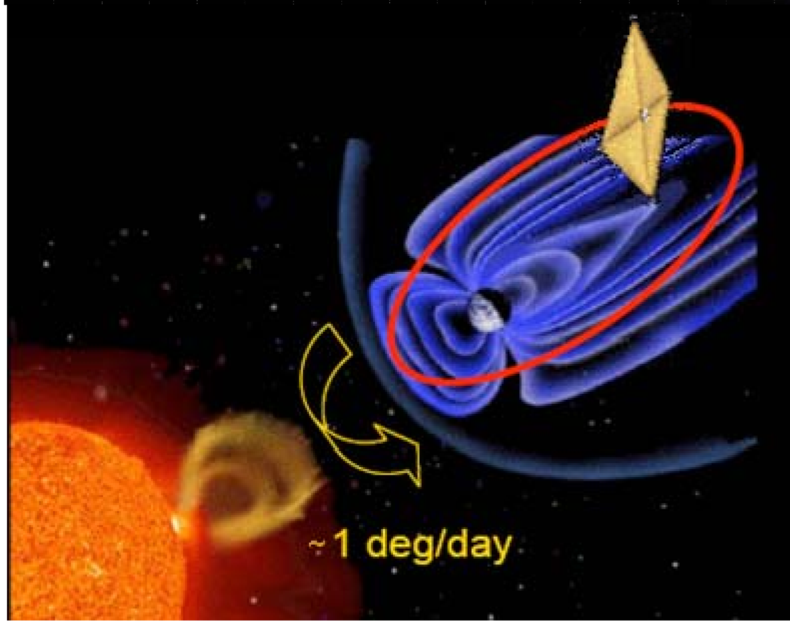
http://lwstrt.gsfc.nasa.gov/lwsscience_radtgreport.pdf

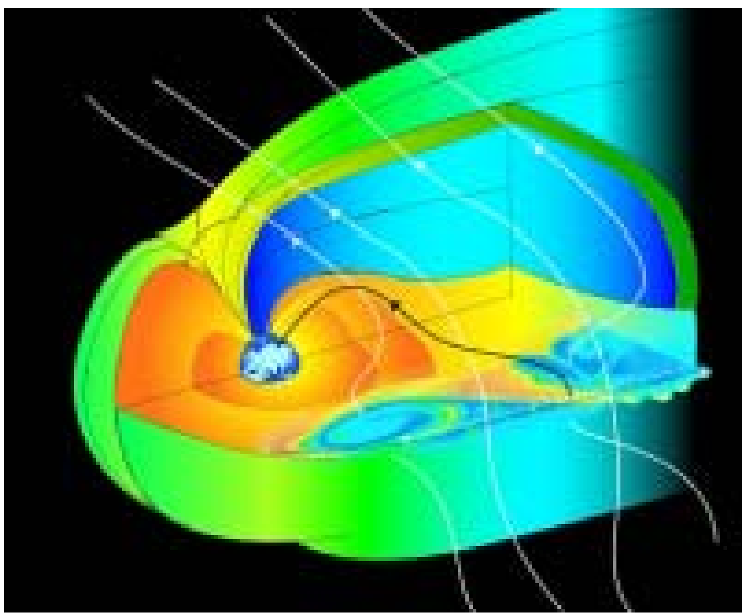
Solar sails can *significantly* increase warning time




Missions Supported

GeoSail





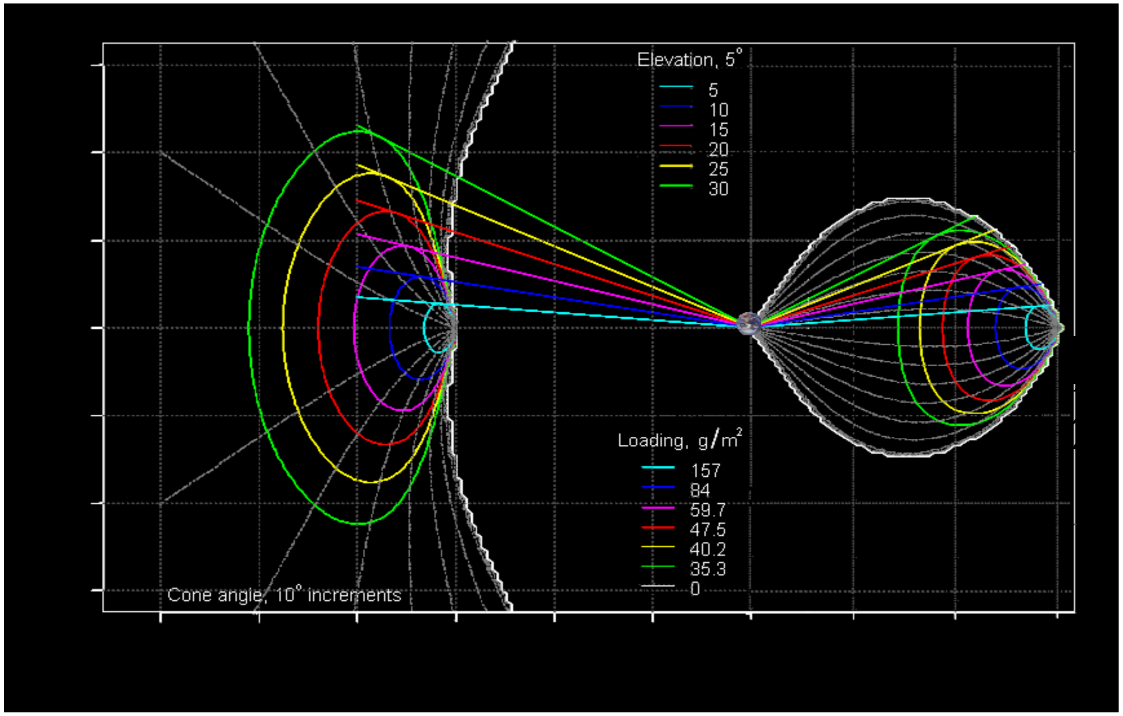
Science Objectives

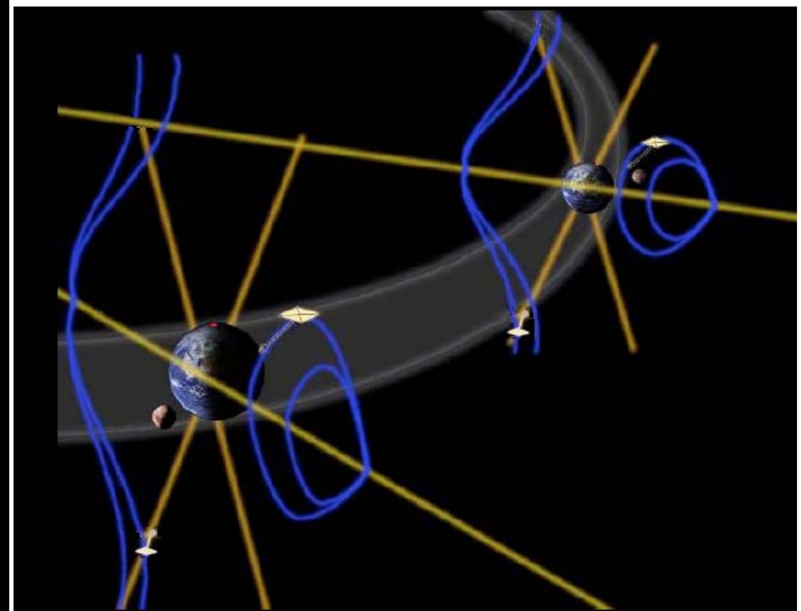
- Understand how spontaneous magnetic reconnection occurs in a magnetic current sheet
- Understand the mechanism behind reconnection mode destabilization and saturation in the magnetotail
- Analyze the plasma structure at the sub-second resolution
- Understand reconnection and particle dynamics at the day/dawn side low-latitude boundary layer along the earth's magnetopause

Mission Description

- Precess orbit apsis line to stay permanently in Geomagnetic tail
- Launch direct to operational orbit (10 x 30 $_{ER}$), minimal mission if sail fails to deploy
- 40 m square sail @ 55 g/m^2 with characteristic acceleration ~ 0.1 mms^2
- Demonstrate new science capability on technology demo mission
- Payload: magnetometers (2), electrostatic analyzer, solid state telescope (5 kg / 5 W or enhance 11 kg / 8.5 W)

PoleSitter





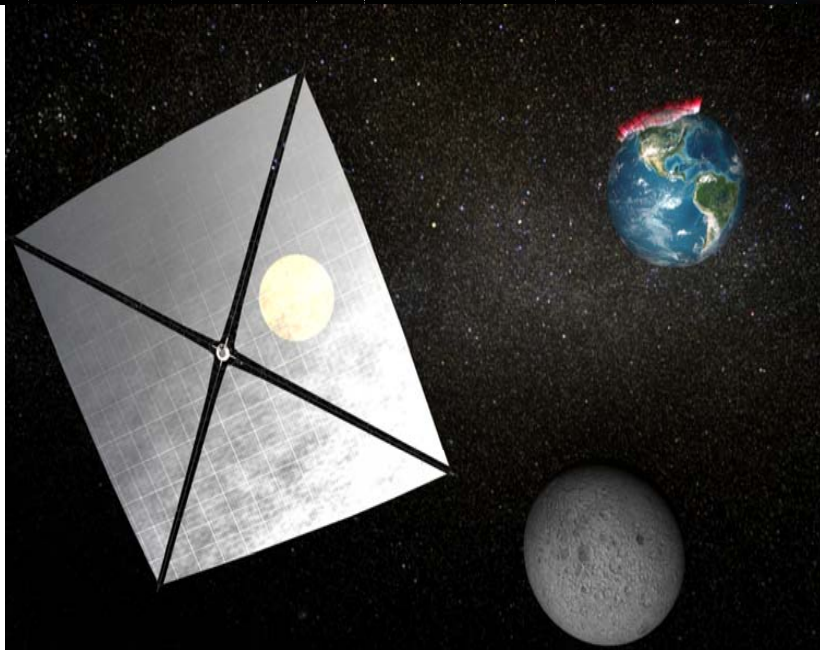
Polesitter Provides:

- **Near real-time imaging of Antarctic weather (Artic as well with sail at North L2 point)**
- **Data relay for the NPOESS satellite system**
- **Continuous communications/high speed data channel for Antarctic bases**
- **<u>Solar sail areal density of 30 – 40 g/m^2, 0.23-0.3 mm^2 characteristic acceleration</u>**

Polesitter Support of ESMD:

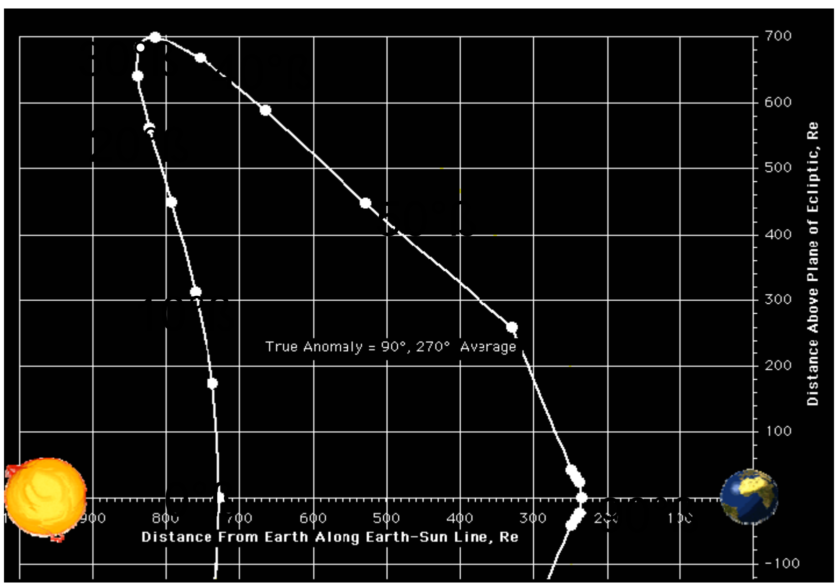
- **Slightly sunward of L1 for small increased leadtime for Coronal Mass Ejections (CMEs) warnings for Lunar astronauts.**
- **Continuous hemispheric visibility including Lunar south pole region for comm/high speed data.**

HelioStorm



Science Objectives

- Understand the Sun-to-Earth evolution of CMEs, shocks and particle radiation from solar eruptions
- Remote- and local sense Earth-impacting solar disturbances
- Determine the structure of the solar wind on spatial and temporal scales that are relevant for driving magnetospheric processes
- Provide warning time to protect lunar and Earth-orbiting and ground assets
- Provide a demonstration platform for Exploration and a pathfinder for the Solar Polar Imager science mission



Mission Description

- Delta II Launch Vehicle
- Trajectory: ballistic transfer from Earth to L1 Halo (~90 days), solar sail transition from L1; <u>80m square sail @ 14.3 g/m2</u>
- Continuous Solar Viewing: 2 years In Final Orbit
- Flight System Concept
- Solar-array powered S/C with solar sail
- Payload: Fields and Particles+ Imaging (33 kg/24 W)

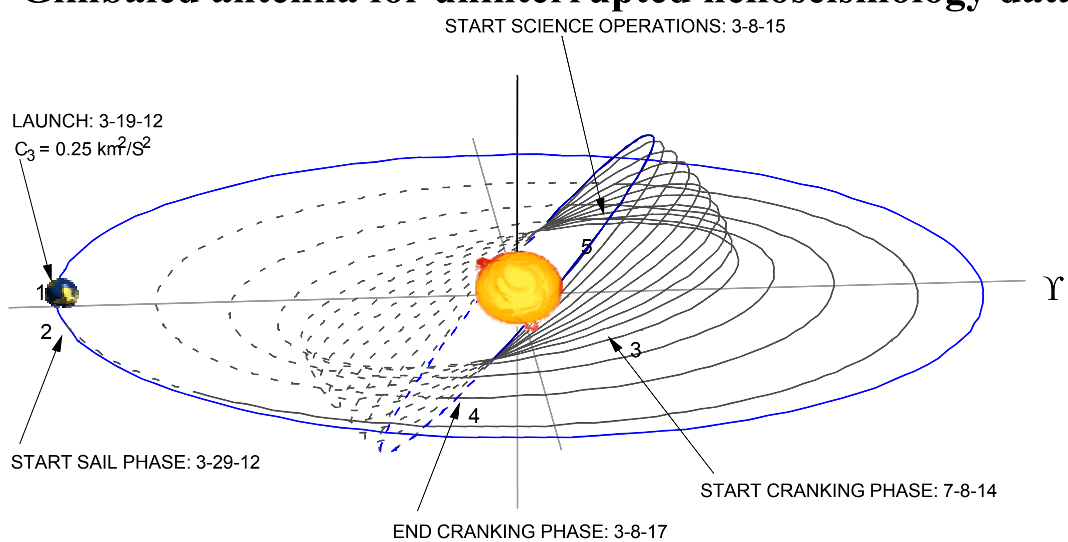
Solar Polar Imager (SPI)

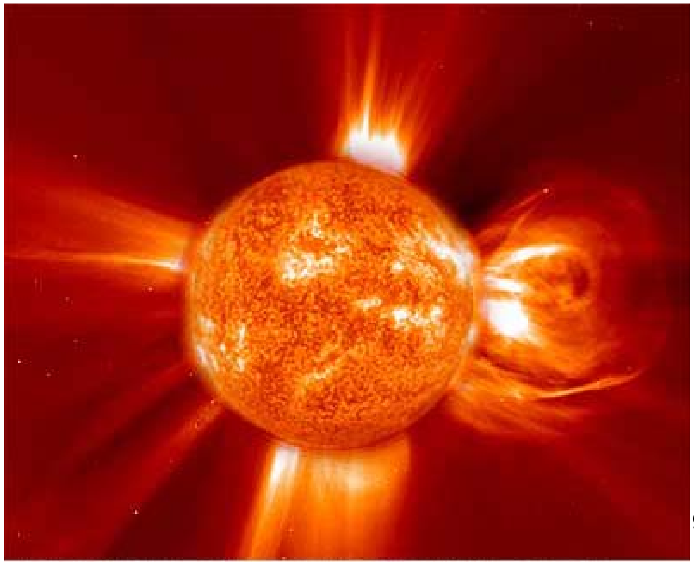
Science Objectives

- What is the relationship between the magnetism and dynamics of the Sun's polar regions and the solar dynamo?
- What advantages does the polar perspective provide for space weather prediction?
- What is the azimuthal structure and dynamics of the corona and CMEs?
- How are variations in the solar wind linked to the Sun at all latitudes?
- How are solar energetic particles accelerated and transported in radius and latitude?
- How does the solar irradiance vary with latitude?

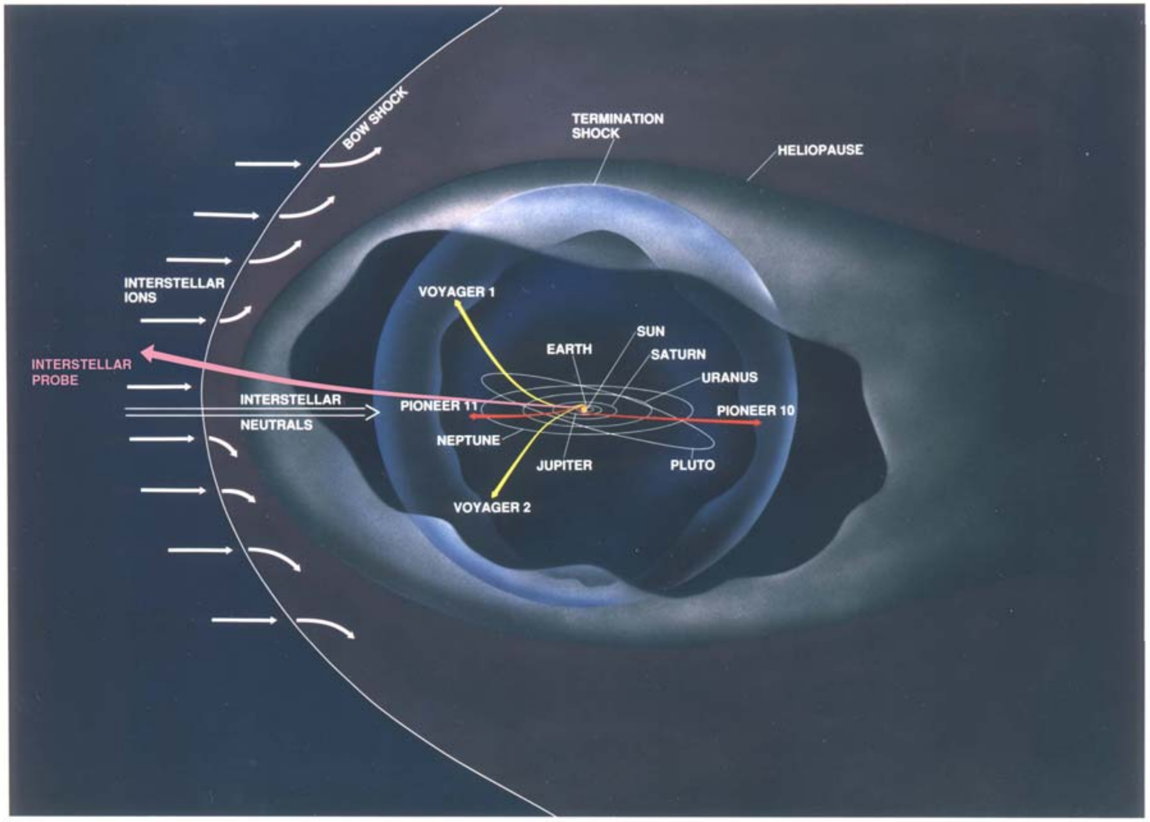
Mission Description

- SC in highly inclined ~75° 3:1 resonant heliocentric 0.48 AU orbit
- Payload: Fields and Particles+ Imaging (44 kg/50 W, 34 kg/24.5 W)
- Uses solar sail to reach high inclination in 5-7 years; <u>150 m square sail @ 13 g/m2</u>
- Collect *in situ* data during cruise
- Average data rate > 60 kbps; store and dump, 2 passes/week
- Gimbaled antenna for uninterrupted helioseismology data





Interstellar Probe



Mission Description

- Example mission design
  - Delta II 7425 launch (719 kg cap. to C3=0)
  - Flight system launch mass: 564 kg
  - Solar sail trajectory targeted for nose of heliosphere
  - 0.25 AU solar pass, 200 AU in 15 yrs.
- Flight system concept
  - Solar sail: < 1 g/m^2 , 200 m radius
  - "Flying Antenna" design implementation (191 kg)
  - Sized for 30 year operations
  - Payload: fields & particles + Imaging

Science Objectives

- Explore interstellar medium and determine directly the properties of the interstellar gas, the interstellar magnetic field, low-energy cosmic rays, and interstellar dust
- Determine structure & dynamics of heliosphere as example of interaction of a star with its environment
- Study, in situ, structure of solar wind termination shock, & acceleration of pickup ions & other species
- Investigate origin and distribution of solar-system matter beyond the orbit of Neptune