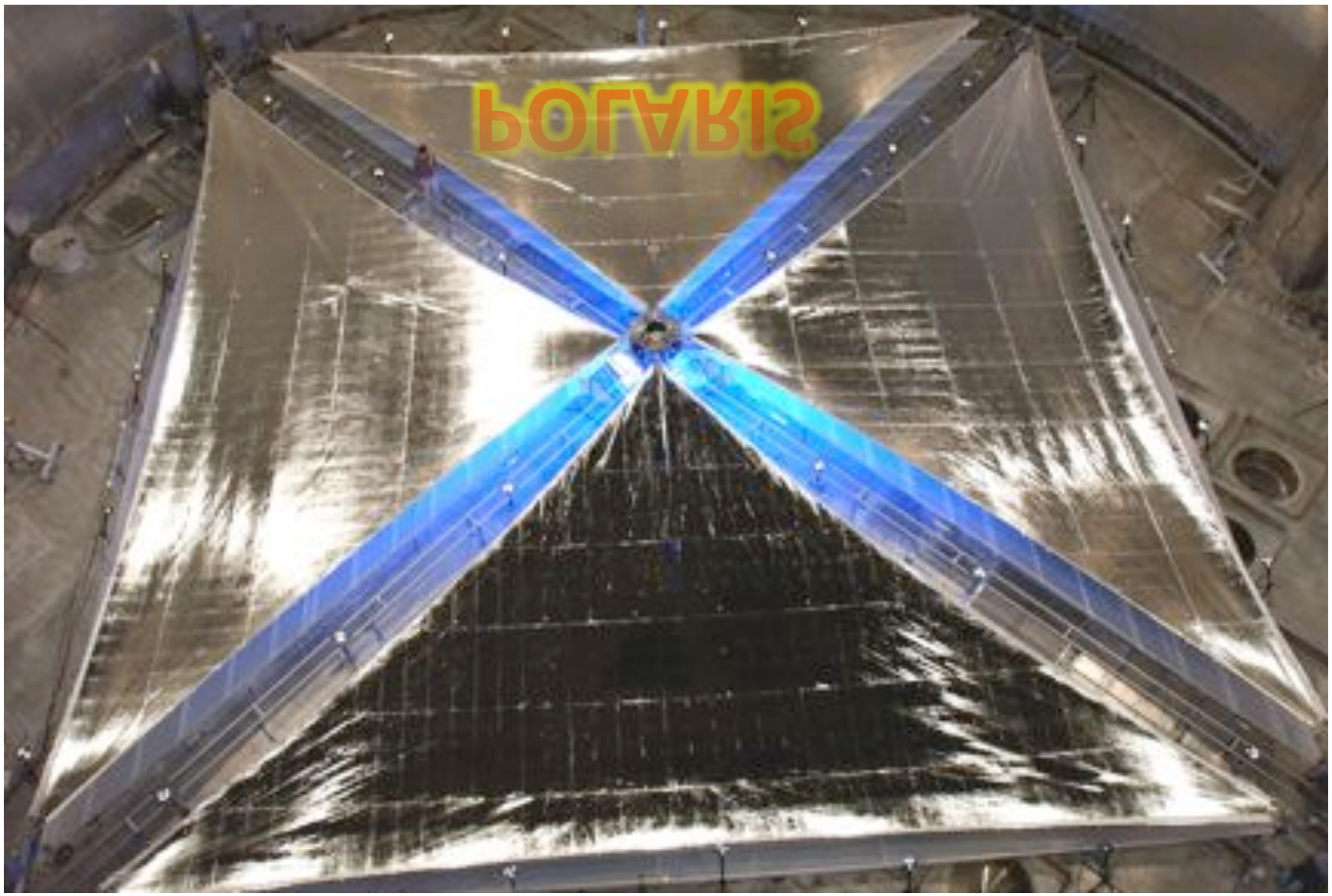
POLAR Investigation of the Sun
POLARIS



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Solar Polar Imager: Observing Solar Activity from a New Perspective

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Our current understanding of the Sun and its atmosphere is severely limited by a lack of observations of the polar regions. The Solar Polar Imager mission uses solar sail propulsion to place a spacecraft in a 0.48 AU circular orbit around the Sun with an inclination of 75°. This first direct view of the polar regions of the Sun enables crucial observations not possible from the usual ecliptic viewpoint and will revolutionize our understanding of the internal structure and dynamics of the Sun. The rapid 4 month polar orbit and the combined in situ and remote sensing instrument suite allows unprecedented studies of the link between the Sun and the solar wind and solar energetic particles. Moreover, SPI can serve as a pathfinder for a permanent solar polar sentinel for space weather prediction in support of the Exploration Initiative.

The Solar Polar Imager will provide the capability to:

- **Monitor Earth-directed CMEs from high latitudes**
- **Greatly improve models of the global heliosphere using better magnetogram coverage in longitude and latitude**
- **Observe active regions for much longer than 13 days**
- **Monitor ARs before they "appear" around the east limb**
- **Provide better coverage of AR sources of CMEs and SEPs**
- **Yield more complete information on subsurface flows and evolving ARs.**
- **Provide in-situ measurements of magnetic fields, solar wind and SEPs out of the ecliptic plane**
- **Determine the latitudinal dependence of the total solar irradiance variability**
- **Monitor Mars-directed CMEs from high latitude**

In this paper we report on the results of a recent Vision Mission study refining the science objectives, instrument suite, orbit and trajectory analysis, solar sail characteristics and measurement strategy. The SPI provides an important step in improving our understanding of the physics governing solar variability on long and short time-scales and on local and global scales.

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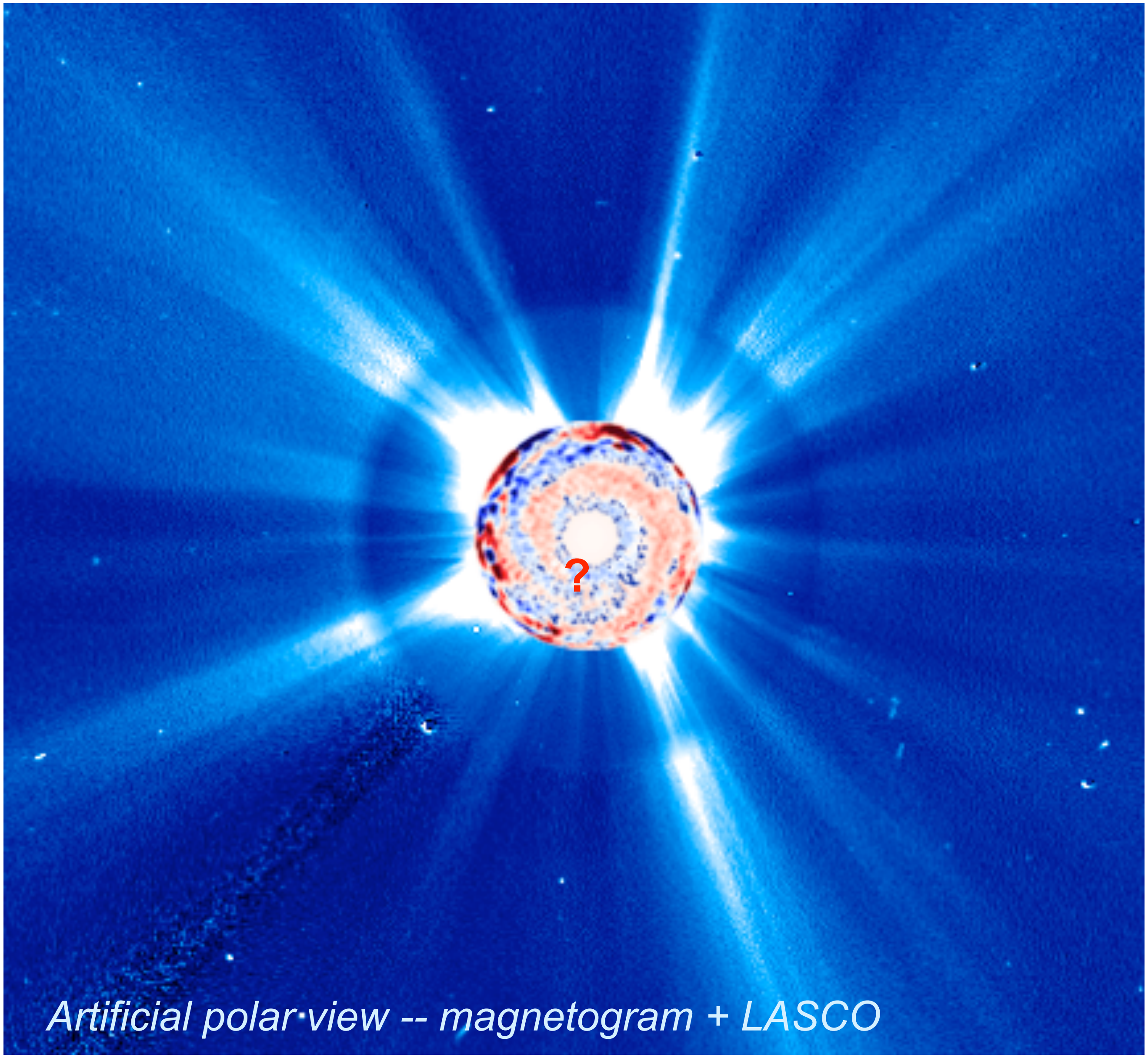
Overview



Artificial polar view -- magnetogram + LASCO

Mission

Spacecraft in highly inclined ~75° heliocentric orbit 0.48AU

Uses solar sail to reach high inclination

Science

Dynamo:Helioeis-molgy & magnetic fields of polar regions

Polar view of corona,CMEs, solar irradiance

Link high latitude solar wind & energetic particles to coronal sources

POLARIS: High Level Science Goals

- 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?

POLARIS is designed to observe the polar regions for extended periods of time.

Concept heritage from
Solar Polar Imager

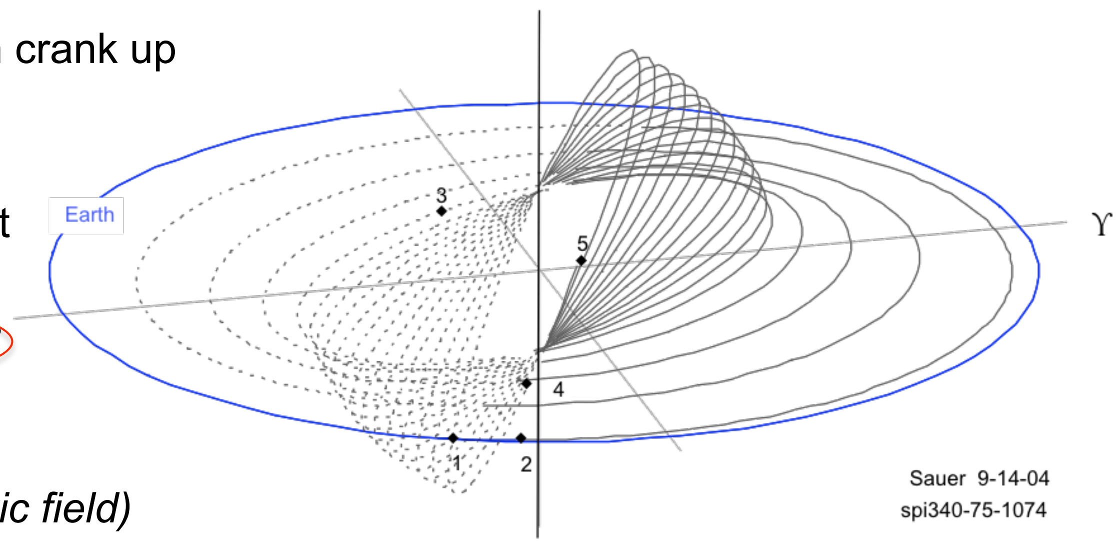
POLARIS: ESA Cosmic Vision concept
SPI: NASA Vision Mission concept

POLARIS - Mission Concept

Uses Solar Sail to attain 75° inclination orbit at 0.5 AU in ~5-7 years

- Spiral in to 0.48 AU (2-3 years), then crank up to 75° final orbit
- *In situ* data collected during cruise
- Imaging data collected after final orbit attained and sail is jettisoned
- 29% of time in final orbit is above 60°

2012 Solar Sail POLARIS
3:1 Resonance, R= 0.48 AU
75 Degrees Heliographic Inclination



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Instruments

- Helioseismograph *(velocities,magnetic field)*
- Coronagraph *(CMEs, coronal structures, blobs)*
- EUV *(2 channels; structure & flares for context)*
- UV Spectrometer *(coronal base outflows)*
- Solar wind protons & electrons (*SW variations)*
- Solar Energetic Particles *(impulsive & gradual)*
- Magnetometer *(in situ magnetic field)*
- Tolar solar irradiance variability

Payload Accommodation

- Total Instrument Mass ~97.5 kg
- Average data rate >60 kbps
- Store &dump data, ~2 DSN passes/week
- Gimbaled antenna for uninterrupted helioseismology observations

Table 3: Baseline Mission Parameters

	[RD1]	[RD2]
Min Solar Approach Radius (AU) (= Cranking Radius)	0.48	0.48
Science phase inclination (degrees) w.r.t. Ecliptic	82.75	67.8
Launch injection mass (kg)	443	733
Sail mass (kg)	195	408
Payload mass (kg)	41	50
Platform mass (kg) (includes payload)	247	325
Sail side length (m)	153	178.9
Transfer duration (years)	5	6.7
Launch Vehicle	Soyuz Fregat 2-1b	Delta IV
Sail Areal Density (g/m^2)	9.298	14.16
Launch C_3 (km^2/s^2)	38	0.25

Table 4: Scenarios studied.

Scenario	**1a**	**1b**	**1c**	**2a**	**2b**	**2c**	**3a**	**3b**
Reference System	RD1	RD2	RD2	RD2	RD2	RD2	RD2	RD2
Platform Mass (kg)	443	325	325	**601**	**656**	**707**	**539**	**467**
Sail side length (m)	153	178.9	**147**	**200**	178.9	178.9	178.9	178.9
Cranking Radius (AU)	0.48	0.48	0.48	0.48	**0.4**	0.48	0.48	**0.4**
Trip Time (years)	**5.5**	**5.51**	**6.74**	6.7	6.7	**8.23**	**8.23**	**6.39**
Sail Areal Density (g/m^2)	9.298	14.16	14.16	14.16	14.16	14.16	**20**	**20**
Launcher	**Dnepr**	**Soyuz Fregat**	**Dnepr**	**Soyuz Fregat**	**Soyuz Fregat**	**Soyuz Fregat**	**Soyuz Fregat**	**Soyuz Fregat**

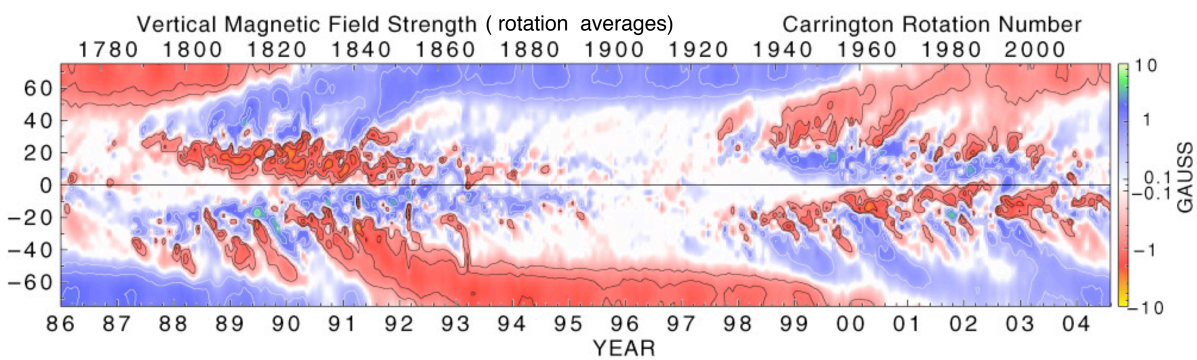
The POLARIS baseline is Scenario 2c (solar sail system of [RD2] and Soyuz Fregat launcher).

RD1 and RD2 are two separate sail studies which consider different performance sails.

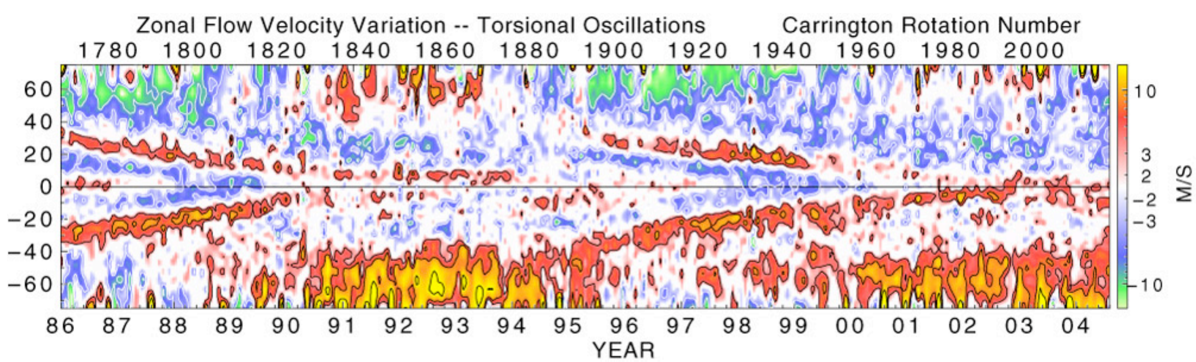
POLARIS Goal 1:

What is the relation between the magnetism and dynamics of the Sun's polar regions and the solar cycle?

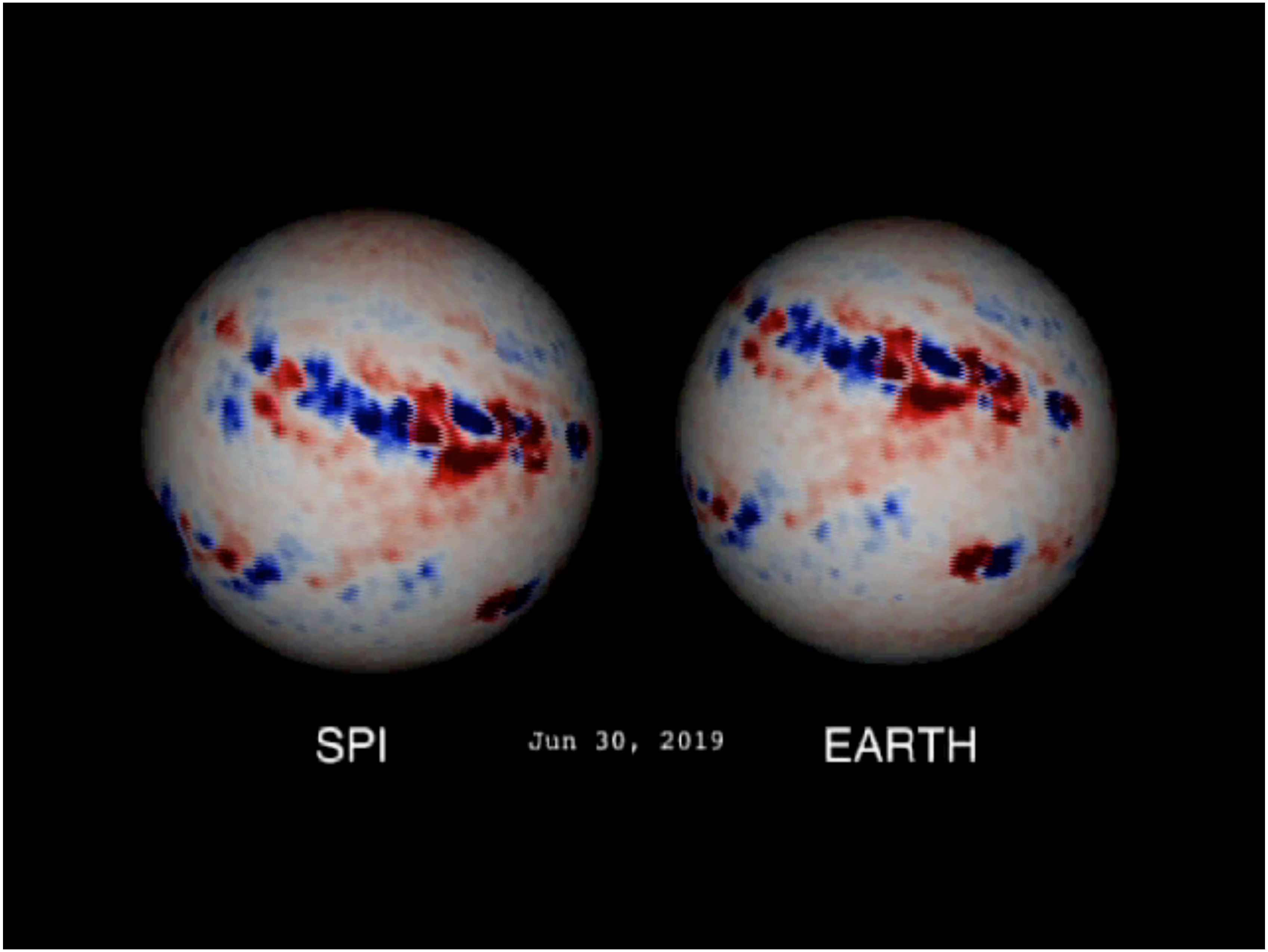
Major Goal: Knowledge of the high-latitude meridional circulation and differential rotation is crucial for understanding magnetic flux transport, polar field reversals, solar cycle models and predictions. **These are the main ingredients of the solar dynamo.**



Magnetic Field Evolution: Magnetic fields first appear associated with ARs. **Meridional flow** moves fields poleward. Trailing spot is poleward of the leading spot. Causes reversal of the global dipole field.



Torsional Oscillations: Solar **differential rotation** undergoes a cyclic pattern of increased and decreased rotation rate called "torsional oscillations". Global magnetic field evolution is closely related to the torsional oscillations.



Courtesy: Roger Ulrich

POLARIS Goal 1 (continued):

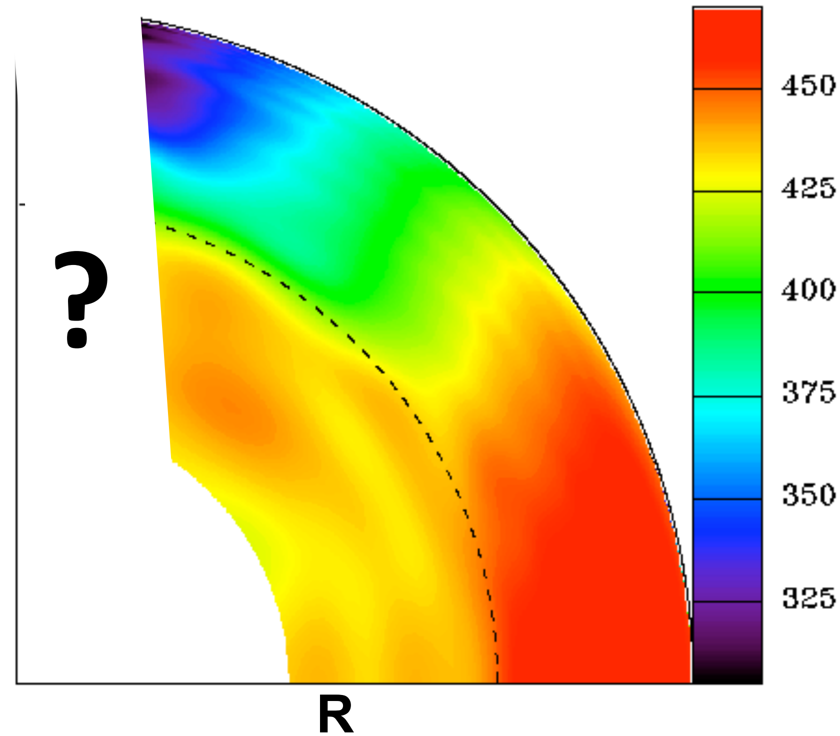
What is the relation between the magnetism and dynamics of the Sun's polar regions and the solar cycle?

Current State of Knowledge

- Internal structure and differential rotation measured with great precision except in the polar regions (75-90º latitude), the energy-generating core and the thin subsurface "superadiabatic" layer. (Global helioseismology)
- Large-scale dynamics investigated in details in the mid-latitude zone from -60 to 60 degrees in the upper convection zone, 30 Mm deep. (Local helioseismology)

POLARIS can fill in polar regions and, in conjunction with SDO or GONG, measure flows in deep interior

Solar Rotation Rate from SOHO/MDI



Solar rotation rate (Ω/2π nHz) with uncertain polar and deep regions shown in white (based on Schou 1998).

POLARIS Goal 1 (continued):

What is the relation between the magnetism and dynamics of the Sun's polar regions and the solar cycle?

- What are the surface & subsurface flow patterns in the polar regions?
- What are the internal flows deep in the convection zone that drive the solar dynamo? (POLARIS + SDO or GONG)
- How do the solar magnetic fields evolve?
  - What are the magnetic fields in the polar regions?
  - How is the flow and dissipation of magnetic energy in the corona affected by the interior and surface flows? *(POLARIS Uses EUV + coronagraph to observe coronal response to flows)*

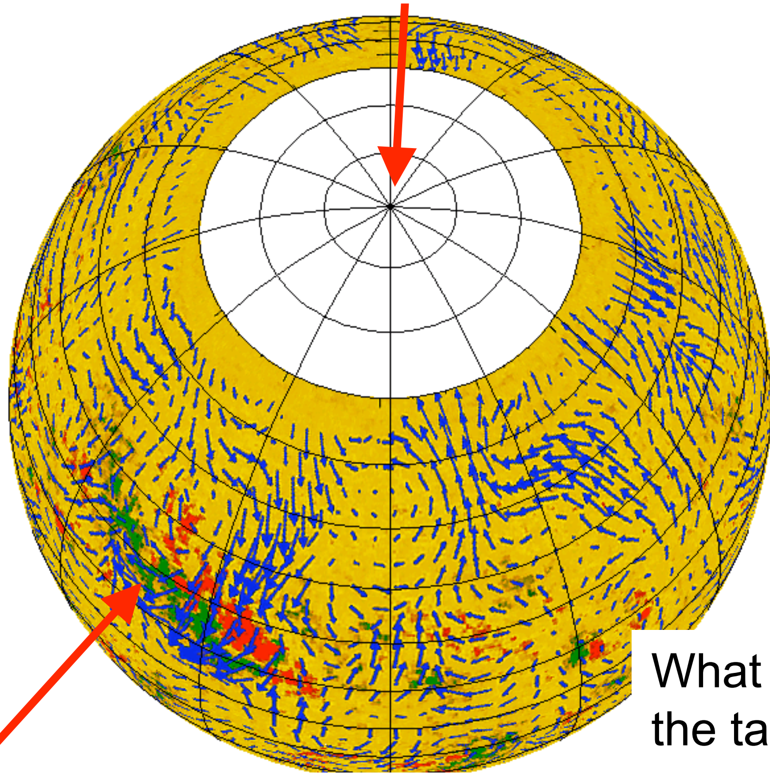
POLARIS will measure (using both global and local helioseismology)

- Differential and torsional oscillations at high latitudes, any polar jets or vortices
- Meridional circulation, latitudinal and longitudinal structures, secondary cells, relationship to active longitudes, magnetic flux transport
- Supergranulation and large-scale convection patterns in polar regions (super-rotation, wave-like behavior, network, flux transport, relationship to coronal holes)
- Tomography of the deep interior (POLARIS + SDO or GONG)

POLARIS Goal 1 (continued):

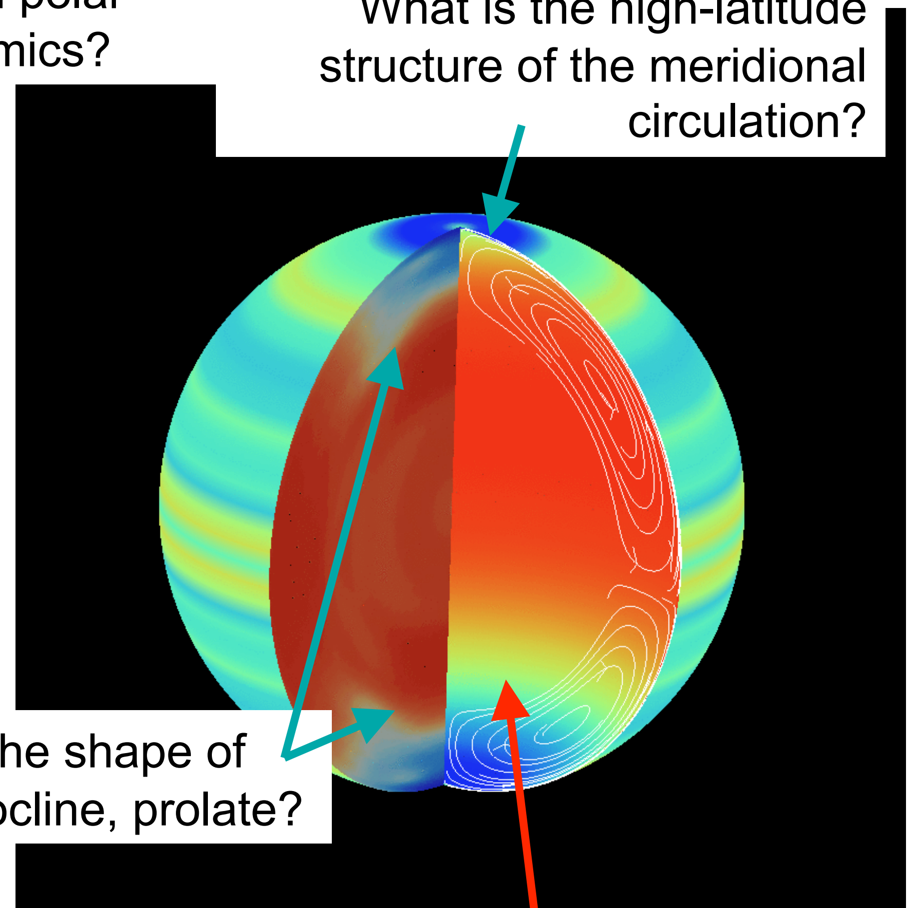
What is the relation between the magnetism and dynamics of the Sun's polar regions and the solar cycle?

What is the large-scale circulation pattern in polar regions and its role the magnetic field dynamics?



Converging flows around active regions play important role in their evolution.

What is the high-latitude structure of the meridional circulation?



What is the shape of the tachocline, prolate?

How deep is the meridional flow?

POLARIS Goal 2:

Coronagraph/EUV Science Goals

Coronagraph

- **Primary**
  - Observe GLOBAL effect of CMEs
  - Determine true longitudinal extent of CMEs/Streamers
    - Accurate mass//density/energy determination
  - 3D reconstruction of CMEs
    - Better determination of CME substructures
  - 360˚ Evolution of Streamer Belt
  - Plume/Coronal Hole structure
    - 3D plume structure (orbit)
    - Coronal sources of plumes
  - Current Sheet/Streamer structure
    - Filamentary? Uniform density?
- **Secondary**
  - Momentum loss in Solar Wind
  - Initiation & Evolution of Earth-directed CMEs.

EUV Imager

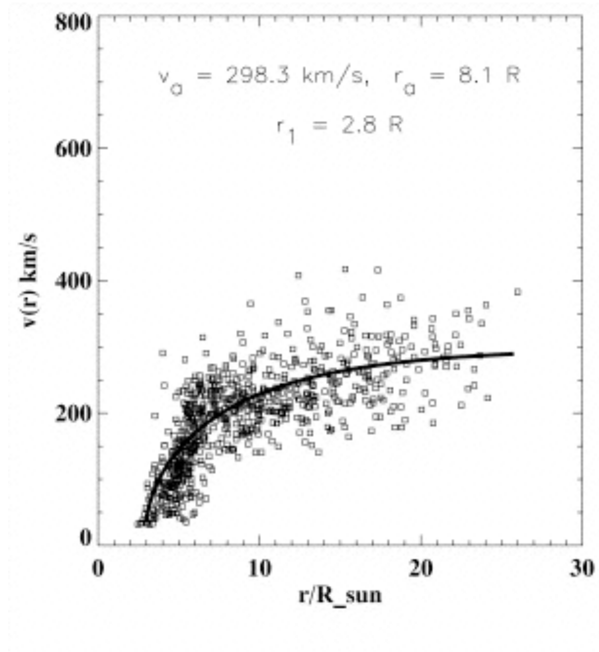
- **Primary**
  - Follow EUV Waves/Shocks over the complete solar surface
  - Locate SEP injection sites
  - Direct observations of geoeffective flares
  - 3D structure of erupting prominence or loop arcades
  - Follow active region evolution over full rotation (360˚?)
- **Secondary**
  - Determine spatial relation between CMEs and their coronal sources
  - Image the network/corona at poles

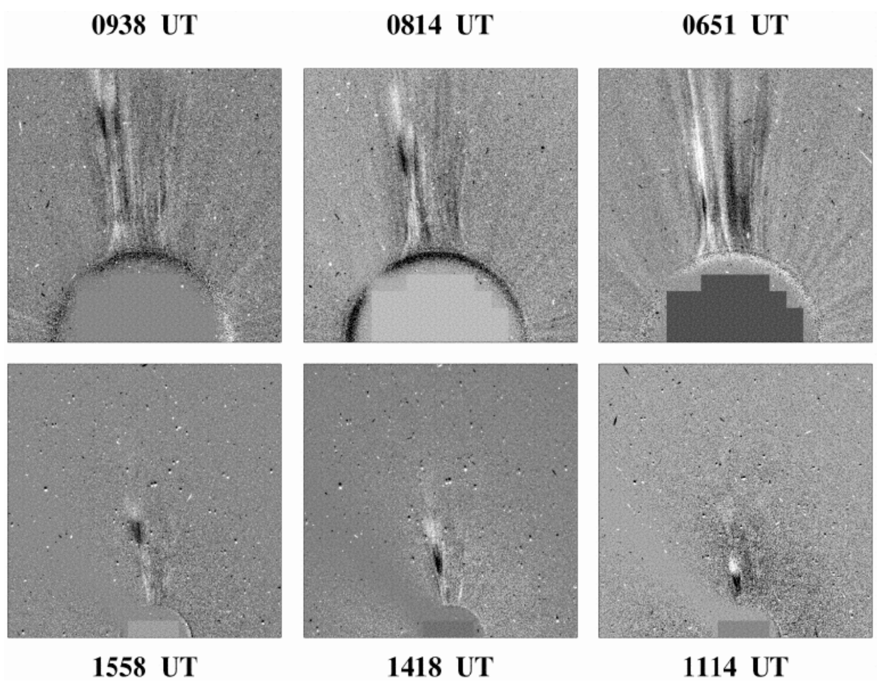
POLARIS Goal 2:

What is the azimuthal structure and dynamics of the corona and CMEs?

- Sheeley, et al., 1997 studied acceleration of solar wind by tracking "blobs" in streamers
- Note large scatter in velocity-height profile
- SPI can reduce scatter by viewing streamer belt from polar perspective (short LOS through streamer belt)

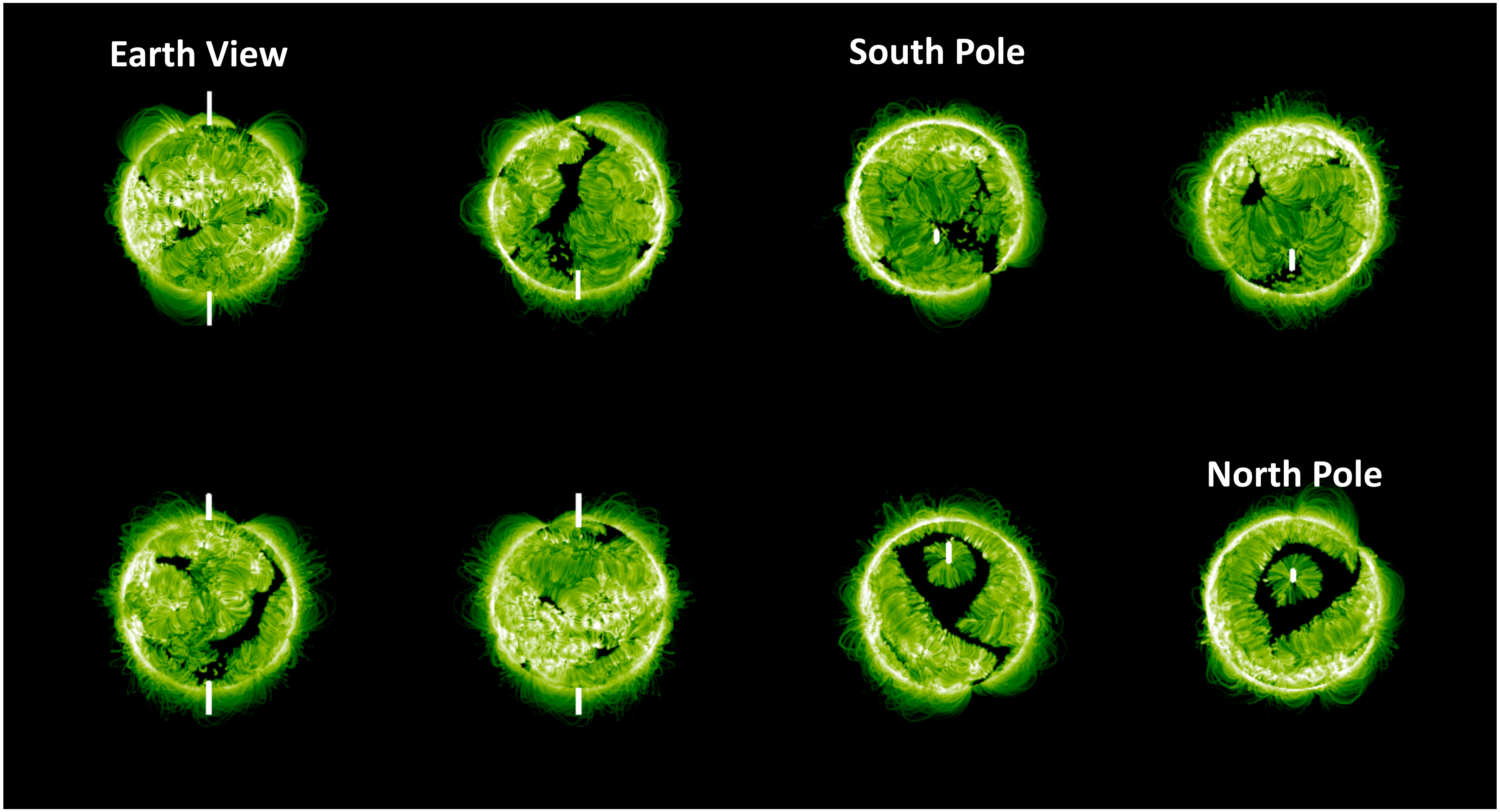
Velocity vs height profile





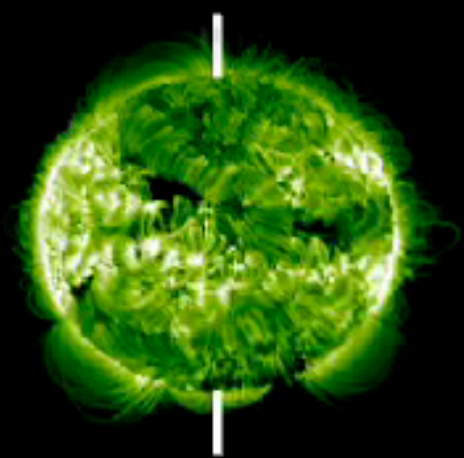
LEFT: Time difference images showing flow of material in streamers

EUV Imager: EUV Simulations

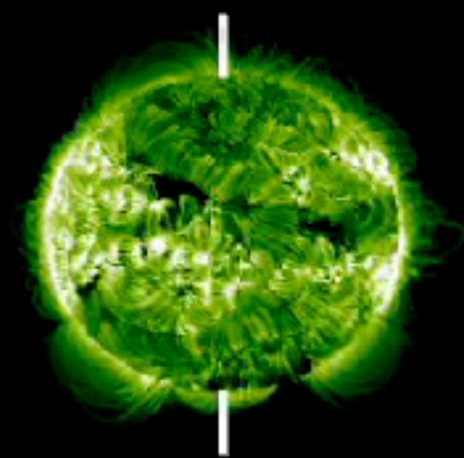


Alexander & Sandman

EUV Imager: EUV Simulations

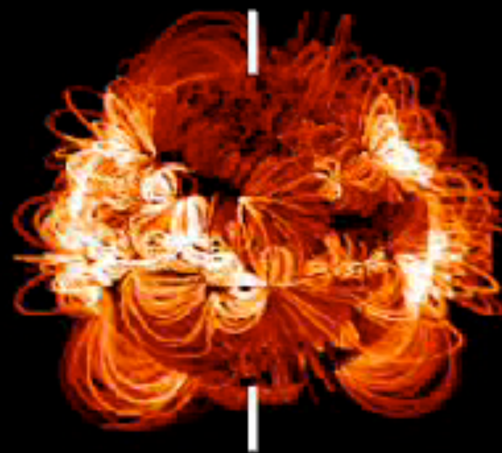


Ecliptic View



POLARIS View

EUV Imager: X-ray Simulations



POLARIS View

POLARIS Goal 2:

Synergy with Magnetograph and Helioseismology Goals

EUV IMAGER

connectivity of magnetic field through coronal emission, subject to optical-thin l-o-s integration, assuming 171Å or 195Å option.

coronal response to field dynamics (emergence, magnetoconvective motions)

coronal hole boundary locations for refining global field topology.

polar crown arcade observations to determine large-scale neutral lines near poles

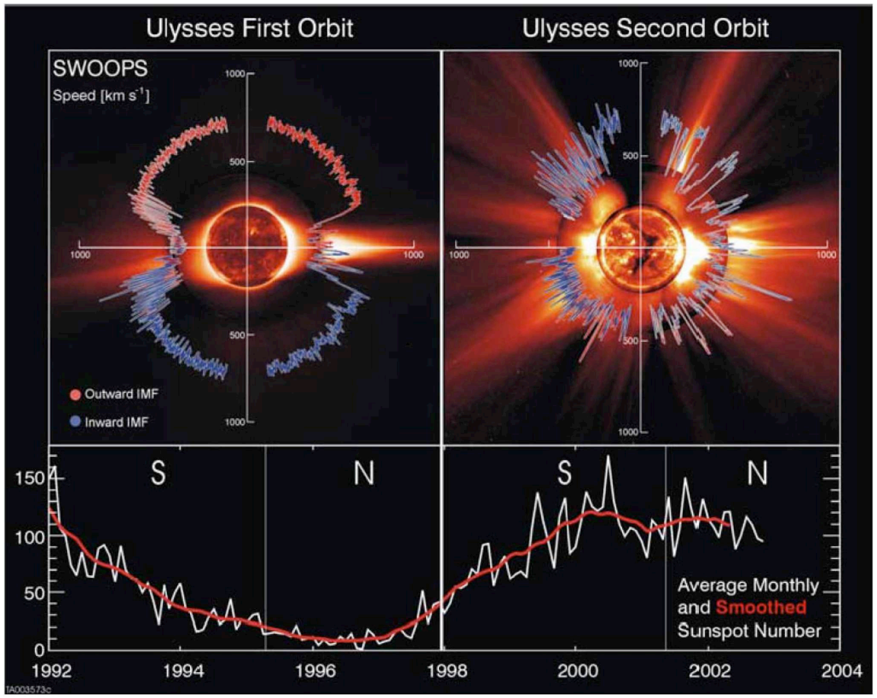
CORONAGRAPH

large-scale (‘global’) magnetic topology

coronal response to “field-reversal” or poleward drift of field

POLARIS Goal 3:

How are variations in the solar wind linked to the Sun at all latitudes?



POLARIS will address these questions better than existing & planned missions.

- Can we identify coronal sources of slow wind?
- What is the underlying cause of the variability of the slow wind?
- What are the processes that create the slow wind?
- Can a direct connection be made between in situ and remote observations of plumes or streamers?

POLARIS can:

- ❑ sample slow wind closer to Sun and polar field lines less wound
- ❑ provide rapid (4 months) latitude scans at fixed radius
- ❑ yield more accurate mapping using magnetograms with increased coverage in longitude and latitude including pole!
- ❑ combine *in situ*, coronagraph, EUV and UV spectrometer information

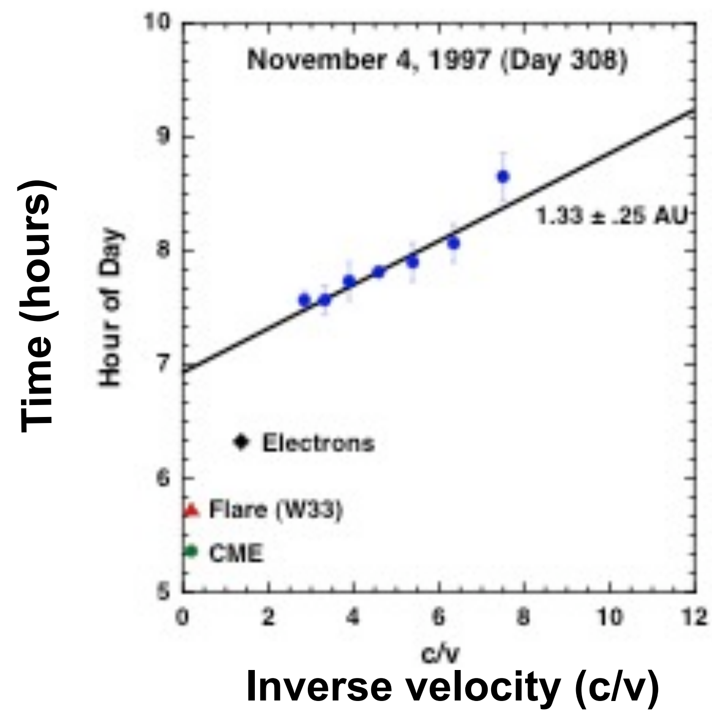
POLARIS Goal 4:

How are solar energetic particles accelerated and transported in radius and latitude?

- What are the relative roles of CME-driven shocks and flare-associated processes in Solar Energetic Particle (SEP) acceleration?
- How do SEPs, created in mid-latitude active regions, get transported to high latitudes?

POLARIS will allow much better determination of SEP event onset time and solar source to address these questions because path length to source is shorter (closer, less field line winding) and dispersion & scattering less.

• *Requires SW plasma, energetic particle instruments, magnetometer, EUV (flare onset) & coronagraph (CME height vs. time)*



Velocity dispersion of observed energetic particles, extrapolated to determine SEP event injection time. Shows injection >1 hour after flare. Suggests SEPS due to CME shock in low corona, not flare. (Mewaldt et al)

POLARIS Goal 5:

What advantages does the polar perspective provide for space weather prediction?

POLARIS can serve as proving ground for a permanent polar orbiter for space weather prediction in support of the Exploration Initiative

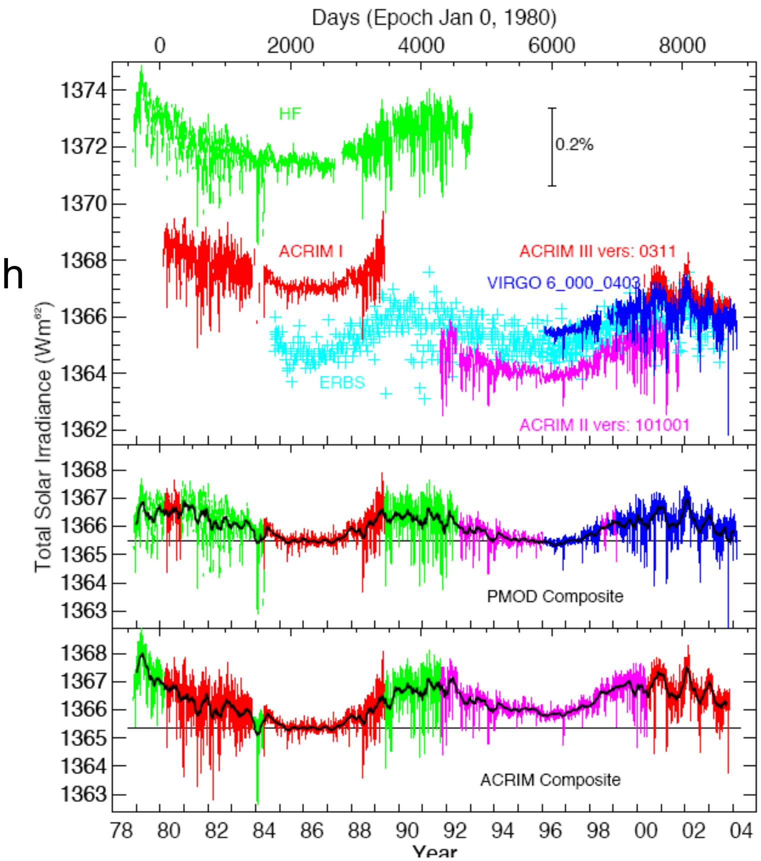
- **Monitor Earth-directed CMEs from high latitudes (get height-time profiles for "halo" CMEs)**
- **Greatly improve models of the global heliosphere using better magnetogram coverage in longitude and latitude (better BCs)**
- **See some active regions much longer than 13 days**
- **See some ARs before "appear" on east limb.**
- **More frequent observations of AR sources of CMEs, SEPs**
- **Much more complete information on subsurface flows and evolving ARs.**
- **Monitor Mars-directed CMEs from high latitude**

POLARIS Goal 6:

How does the solar irradiance vary with latitude?

All current measurements of Total Solar Irradiance (TSI) from ecliptic plane- Measure TSI variations of ~0.1%.

- Why is the variation ~1/3 of variation in other Sun-like stars? Are we seeing them from the polar view point?
- Is missing ecliptic radiation funneled out through the polar regions or does the Sun store this energy?
- Define a irradiance/dynamo relationship for application to stars



Measurements of TSI variation with latitude will answer a basic question in solar physics/astrophysics and constrain models of TSI

Note: Active cavity TSI instruments are notoriously difficult to calibrate, but measure <u>variations</u> in TSI very accurately. Goal of SPI solar irradiance instrument is ONLY to measure VARIATIONS in irradiance. Eliminates need for complex calibrations and simplifies instrument

Instrument Payload

The remote-sensing instruments are:

- Dopplergraph and magnetograph imager [MDI, HMI, SoLO heritage]

  The Doppler and Stokes imager will provide solar radial velocity every 45 seconds (in order to resolve the helioseismology oscillations), with a pixel resolution of 4", and vector magnetic field maps of the whole Sun every five minutes with a pixel resolution of 2".
- White-light coronagraph [COR2 heritage]

  The optical design has been modified to incorporate a 5-element external occulter and to achieve good stray light performance over a 16° field of view with a 60-cm long instrument. The coronagraph will observe the corona from 1.5 to 15 solar radii with 28" pixels.
- EUV imager [SoLO heritage, new Fresnel zone- based instrument]

  Two telescopes with baselined lines centered at 195 and 304 Å respectively. full-disk observations of the corona out to 1.4 R_{Sun} with 2.6" pixels
- UV spectrograph [RAISE heritage]

  The spectrograph includes a single-element off-axis parabola mirror and a toroidal variable line space grating with an instantaneous field of view of the entrance slit of 10" x 85' (full solar disk at 0.48 AU), with a spatial resolution of 10", corresponding to 3700 km on the Sun. A single raster scan can produce a full-Sun spectroheliogram in 17 minutes. The baseline design we have chosen covers the 1166Å – 1266Å wavelength range.
- Total Solar Irradiance monitor

  The POLARIS TSI Monitor is a new generation, room-temperature absolute radiometer based on the electrical substitution principle (ESR). It employs 3 cavities that are all pointed towards the Sun but can be shaded individually.

All imaging instruments will have a typical pixel resolution of 2 to 4 arcseconds.

Instrument Payload

The *in-situ instruments* are:

- Magnetometer
- Solar-wind ion composition and electron spectrometer
- Energetic particle package
- Radio and plasma wave package

Table 1 summarizes the scientific objectives that are addressed by each instrument, while Table 2 sums up the required resources. All remote instruments shall be no longer than one meter.

Table 1: Science Objectives and Contributing Instruments

	Remote sensing					*In situ*			
Scientific Objectives	**DSI**	**COR**	**EUVI**	**TSI**	**UVS**	**MAG**	**SW**	**EPP**	**RPW**
What is the 3D structure of the solar magnetic field, and how does it vary over a solar cycle?	×	×	×	×		×			
What is the 3D Structure of Convection and Circulation Flows Below the Surface, and How does it affect Solar Activity?	×	×	×	×	×				
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 spectral and total solar irradiance vary with latitude?	×		×	×	×				
What advantages does the polar perspective provide for space weather prediction?	×	×	×		×	×	×	×	×

COR: Coronagraph

TSI: Total Solar Irradiance Monitor

EUVI: Extreme Ultra-Violet Imager

DSI: Doppler-Stokes Imager

UVS: Ultra-Violet Spectrograph

MAG: Magnetometer

SW: Solar Wind Ion Comp. and Electron Spec.

EPP: Energetic Particles Package (20 keV – 10 MeV).

RPW: Radio and Plasma Waves

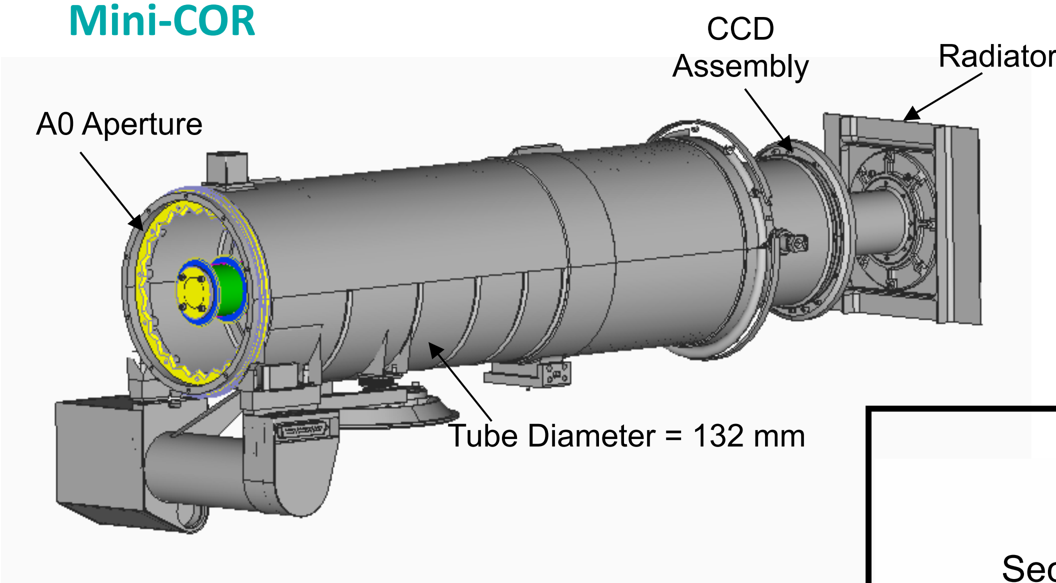
Table 2: Payload Resource Summary

	Remote Sensing Instruments					*In-situ* Instruments			
	DSI	COR	EUVI	TSI	UVS	MAG	SW	EPP	RPW
Mass (kg)	25	10	10	7	15	1.5	10	9	10
Power (W)	37	15	12	14	22	2.5	15	9	15
Absolute pointing (3 σ)	30′	10″	30′	30′	0.5′	N/A	120′	N/A	N/A
Pointing stability (3 σ)	0.2″ in 10 s	7″ in 1s	1″ in 10 s	6′ in 1 s	N/A	N/A	6′ in 1 s	N/A	N/A
Data rate (kbps)	75	40	40	0.4	10	0.6	0.2	1.0	5
FOV	1.5°×1.5°	16°	1.5°	2.5°	10″ × 1.4°	N/A	20° × 160°	See text	4 π

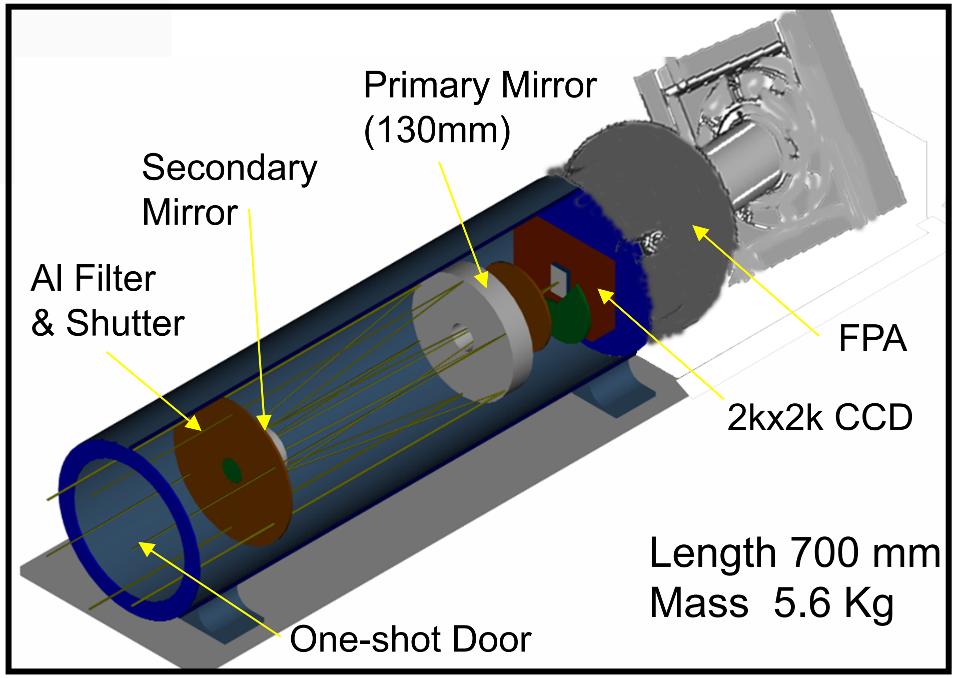
Outlined in grey: the instruments requiring internal pointing

Coronagraph/EUV Imager

Mini-COR



Total Length = 605 mm
Total Mass = 5.25 Kg



EUV Imager

see Vourlidas

Implications/Lessons for Solar-C Plan A

When considering polar orbits, mission becomes more like a planetary mission:

Time to science orbit much longer than solar physicists are used to.

Implications/Lessons for Solar-C Plan A

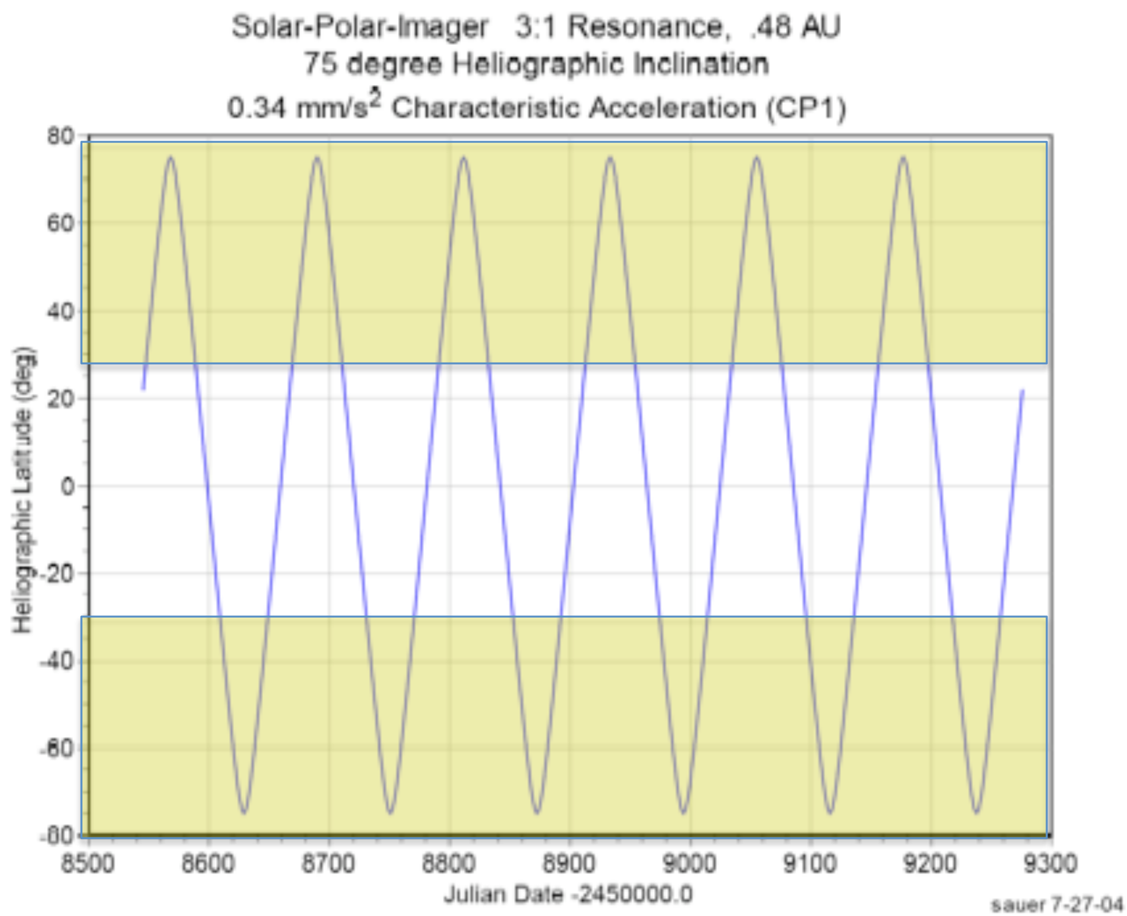


Figure 1.A.1-6 ORBIT INCLination vs day for 2 year science orbit

~30% of orbit > 60° latitude : ~50% of orbit > 30° latitude

Implications/Lessons for Solar-C Plan A

Rationale for as high an inclination orbit as possible:

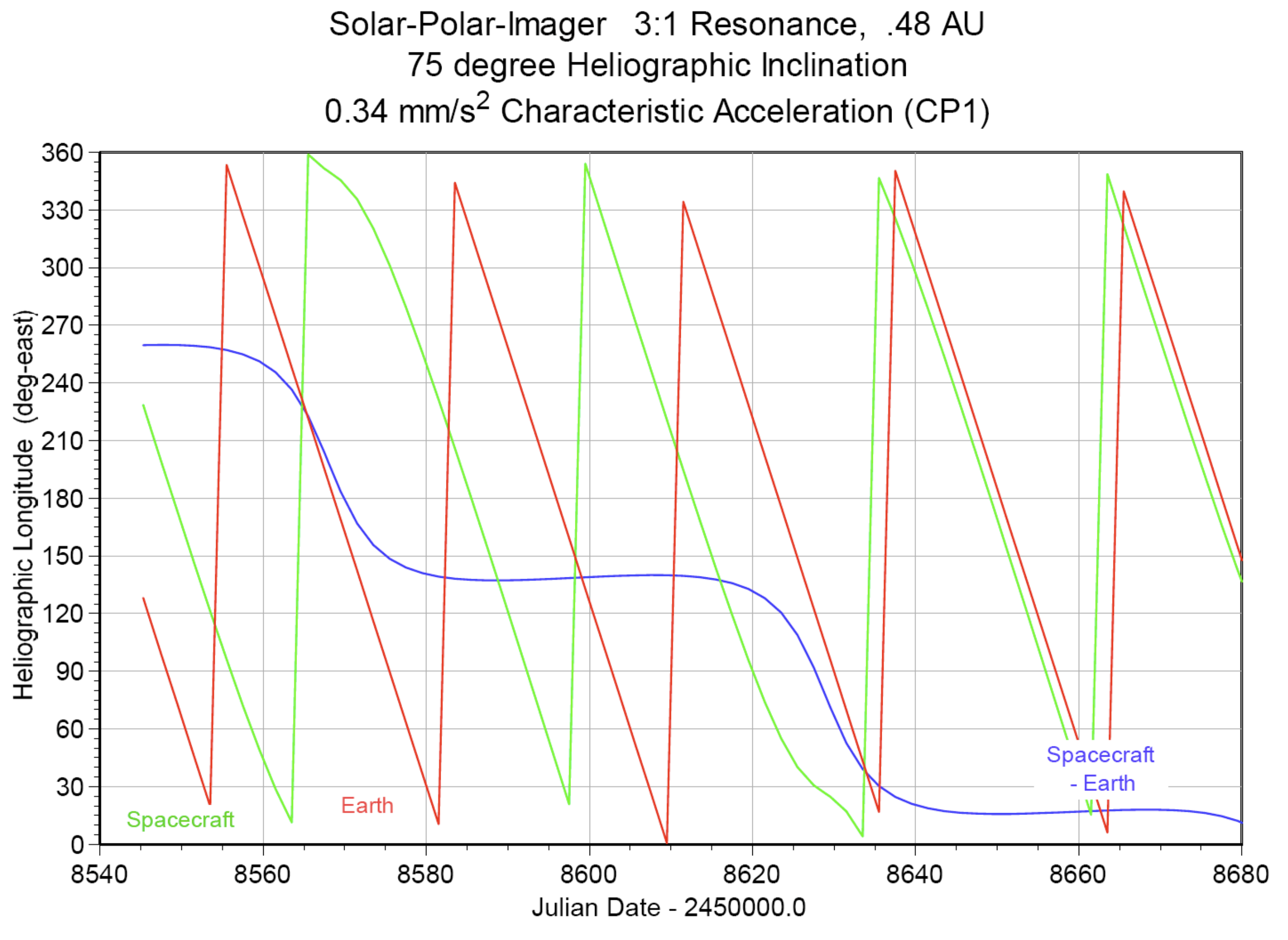
If you are going to look at the pole do it properly

Increase observation time above latitude of interest (say 30°)

360° view of interesting latitudes for flux emergence and cycle studies

Increased viewing time of features of interest

Implications/Lessons for Solar-C Plan A



Good situation for stereoscopic helioseismology (see Gizon)

Implications/Lessons for Solar-C Plan A

Circular vs. elliptical orbit (e.g. e=0.3 SEP option)

	CIRCULAR	ELLIPTICAL
PROS	• Fixed solar distance • Uniform orbital velocity • “fixed” radial velocity • thermal issues cleaner	• Longer dwell times at highest inclinations (but only in one hemisphere) • Different viewing angles than Earth • Higher res. at perihelion
CONS	• Limited time at high latitude • Potentially not ideal for stereoscopy	• Telemetry • Thermal issues at perihelion

Implications/Lessons for Solar-C Plan A

If helioseismology/dynamo/polar magnetic field is primary science then this should drive the orbit design and instrument choices:

- single instrument mission?