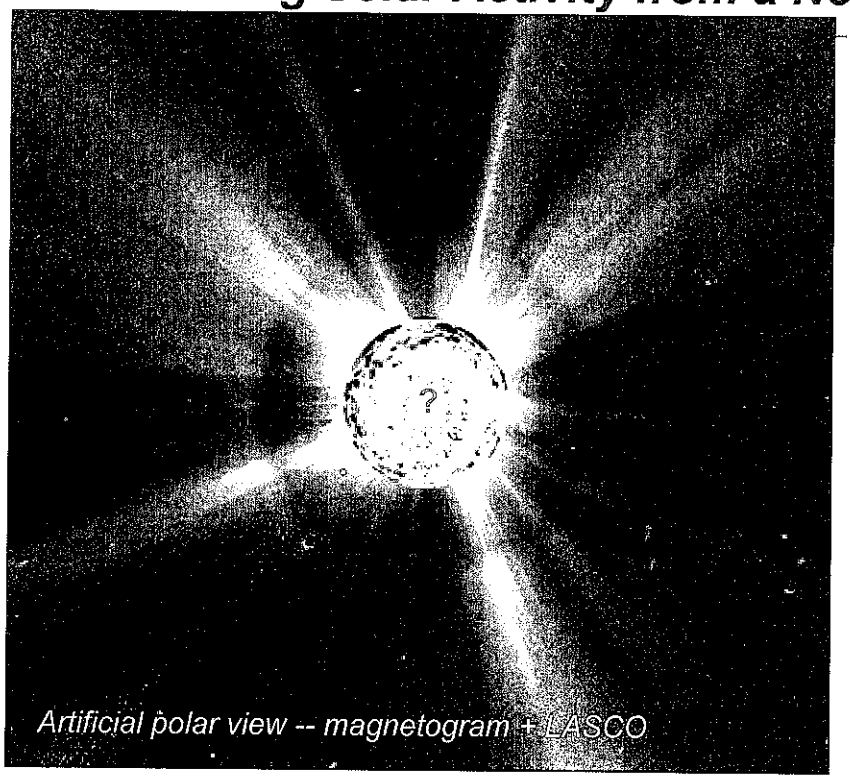
Vision Mission Study

Solar Polar Imager: Observing Solar Activity from a New Perspective



Mission

Spacecraft in highly inclined ~75° heliocentric orbit 0.5AU

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

Solar Polar Orbiter - Mission Concept

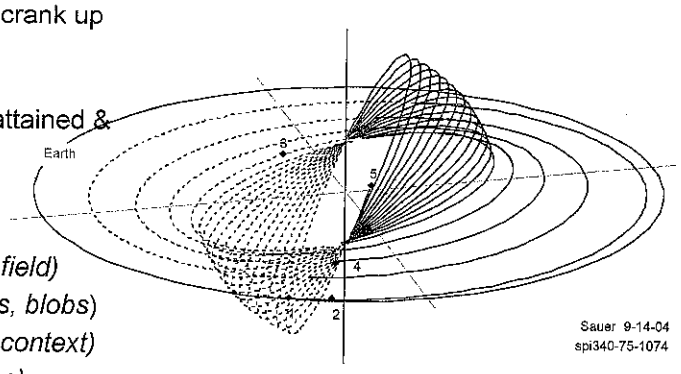
Uses Solar Sail to attain 75° inclination orbit at 0.5 AU in ~5-7 years

- 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 & sail is jettisoned
- 29% of time in final orbit is above 60°

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

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



Payload Accommodation

- Total Instrument Mass ~45 kG
- Average data rate >60 kbps
- Store &dump data, ~2 DSN passes/week
- Gimbaled antenna for uninterrupted helioseismology observations

Solar Polar Imager
High Level Science Goals

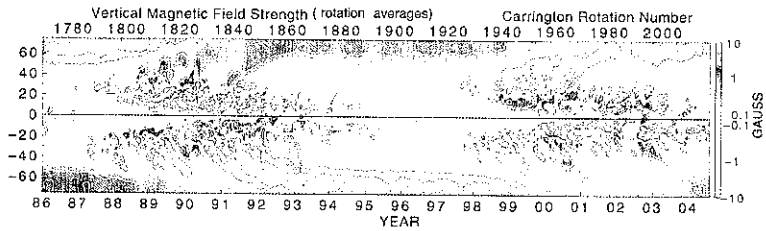
- What is the relationship between the magnetism and dynamics of the Sun's polar regions and the solar dynamo?
- What advantages does the polar perspective provide for space weather prediction?
- What is the azimuthal structure and dynamics of the corona and CMEs?
- How are variations in the solar wind 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?

Solar Polar Imager Science Goals & Relation to Other Missions

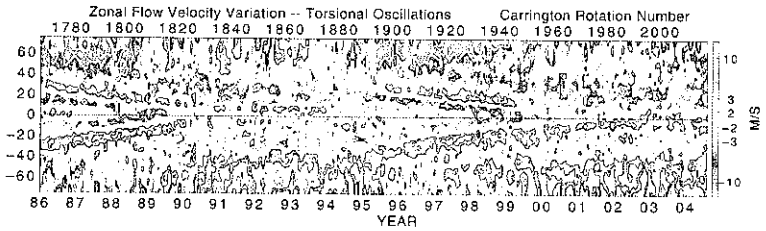
- A Solar Polar Imager reaching 75° inclination can answer a class of SSSC science questions not possible using any other existing or planned mission.
  - Major breakthroughs in both solar & heliospheric physics will results from observations made possible by its unique 4-month polar orbit
- Because it carries both *in situ* and remote sensing instrument, it can also address many scientific issues requiring data from multiple heliospheric spacecraft
  - But NASA is planning other in-ecliptic missions which address such issues(e.g., STEREO. Sentinels, Solar Polar Orbiter)
- **In this study, we focus on science investigations which are enabled by SPI's unique 0.5 AU polar orbit**

Solar Polar Imager 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. **Meriodional flow** moves fields poleward. Trailing spot is poleward of the leading spot. Causes reverses the global dipole field.



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

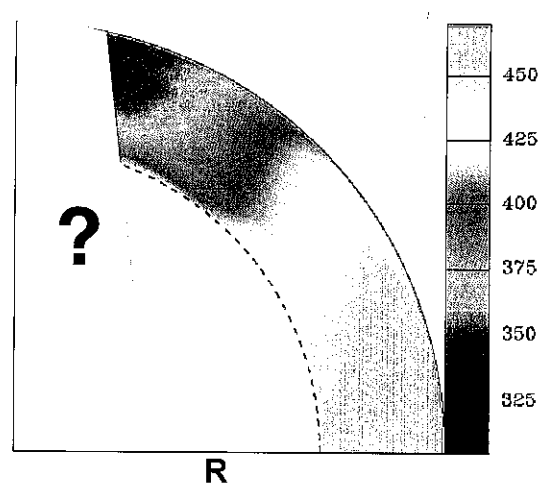
Solar Polar Imager Goal 1 (continued):
What is the relation between the magnetism and dynamics of the Sun's polar regions and the solar cycle?

Current State of Knowledge

- Internal structure and differential rotation measured with great precision except in the polar regions (75-90° 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)

SPI 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 ($\Omega/2\pi$ nHz) with uncertain polar and deep regions shown in white (Based on Schou 1998).

Solar Polar Imager 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? (SPI + 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? *(SPI Uses EUV + coronagraph to observe coronal response to flows)*

SPI 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 (SPI + SDO or GONG)

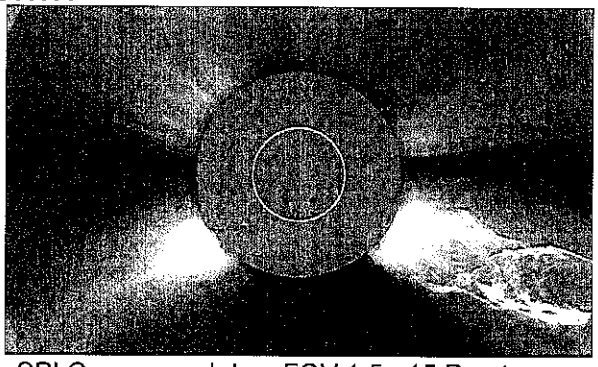
Solar Polar Imager Goal 2:

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

- What is the longitudinal structure and extent of CMEs?
- How do CMEs affect the global corona? Are some CMEs global or do CMEs trigger other CMEs?
- How does the corona recover from a CME?
- How do helmet streamers form?

• Polar perspective allows new views the formation, evolution, and demise of structures such as CMEs, helmet streamers, active regions, coronal holes

• Also, from polar perspective, measure SW velocity from "blobs" in streamers ala Sheeley with less line-of-sight confusion



SPI Coronagraph has FOV 1.5 - 15 R_{sun} to overlap EUV FOV

Solar Polar Imager Goal 3:

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

- 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?

Solar Polar Imager can address these questions better than existing & planned missions because

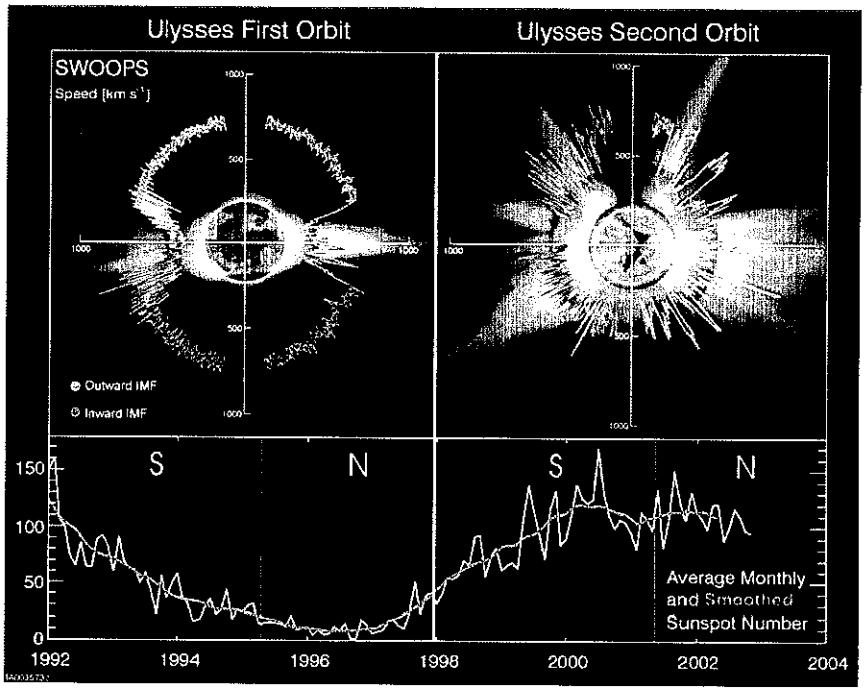
- It samples slow wind much less affected by stream-stream interactions (closer to Sun and polar field lines less wound)
- It provides rapid (4 months) latitude scans at fixed radius
- More accurate mapping will be possible using magnetogram with increased coverage in longitude and latitude including pole!
- It has *in situ* (including composition), coronagraph (streamers, blobs) & EUV (context) & UV spectrometer (network outflows)

Solar Polar Imager Goal 3 (continued):

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

Right: Polar plots of solar wind speed as a function of latitude for Ulysses' first two orbits superimposed on characteristic coronal images.

SPI will provide 3 such polar plots at constant 0.5 AU radius every year



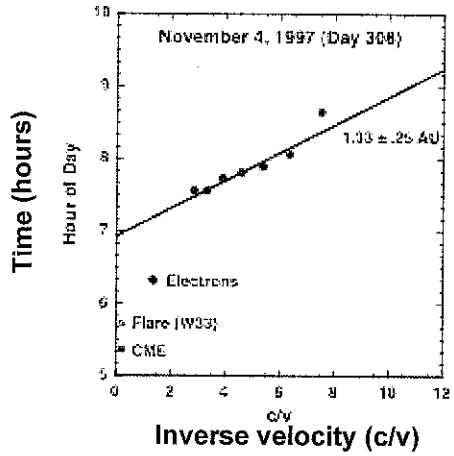
Solar Polar Imager Goal 4:

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?

SPI 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.

Right: ACE SEP event - Velocity dispersion of observed energetic particles is 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)



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

Solar Polar Imager Goal 5:

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

Solar Polar Orbiter 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**

Solar Polar Imager 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%.

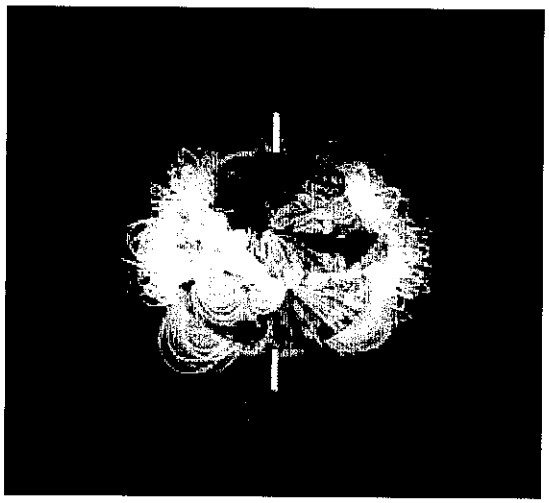
- Why is the variation ~1/3 of variation in other Sun-like stars? Are we seeing them from the polar view point?
- Is missing ecliptic radiation funneled out through the polar regions or does the Sun store this energy?

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

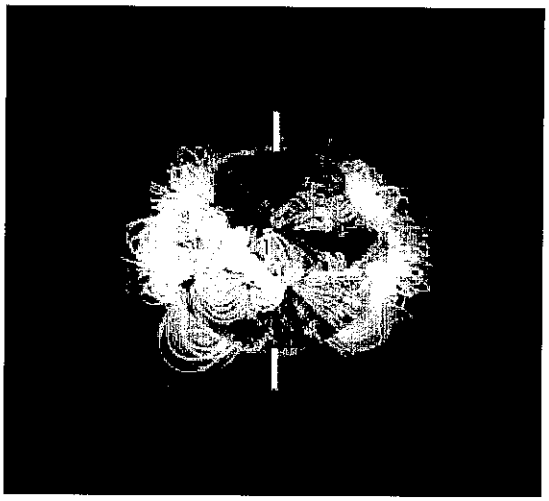
Note: Active cavity TSI instruments are notoriously difficult to calibrate, but measure variations in TSI very accurately. Goal of SPI solar irradiance instrument is ONLY to measure VARIATIONS in irradiance. Eliminates need for complex calibrations and simplifies instrument

Simulated Views of X-ray Corona

(See Paulett's laptop for movies)



View from Earth



View from SPI

Solar Polar Imager: Relation to 2003 SEC Goals

- Addresses all 3 SEC 2003 Science Objectives & Many Research Focus Areas (RFAs) & Investigations, e.g.,
- SPI Primary focus on RFA: "*Understand the structure and dynamics of the Sun and the solar wind and the origins of magnetic variability*"
  - SPI will give more information about solar structure and dynamics that we learned from SOHO/MDI: High latitude +deeper (2 SC) -- And SOHO/MDI revolutionized our knowledge of solar flows & dynamo
  - SPI will *"Determine through direct and indirect measurements the origins of the solar wind, its magnetic field and energetic particles" (SEC Investigation & SPI Objectives 3&4)*

Solar Polar Imager: Relation to Other SEC Missions

- Telemachus will provide first views of polar region, but insufficient polar viewing time for robust helioseismology
  - Solar Probe has an even shorter polar viewing time & less data
- Solar Orbiter gives only a glimpse of polar region (always below 40 degrees heliographic latitude)
- SPI in conjunction with other spacecraft (SDO, Sentinels, Solar Orbiter) can provide much additional "two-spacecraft" and "stereo" science
  - And SPI extends magnetograph coverage in latitude and longitude for better magnetic field extrapolations
- SPI is a Pathfinder for a permanent solar polar orbiting sentinel in support of the Exploration Initiative

Solar Polar Imager Vision Mission Study Team

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- Marco Velli, JPL
- Angelous Vourlidas, NRL
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Backup Material

SPI Vision Mission Study Goals

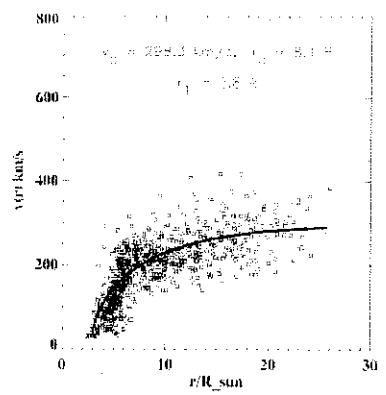
- Refine and prioritize primary and secondary science goals
- Study instruments, data and orbit requirements to achieve goals
- Study mission design trade space: trades between payload mass, sail capability and mission life time
- Generate requirements on the solar sail system to feed into NASA's In Space Propulsion program's technology roadmap for solar sails
- Explore use of manned space assets to mitigate risks associated with sail deployment
- Identify other technology needs/ drivers

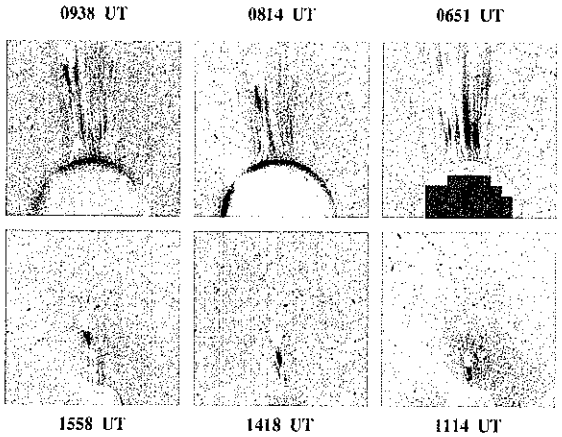
Solar Polar Imager Goal 2:

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

Mission Design

Solar Sail Trajectory Overview

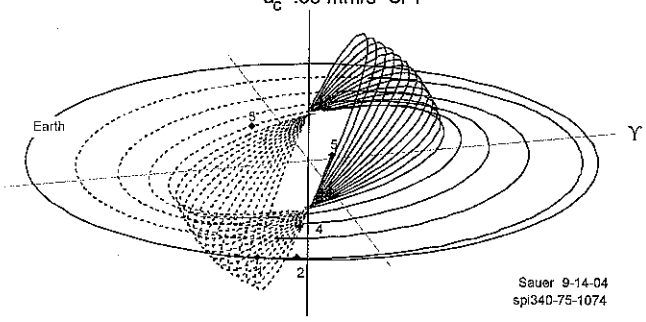
Transfer Flight Path

- General Design Optimizes Thrust Vector Pointing
  - * Cruise trajectory produces 15° heliocentric inclination change
  - * Thrust vector change rates are minimized
  - * Solar-vector to Sail-Normal-vector angle is constrained to ≤ 45°
- 2-phase Approach Optimized for Insertion to OPS Orbit in ~6.8 years
  - * Cruise trajectory produces 15° heliocentric inclination change
  - * Cranking orbit effects ~48° inclination change into the OPS orbit 60° heliographic inclination
  - * Orbit trim is designed for final orbit shaping and velocity matching

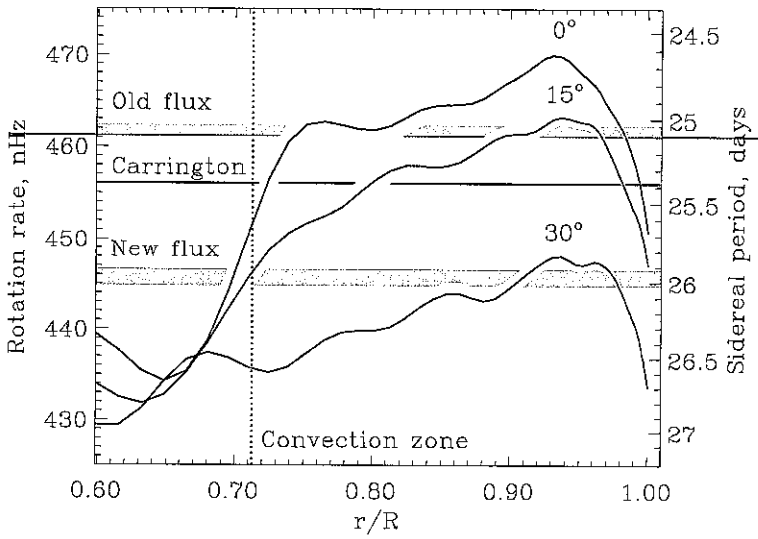
Science OPS Orbit

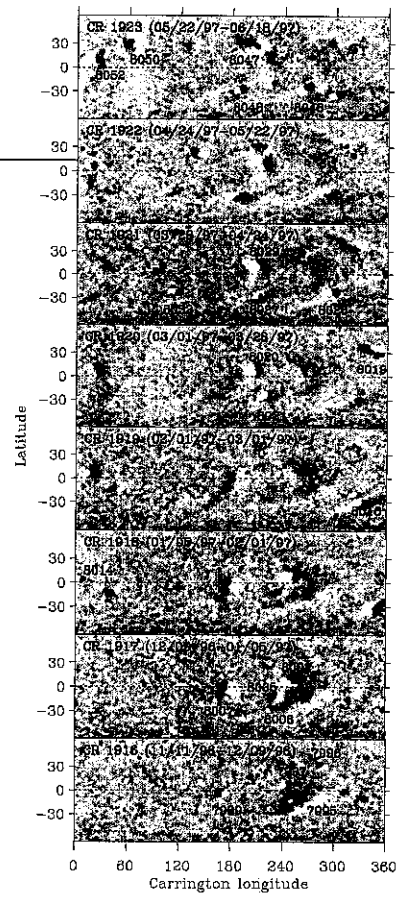
- Designed for High Latitude Coverage with 3:1 Earth Resonance
  - * Nodal phasing included for control of Earth-Sun-S/C angle

2012 Solar Sail Solar Polar Imager
3:1 Resonance, R= 0.48 AU
75 Degrees Heliographic Inclination
a_c=.35 mm/s^2 CP1



	DATE	Δ Days	Δ Years	MET Days	MET Years
Launch C_3=0.25 km^2/s^2	05/24/12	0	0	0	0.000
Start of Sail Phase	06/03/12	10	0.027	10	0.027
Start of Cranking Phase	12/10/14	920	2.519	930	2.546
End of Cranking Phase	02/05/19	1518	4.156	2448	6.702
Start of Science OPS Phase	03/02/19	25	0.068	2473	6.771





What is the relationship between active longitudes and polar magnetic field?

Yohkoh and EIT observations revealed giants loop structure connecting active regions and polar regions.

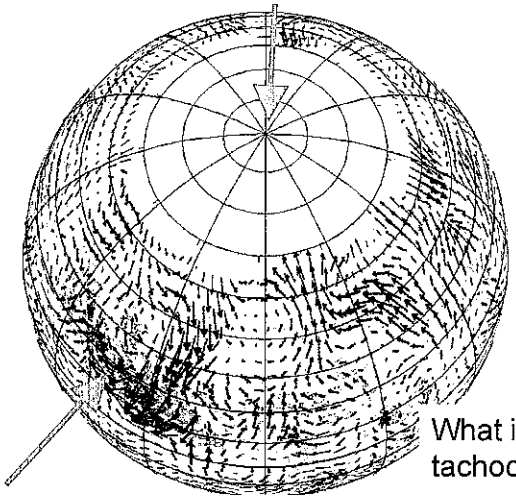
How deep is the link between plasma and flows in polar regions?

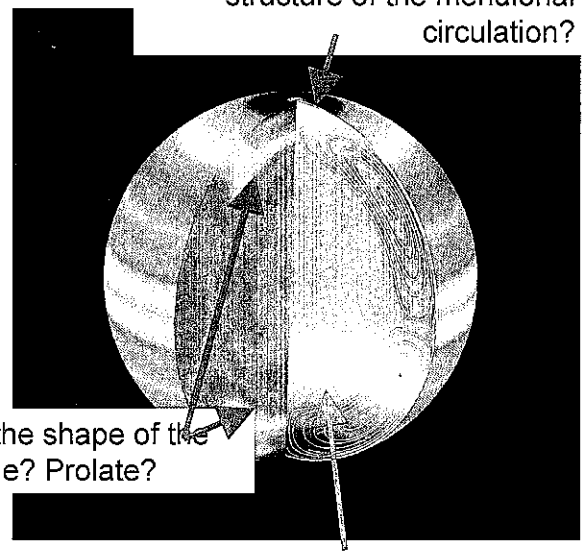
Solar Polar Imager Goal 1 (continued):

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?

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





What is the shape of the tachocline? Prolate?

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

How deep is the meridional flow?