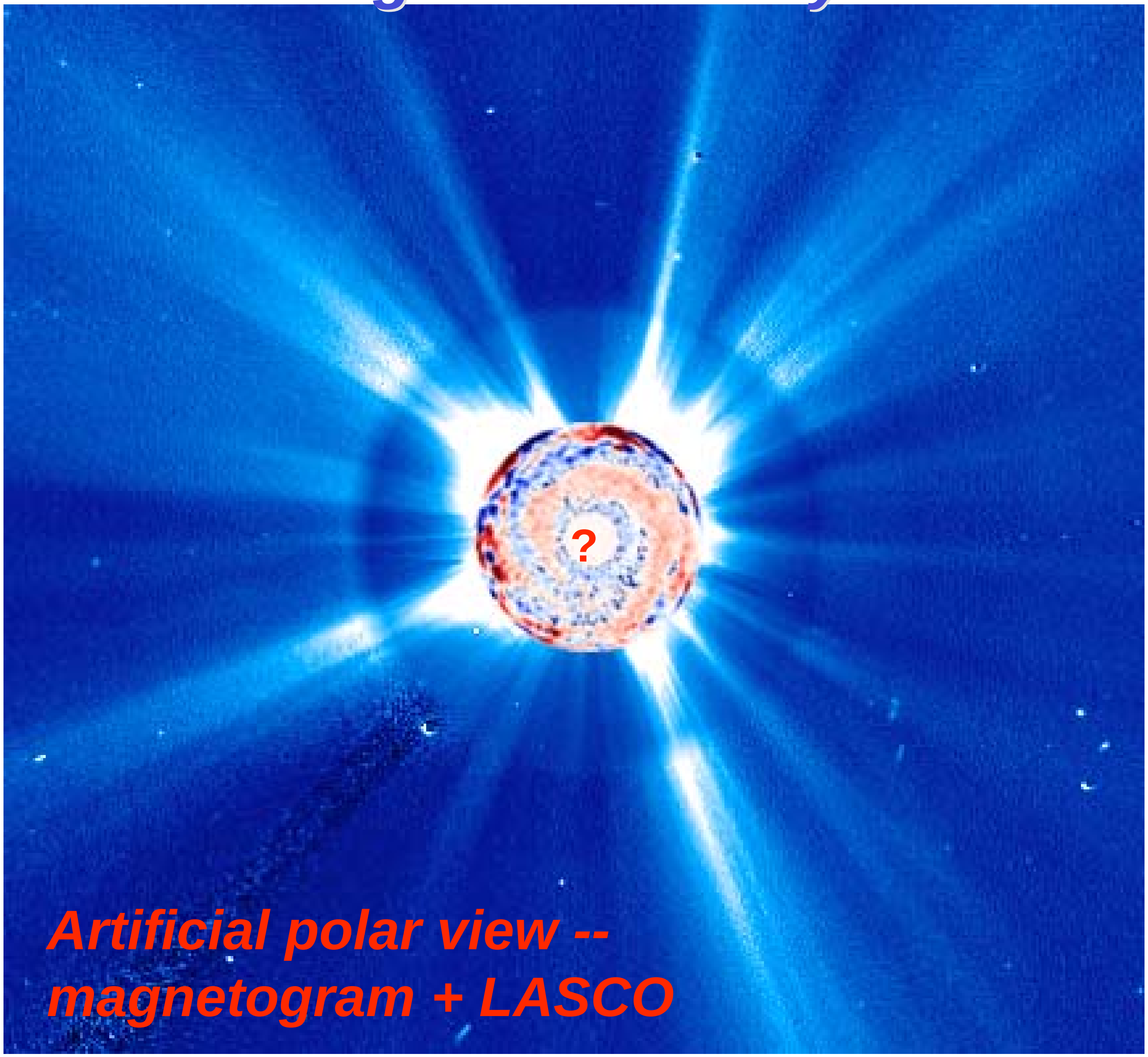
Vision Mission Study

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

Helioseismology & magnetic fields of polar regions

Polar view of corona,CMEs, solar irradiance

Link high latitude solar wind & energetic particles to coronal sources

Solar Polar Imager
Vision Mission Study Team

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Solar Polar Imager Vision Mission Study Goals

- Refine primary and secondary science goals
- Prioritize corresponding instruments package to achieve goals
- Determine orbit, viewing and data requirements on mission
- Estimate mass, power, data rate and pointing requirements to achieve objectives
- Study mission design trade space (flight time, sail areal density, flight system mass)

Solar Polar Imager
Strawman Science Goals & Instruments

- **Determine the convective motions on the surface and in the solar interior that are needed to understand the dynamo (Doppler imager)**
- **Determine the magnetic field in the polar region needed to understand the evolution of the solar field and to extrapolate the solar field into the heliosphere (magnetograph)**
- **Determine the azimuthal & 3D structure and dynamics of the corona & CMEs (coronagraph)**
- **Relate the high latitude solar wind relate to the structure and dynamics of the corona (in situ fields & particles, magnetograph, EUV imager)**
- **Compare the solar irradiance in the polar regions to that in the ecliptic (solar irradiance monitor)**
- **LWS Goal: Track CMEs from Sun to Earth (All Sky Imager)**

Solar Polar Imager
Vision Mission Major Issues

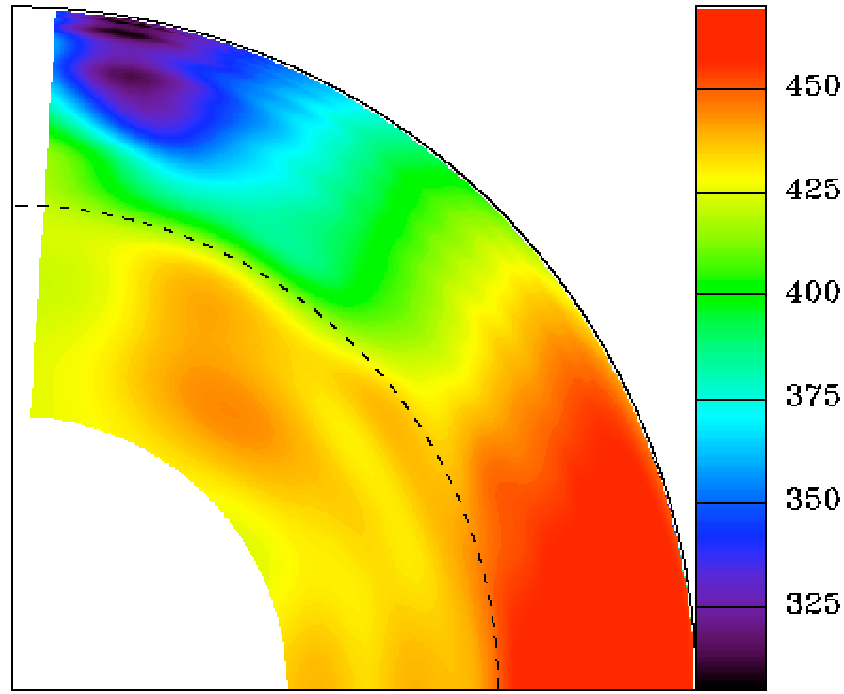
- Mass !!! -- Solar sail propulsion places severe limits on science payload mass (34 kG for SEC 2003 Roadmap SPI study - summarized at end of poster)
  - Is an EUV imager necessary for the science goals?
  - Is it important to measure the solar irradiance from the polar view point?
  - How important is an All Sky Imager?

- Telemetry -- Helioseismology science return depends on data volume; Earth-SC distance typically >1 AU
- Timing -- When to go in solar cycle? How long?

Helioseismology: Solar Dynamo and Solar Cycle

Large uncertainties in ecliptic observations above 60º

- What are the convective flows that control the generation and evolution of the solar magnetic field?
  - What are the surface and subsurface flows in the polar regions? How do they vary in time? Is there a polar jet stream? How does the Sun handle the singularity at the pole? Is there a polar vortex? (requires SC latitude > 60º)
  - What are the flows deep in the Sun near the tachocline where the solar fields may be generated? (requires SPI plus near Earth SC)



Contours of solar rotation rate ($\Omega/2\pi$ nHz) from SOHO/MDI. There are large uncertainties in the measurements above 70˚ and no measurements in the white regions at the pole and below 0.4 R_{SUN}. (Based on Schou 1998).

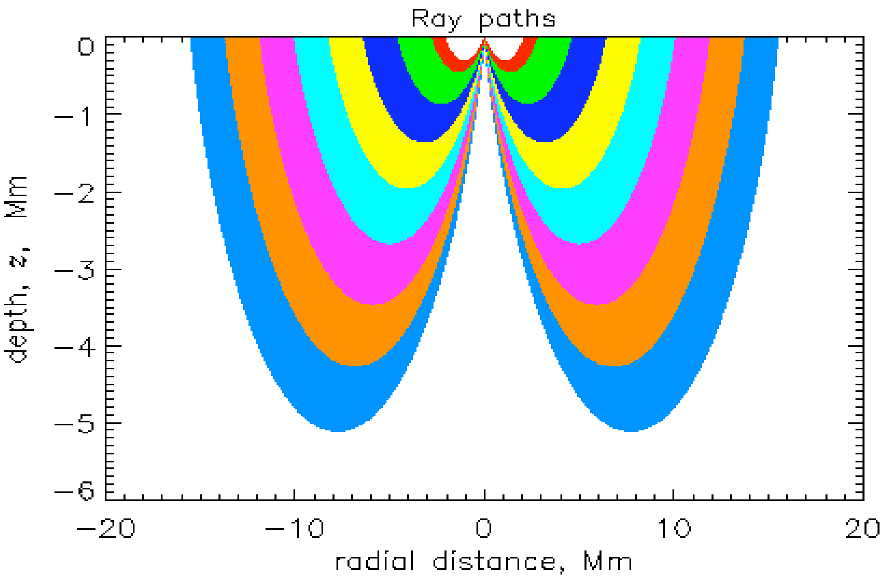
These measurements are needed to understand the dynamo

Techniques in Helioseismology

Types of analysis of Helioseismological Doppler Data

1. Global Helioseismology--assumes cylindrical symmetry
2. Direct Doppler - for surface flows
3. Time-Distance - for subsurface flows
4. Dense Ring pack for vector surface and subsurface flows

Single spacecraft measurements limited to a depth of about 0.4Rsun. Use time-distance techniques correlating SPI with near-Earth instrument for deeper ray paths to determine deeper subsurface flows-down to the tachocline where solar field may be generated by velocity shear



Magnetic Field and Solar Irradiance from the Polar Viewpoint

What is the magnetic field near the pole?

- *Line of sight measurements from the ecliptic plane have a large uncertainty because B is nearly perpendicular to LOS*
- *Need B to understand evolution of solar magnetic fields*
- *Photospheric magnetic field at* ***all latitudes*** *needed to extrapolate solar magnetic fields into the heliosphere*

Models of interplanetary solar wind and magnetic field are required for an operational space weather predictive capability (to link Sun and solar wind) & to interpret EUV and WL images

Sophisticated models deserve accurate boundary conditions

What is the total solar irradiance from the polar viewpoint?

- *Other stars show much more variation in total irradiance than our Sun. Are we seeing them from the polar view point?*

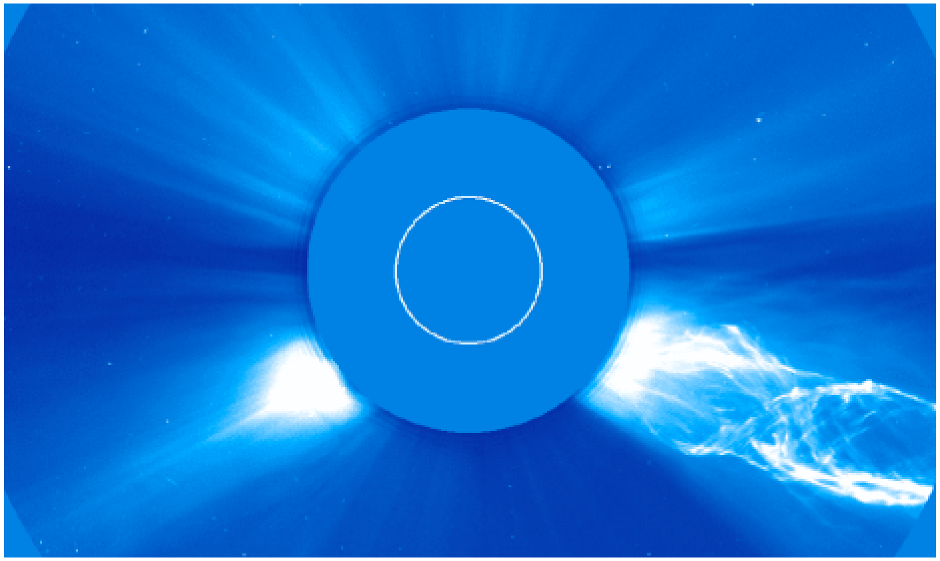
What is the Azimuthal & 3D structure of the corona ?

First polar views of the solar corona with a coronagraph

How do CMEs and other dynamic events affect the global structure of the corona?

How are nearly simultaneous CMEs on opposites sides of Sun related?

How does the corona recover after a CME?



What is the 3D structure and azimuthal extent of CMEs and streamers?

Polar view gives new information on 3D structure

Stereoscopic viewing with near-Earth coronagraph --STEREO will give stereo views in ecliptic

Is the current sheet of uniform density or highly filamentary?

Evidence for AR source of filaments away from solar minimum

What is the structure of the WL corona under helmet streamers?

LASCO/C1 structures difficult to interpret because of LOS effects

Study the Source and Acceleration of the Solar Wind

SPI orbit samples polar regions of solar wind at 0.5 AU

Orbit allows study of variation in latitude at constant R

Does solar wind carry imprint of source and acceleration at 0.5 AU over the poles?

- Polar wind is less affected by dynamical evolution because of smaller Parker winding angle -- Ulysses sampled solar wind at >2 AU over the poles
- Less evolution because closer to the Sun
- Study super-radial expansion of solar wind over the poles

What are the source regions of slow solar wind?

- Link particles and fields observations to solar and coronal sources at all latitudes
- Combine in situ measurements with improved global models using all-latitude magnetograms to map solar wind to source at solar surface

What is the nature of polar plumes and coronal streamers?

- In situ sampling in polar and ecliptic regions of solar wind at 0.5 AU
- Direct sampling of coronal features imaged by near-Earth coronagraphs

How are energetic particles accelerated and transported?

Understanding the production and transport of energetic particles at interplanetary shocks is an important goal for LWS

How are particles accelerated in CME shocks?

Why do only some CME shocks produce energetic particles?

A model: "Gradual Events" the result of acceleration by scattering of trapped energetic particles in self-excited turbulence at IP shocks

- High latitude observations have new geometry & new information
- Time-intensity profile depends on longitude in ecliptic - related to magnetic connection to source
- B field is more nearly radial over poles--should simplify the interpretation

What is the solar source of flare-accelerated particles?

- Less velocity and angular dispersion at 0.5 AU
- Relate to source using imaging and improved magnetic field models

What are the cosmic ray diffusion coefficients K_{par} and K_{perp}?

- Determine latitudinal gradient along orbit (90° in 1 month)
- Determine radial gradients by comparison with near Earth

How much angular momentum is lost via the solar wind?

Sun loses negligible mass via solar wind, but significant angular momentum

Measure angular momentum flux in solar wind with in situ instruments

- Global loss not well determined from ecliptic measurements (Pizzo et al, 1983)
- SPI gives improved measurement because of larger tangential velocities and less dynamic evolution of the wind

Determine radius at which corona stops co-rotating with the Sun

- Use coronagraph and polar viewpoint
- Expected to occur at critical point

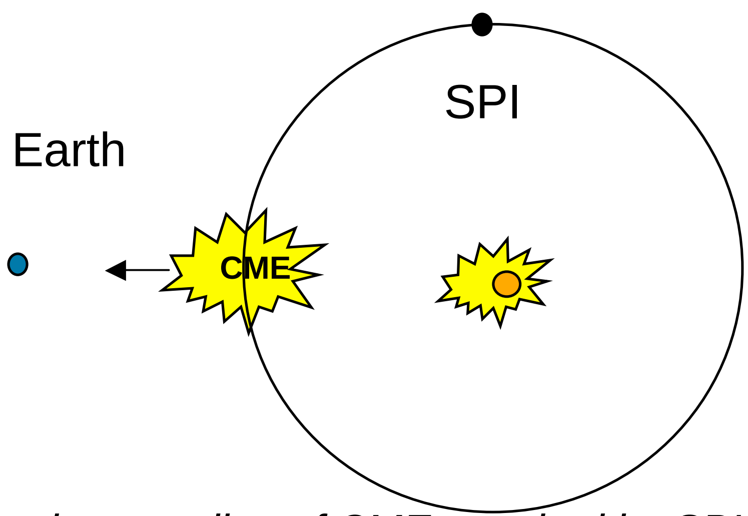
Results relevant to study of angular momentum loss in rapidly rotating stars

1st polar views using an All-Sky Heliospheric Imager

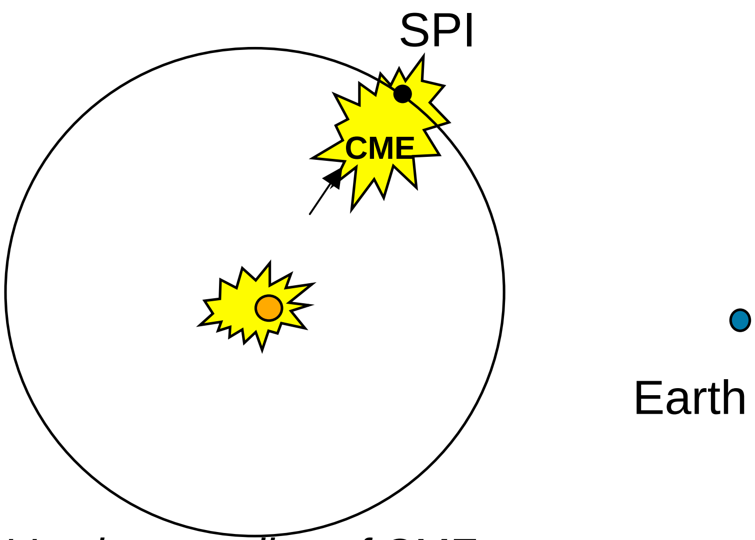
All Sky Heliospheric Imager + coronagraph allows CME tracking from Sun to Earth

How do CMEs propagate to Earth?

- *Test utility of polar orbit for CME monitor for operational space weather system*
- *STEREO-type science: near-Earth spacecraft measure geoeffectiveness of CME tracked by SPI & visa versa*



In situ sampling of CMEs tracked by SPI. Earth also sees EUV disc



SPI In situ sampling of CMEs tracked by near-Earth coronagraph

Reference Mission Design

Solar Polar Imager

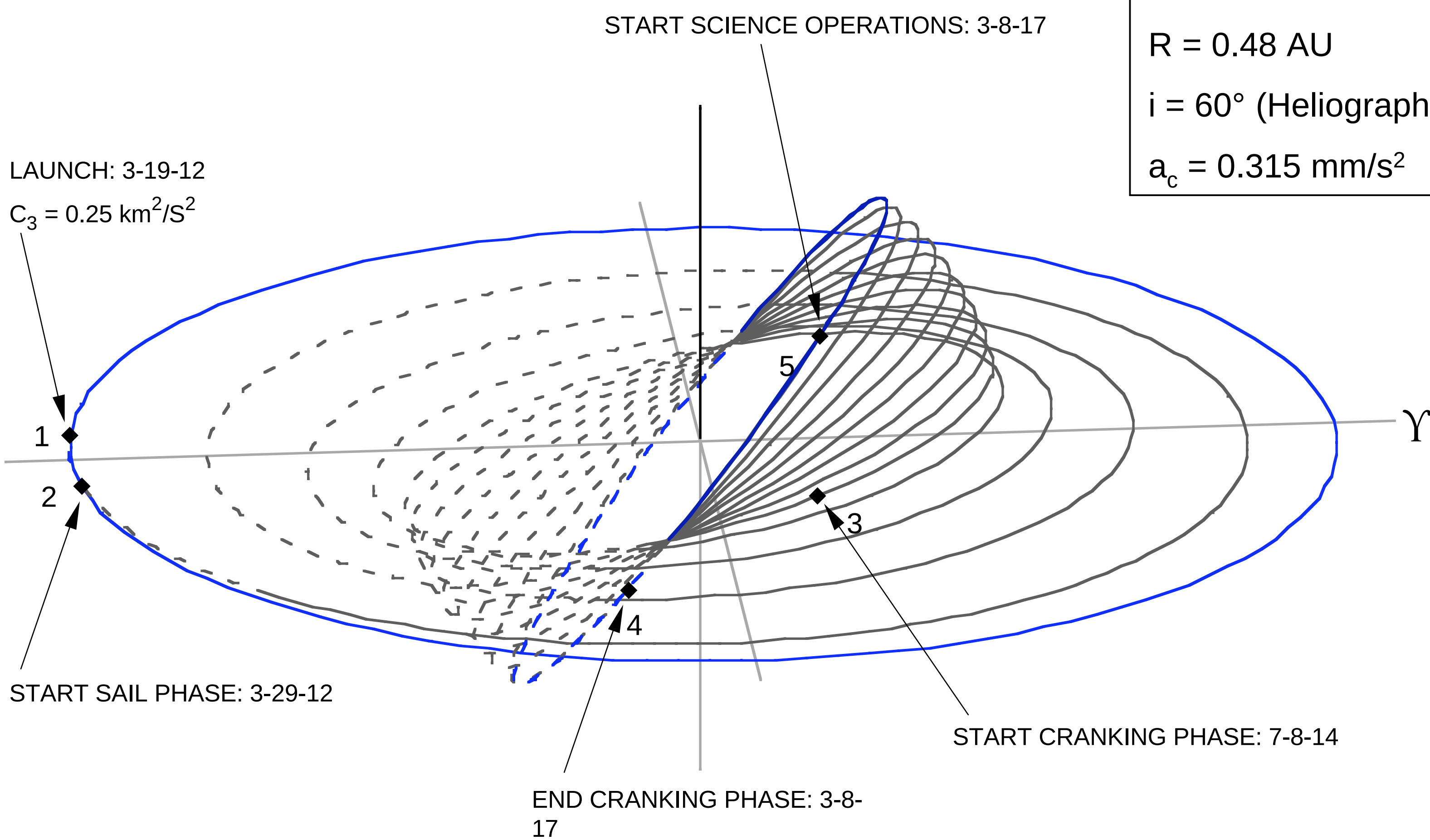
SEC 2003 Roadmap Study

3:1 Resonance

R = 0.48 AU

i = 60° (Heliographic)

a_c = 0.315 mm/s^2



Mission Concept

Guidelines and Constraints

Technology Cutoff: 2008

Project Start: 2009

Launch: by March 19, 2012

- Optimize Injection for Earth Escape
  - * Sail provides all interplanetary ΔV

Launch Vehicle

- Constrain to NLS Contract
  - * Minimum cost for vehicle availability
  - * Positive performance margin req'd.

Trajectory

- Allow for Initial Sail Checkout Phase
- 5-years or Less to Science OPS Orbit
- Science OPS Orbit:
  - * ≥60° inclination (heliographic)
  - * Earth-resonant orbit with phasing
- Jettison Sail Prior to Science OPS

Lifetime Considerations:

- Mission Duration
  - * 4 - 5 year flight time
  - * 2 year science operations
  - * 3 year extended mission
- Environment: 1 AU to 0.48 AU

Payload Accommodations

- Total Mass: 34 kg
- Total Power: 24.5 W (avg)
- Average Data Rate: 15.6 kbps
- 10 arc-s (3σ) Pointing Control
- 1 arc-s (3σ) Pointing Knowledge

Data Strategy

- Store and Forward: ≤2 DSN passes/week
- Coordinate with Navigation
- Accommodate any Black-out Periods
- Minimize Operational Costs

Instrument Summary

Overview/Characteristics

	Remote Sensing Instrument Package					IN-SITU INSTRUMENT PACKAGE		
	Corona-graph	All Sky Camera	EUV Imager	Magnetograph-Helioseis-mograph	Total Package	Magnetometer	Solar Wind Ion Composition and Electron Spectrometer	Energetic Particle (20 keV-2 MeV)
Mass (kg)					25	2 (inc. boom)	4	3
Power (W)					17	2	3.5	2
Pointing Control	10 arcs[1] (3-s)				10 arcs[1] (3-s)		1°	3°
Pointing Know.			~1.0 arcs (Sun relative)[2]		~1.0 arcs (Sun relative)[2]	0.1°	0.1°	3°
Pointing Stability			2.5 arcs for 30 sec (3σ)[3]		2.5 arcs for 30 sec (3σ)[3]	0.1°/ sec	0.1°/30 sec	
Data Rate (kbps)					15[4]	0.2	0.2	0.2
Bus Xfr Rate (Mbps)	1	4	0.5	0.5		0.135	0.24	.00005
Clear FOV	Sun ± 15°	Hemisphere ⊥ to Sun ± 90°	Sun ± 0.35°[2]	Sun ± 0.35°			Boom Mounted	Sun ± ~35°
Processing RAM					128Mbytes			
Processor Speed (MIP)	3	3	3	10				
Thermal (operational) °C					box: 0-40 op[5] ccd: -75 to –55[6]	-30 to 50	-20 to 50	-25 to 35
COST ($M)					45			

1 Driven by need to keep coronagraph occultor accurately Sun-centered to prevent sunlight spill-over.
2 Determined by requirement to know center of Sun to support relative pointing control of 10 arcs. Knowledge reference is provided by EUV Imager to ACS
3 Assumes 2.5 arcs pixel & 1024x1024 CCD, with exposure time from 15 to 30 seconds, and Jitter amplitude < 1 pixel over exposure time.
4 Helio-seismology requires bursts of 10kbps; other 3 instruments will share remaining 5 kbps during HS bursts
5 -20°-55° survival
6 -80° to –55° non-operational

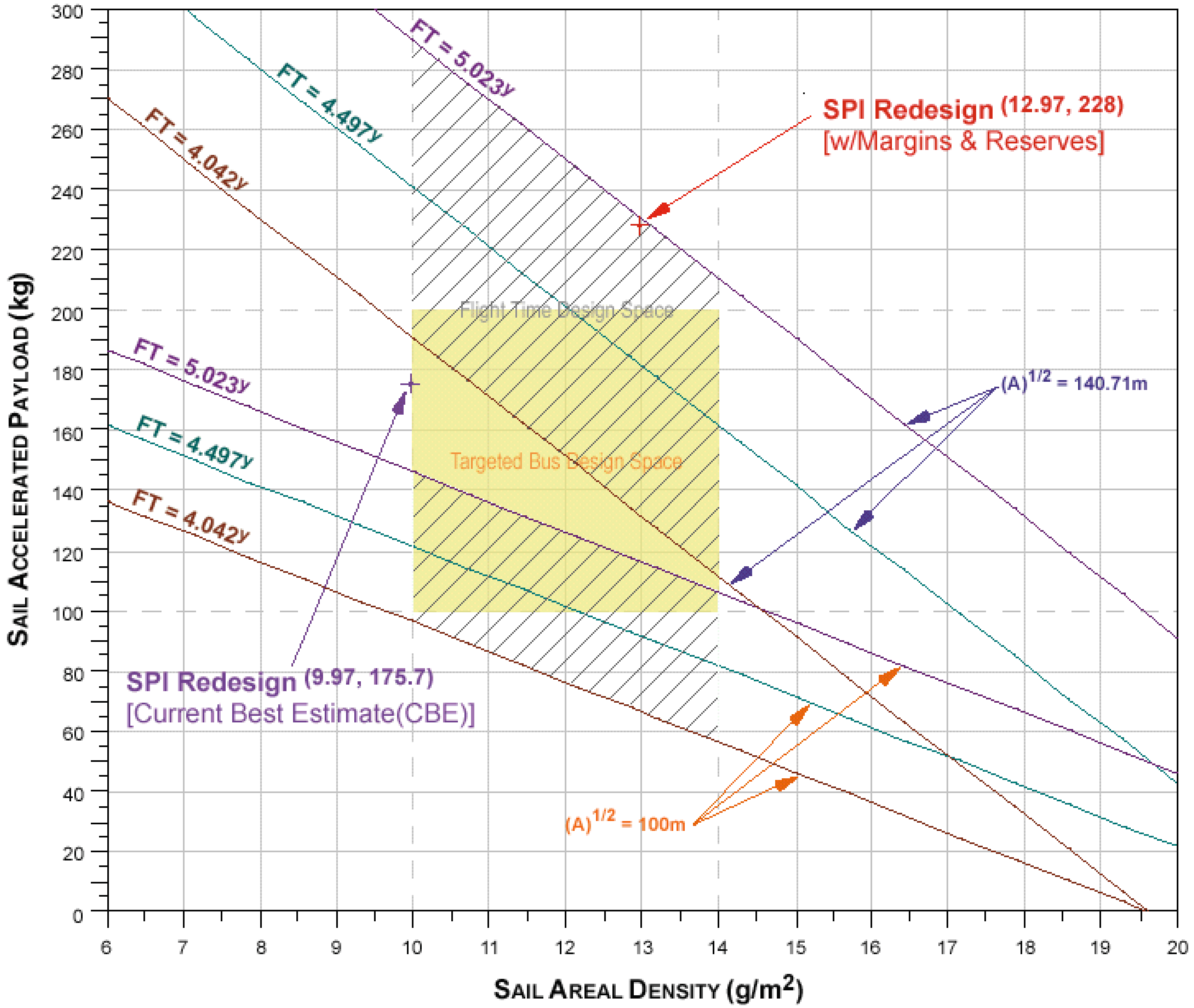
Solar Polar Imager Mission Profile

2003 SEC Roadmap Reference Mission Summary

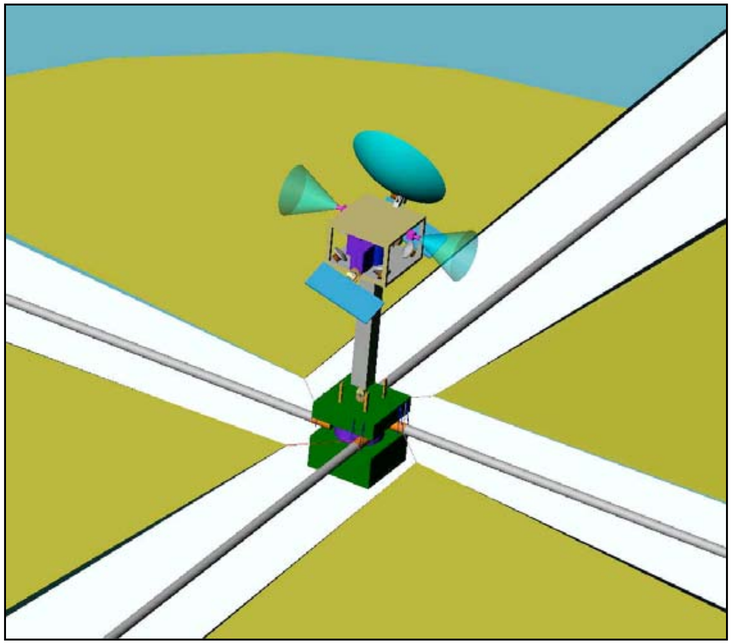
- **Mission Objective: Establish an operational platform at 0.48 AU with high inclination, allowing observations of the solar polar regions, responsive to science requirements and programmatic constraints**
- **Launch: March 19, 2012 (direct ascent)**
  - Delta II 2425 launch vehicle
  - ≥ 20-day window
  - $C_3 = 0.25\ km^2/s^2$
- **Trajectory: Solar Sail**
  - Heliocentric Spiral Transfer to Cranking Orbit at 0.48 AU
  - Characteristic Acceleration (a_c) = 0.315 mm/s^2
  - Provides 60° Heliocentric Inclination, and Required Earth Phasing (for Science OPS)
- **Primary Mission** (2-year duration)
  - Acquisition of:
    - In-situ Particles and Fields
    - Solar Irradiance
    - Coronal and Heliospheric Imaging (inc. high lat. coverage)
    - Surface Velocity Fields for Helioseismology
  - Twice weekly return of science data
    - 2 passes/week, each of 4-hours duration
  - Accommodation of solar conjunctions
  - Prime shift operations with off-hour skeleton support
- **Extended Mission**
  - Resources sized for additional 3-years Extended Mission

Mission Design

Design Tradespace



Flight System Concept/Configuration
Overview



Assumptions

- Technology Cutoff Date: 2008
- 30% Mass Contingency
- 30% Power Contingency
- 2 Year Primary Mission Lifetime
- Accommodate Extended Mission
  - * Consumables sized for 5 years of science ops

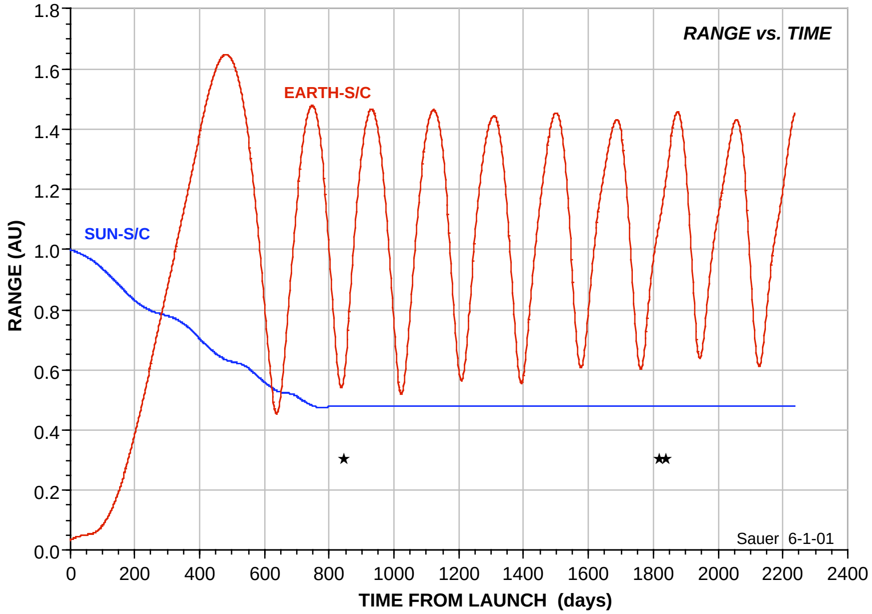
Key Characteristics

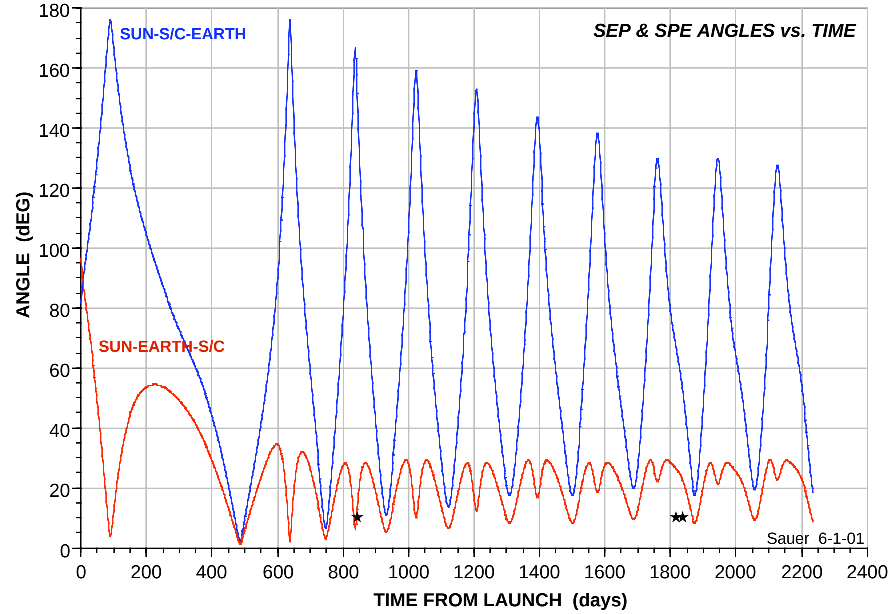
- Observatory
  - * Provides attitude and thrust vector control
    - 10 arc sec pointing and 0.08 arc sec/s stability
  - * Provides instrument accommodations
    - Coronagraph
    - All Sky Camera
    - EUV Imager
    - Magnetograph-Helioseismograph
    - Magnetometer
    - Solar Wind Ion Comp & Electron Spectrometer
    - Energetic Particle
  - * Provides data return to ground
- Solar Sail
  - * 150m x 150m square design
  - * Deployed after launch
  - * Provide low-thrust propulsion to reach science orbit
  - * Jettisoned after science orbit achieved
- Deployment Module
  - * Provides for controlled deployment of sail
    - Drive Motors
    - Batteries
  - * Provides power during launch and sail deployment
  - * Jettisoned after sail is deployed

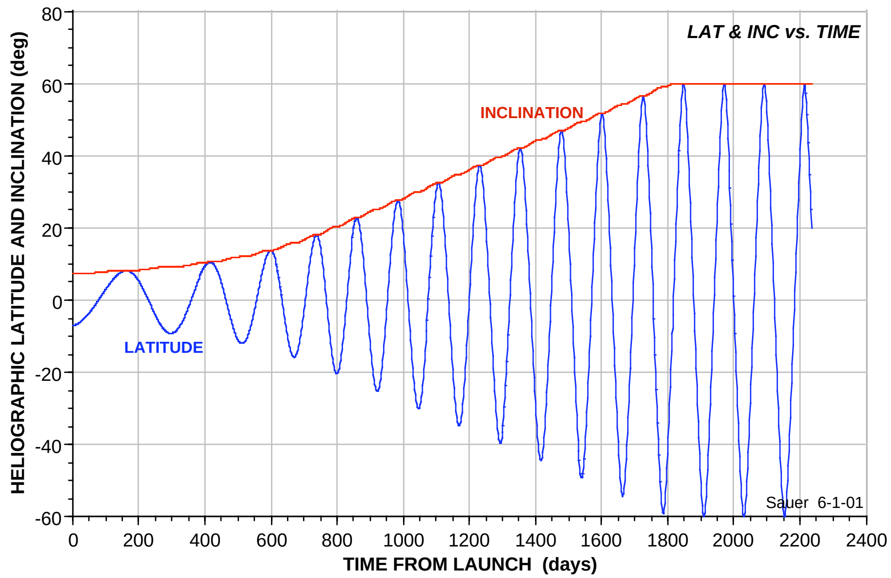
Backup Material

Trajectory Characteristics

Range, Angles, Latitude and Inclination







ALL CASES:

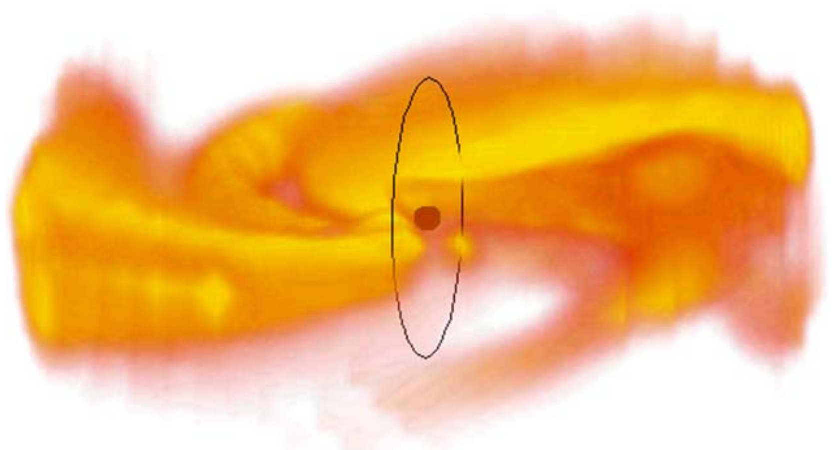
Nbody Trajectory Integration

10 day Initial Coast

C_3 = 0.25 km^2/s^2

a_c =0.315 mm/s^2

Solar Polar Imager
Mission Concept Summary
(taken from 2003 SEC Roadmap)



The first observation of the Sun from above the poles will provide valuable information concerning the solar cycle, solar activity, the 3-D structure of the dynamic solar corona and solar wind, and even space weather.

Technology

- Solar Sail propulsion –
- Lightweight subsysems and instruments
- High-rate telemetry from deep space
- AI event selection and spacecraft autonomy

Fundamental Question:

How do the polar regions of the Sun affect the dynamics of the global corona and reveal the secrets of the solar cycle?

Science Objectives:

- Examine solar and coronal structures from a revealing new polar perspective
- Image global effects of dynamic events on a full 3-D structure of the corona
- Track the complete life cycle of active regions and coronal holes
- Link variations in the high-latitude heliosphere to surface conditions
- Make pioneering measurements of the Sun's evolving polar magnetic field
- Refine solar dynamo theory by using measurements of subsurface polar motions
- Measure angular momentum loss in the solar wind

Mission Description:

- Circular 0.5-AU 90° solar orbit in 3:1 Resonance with Earth
- 30° to 150° separation from Earth to complement space weather program
- Solar array-powered three-axis or spin-stabilized platform
- Lightweight spacecraft with solar sail propulsion
- Minimum 2 years in final orbit, spanning the time of solar polar field reversal

Measurement Strategy

- Image Corona and Inner Heliosphere From Over Poles
- Reconstruct 3-D structure of coronal mass ejections (CMEs) from Sun to 1 AU
- Measure high latitude magnetic fields and coronal Holes
- Determine surface velocity for local helioseismology
- Gather In-situ particle and field measurements
- Measure solar irradiance from a new perspective

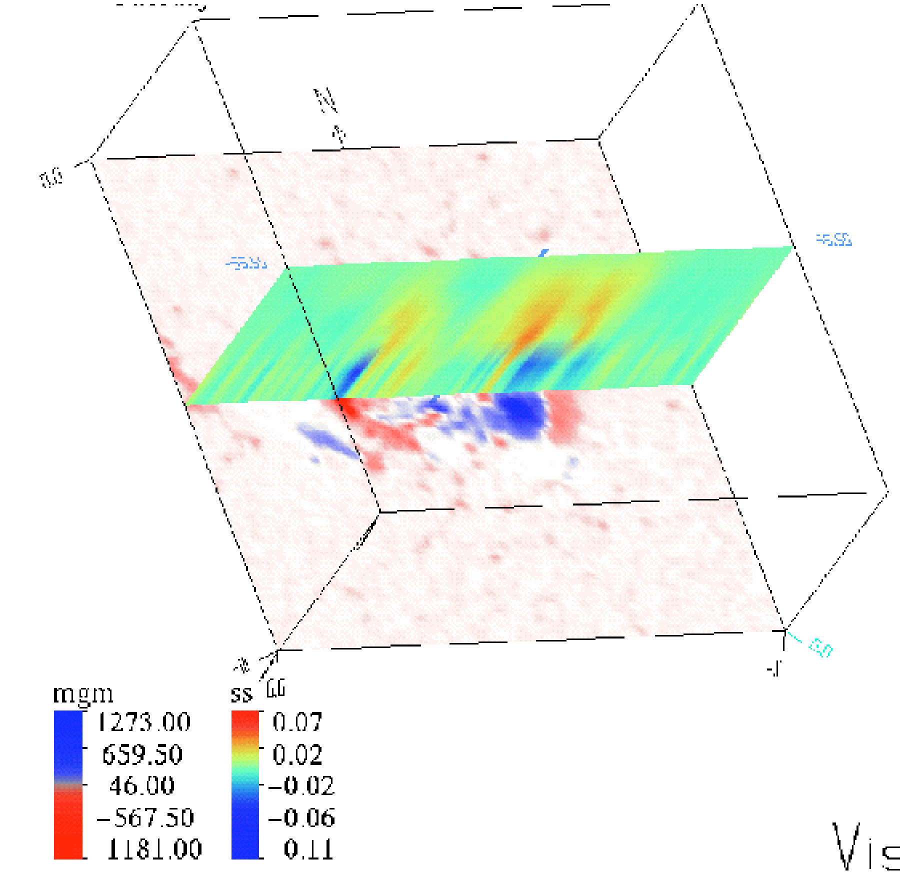
Formation and evolution of ARs crucial problem for LWS

Follow rising flux in AR for more than 13 days (SOHO/MDI limit)

• Polar view of Sun allows longer viewing of an AR than ecliptic view

Some ARs may be visible over there entire lifetime

• Use high resolution time-distance helioseismology to see flows beneath AR



View 3D structure of the EUV corona above the evolving AR using stereoscopic viewing with near-Earth EUV telescope

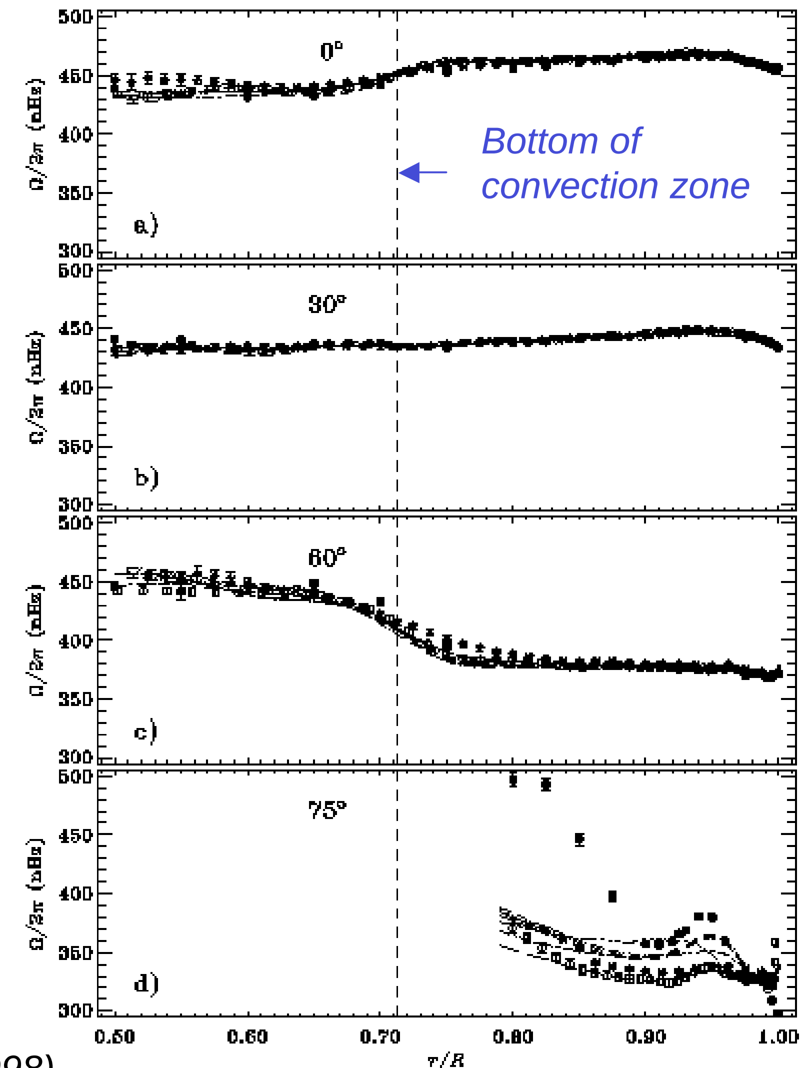
What is driving the solar cycle?

Dynamo may be driven by shear at base of convection zone

Global mode analysis of SOHO/MDI measurements has given internal rotation rate vs. depth

- *Measurements do not include information from polar regions*
- *Measurements from polar regions can validate or contradict global mode approach*
- *Possibility (promise?) of new results from "surprises"*

Rotation rate vs. depth at 4 latitudes



(from Schou et al, Ap J 1998)