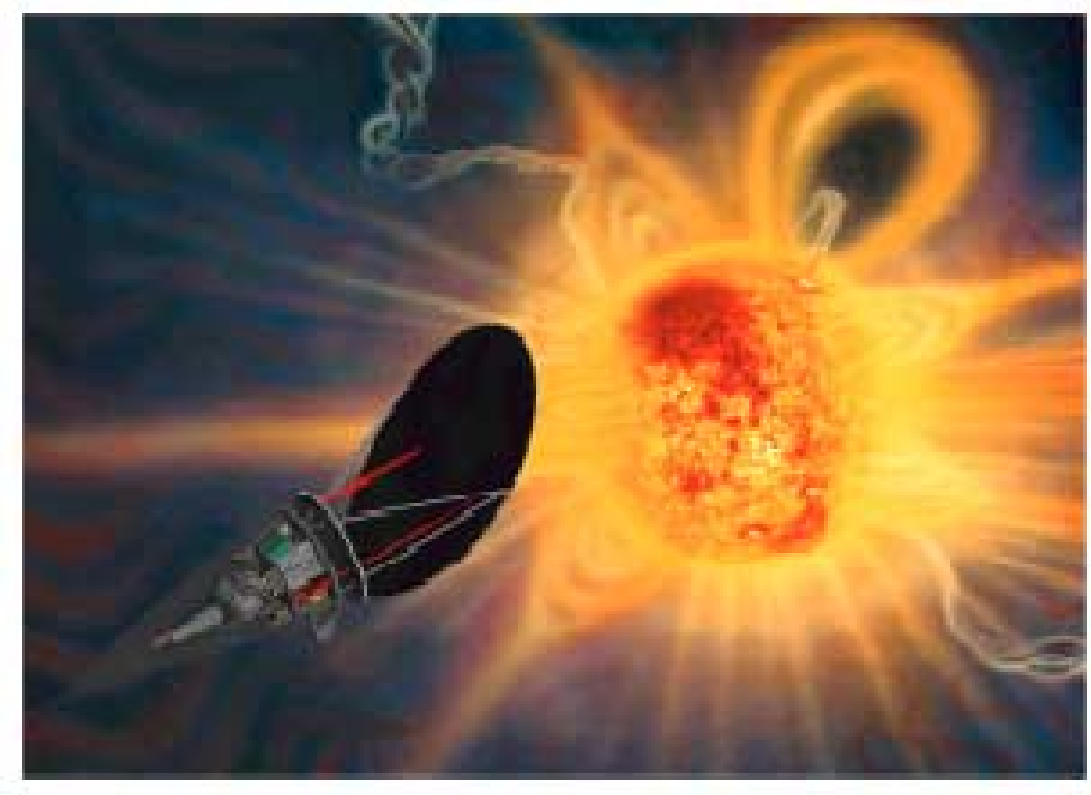
Future Capabilities:
Space-Based Solar Physics



Donald M. Hassler
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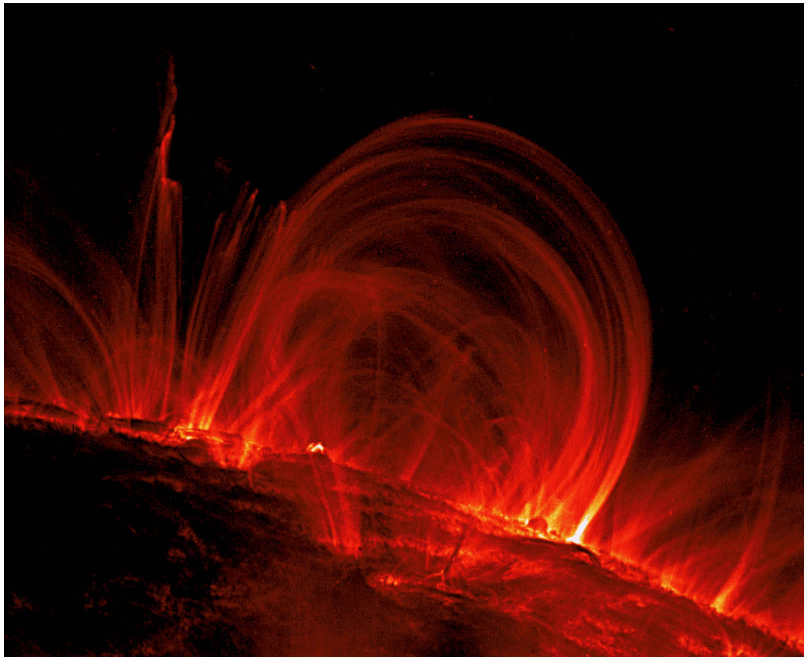
For 60 years there have been 3 major problems in Solar Coronal Physics!

- Why is the corona hot?
- Why does the corona have structure?
- Why is the corona active and unstable?

- Status? Progress means listing possible mechanisms. No agreement yet!

We know that parts of the corona are highly structured, multi-thermal, and dynamic!



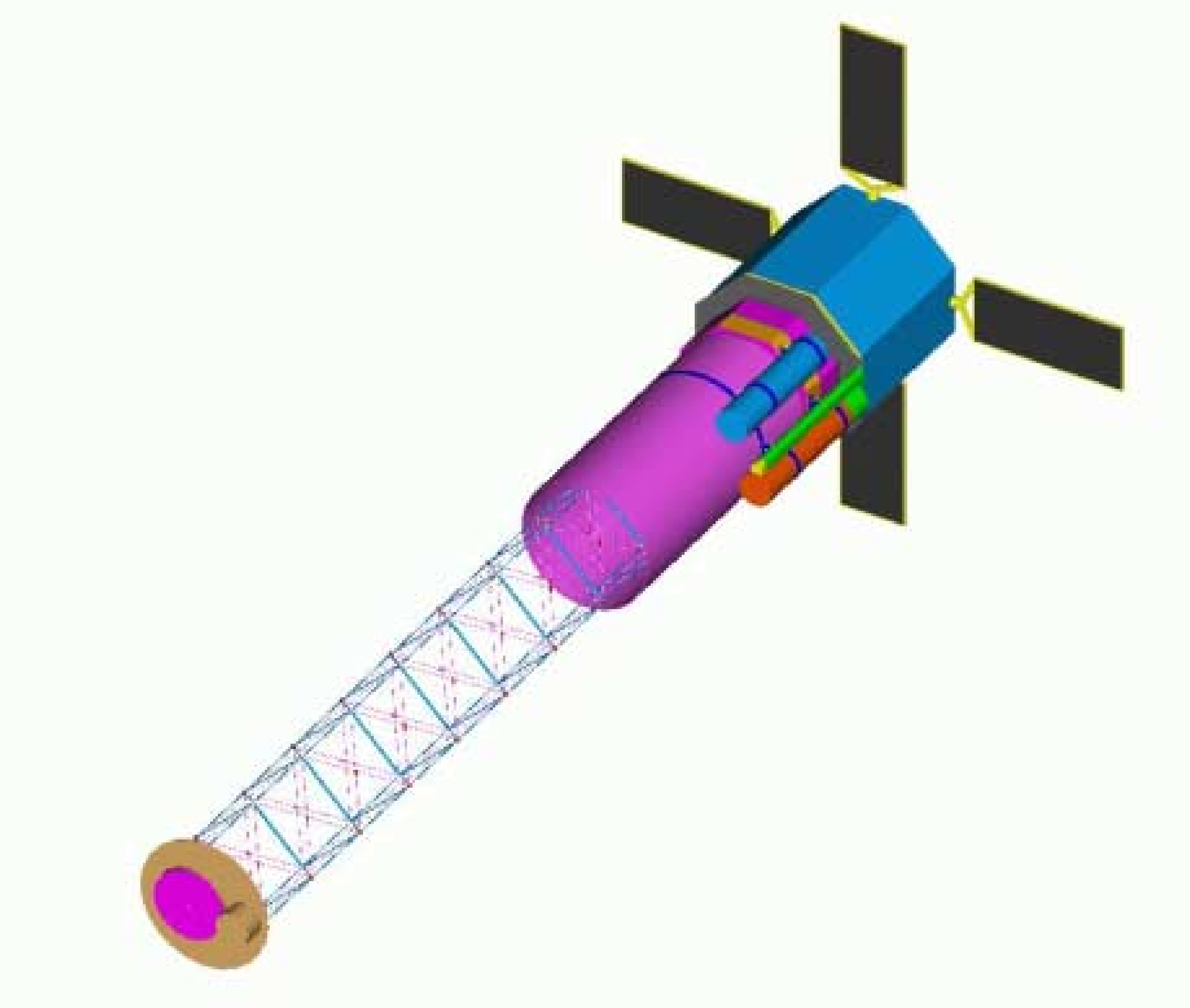
- **What do we need to make progress?!**

What do we need to make progress? (selected topics)

- Moderate time cadence, simultaneous, multi-thermal synoptic imaging and imaging spectroscopy (Solar Dynamics Observatory).
- Very high time and spatial (10-100 km) resolution imaging (RAM).
- Simultaneous, high time and spatial resolution imaging spectroscopy (spectral images) (ESSEX).
- Polar observations (to constrain theories of the Solar Dynamo and the Solar Cycle) (Solar Probe).
- *In-situ* direct measurements of the corona (Solar Probe).

Future Capability 1:

Very high spatial (10-100 km) resolution imaging (RAM)



Science Drivers: Spatial Scales

• **“Global” MHD Scales**	
– **Active Regions;**	**10^5 km**
– **granulation scales**	**10^3 km**
• **Transverse scales**	
– **δT, δn**	**10^1 - 10^3 km**
– **$\delta B_\perp$ and j**	**<10 km**
• **Reconnection sites**	
– **location**	**<10 km**
– **size**	
– **dynamics**	

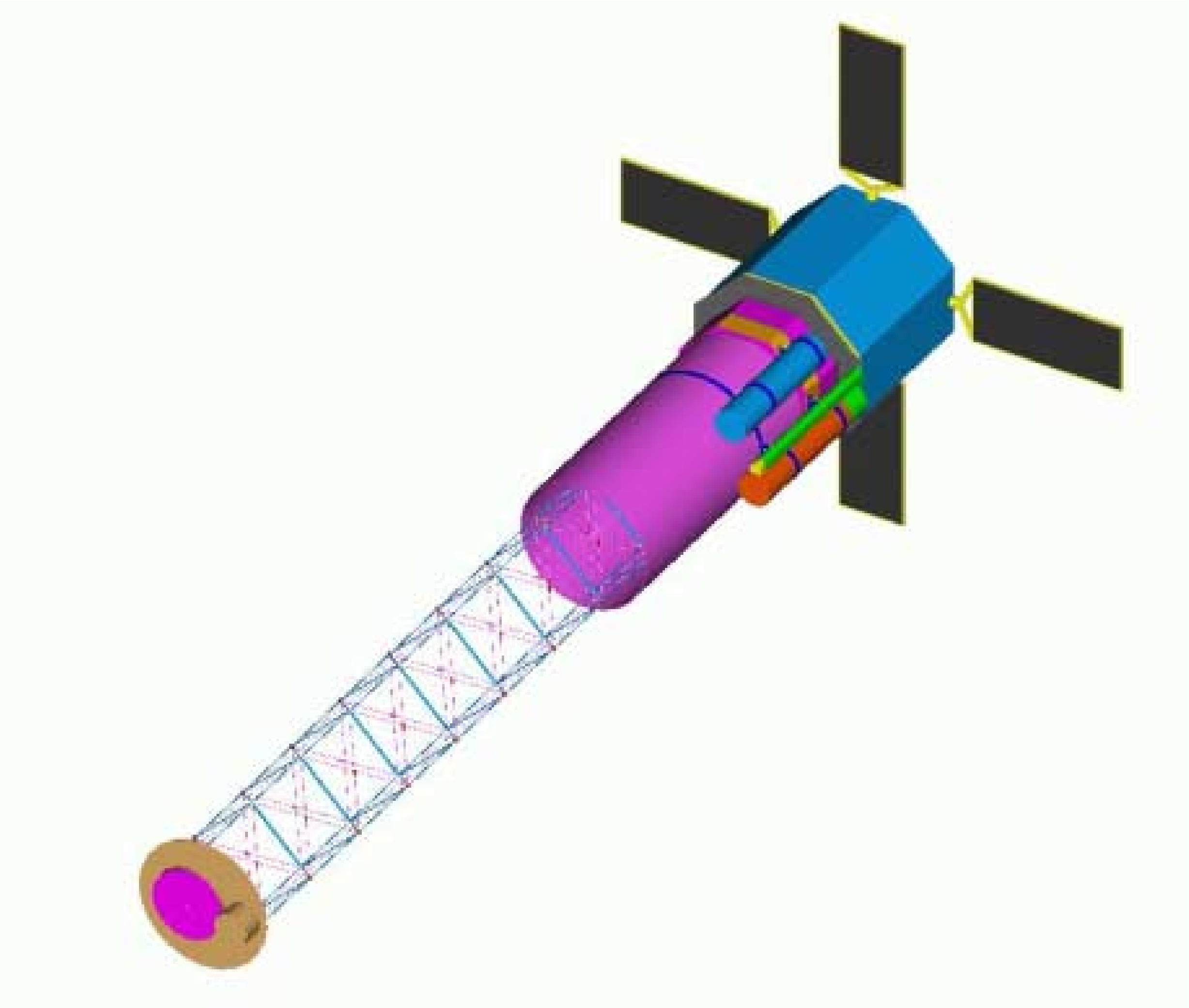
Science Drivers: Time Scales

• **Loop Alfven time**	• **~10 sec**
• **Sound speed vs. loop length**	• **~100 sec**
• **Ion formation times**	• **~1 - 10 sec**
• **Plasma instability times**	• **~10 - 100 sec**
• **Transverse motions**	• **1 - 100 sec**
• **Surface B evolution times**	• **minutes - months**

Imaging Requirements

- High spatial resolution
  - Magnetic reconnection sites
  - Loop - loop interactions
  - Loop oscillations
- High time resolution
  - Follow loop evolution
  - Detect waves - longitudinal and transverse
- Broad temperature response
  - Heating and cooling events
  - Density diagnostics

Reconnection Microscope (RAM)



Current Instrument Complement

- **RAM has an EUV imaging instrument:**
  - **A High Resolution Telescope - 0.01” second pixels.**

- **RAM has an EUV spectrograph:**
  - **High time resolution Imaging Spectrograph, with 0.01-0.2” performance**

- **RAM has an X-ray calorimeter, for imaging spectroscopy. 2 ev resolution from 0.3 to 10 keV**

- **RAM has an EUV context imager.**

Key Technologies

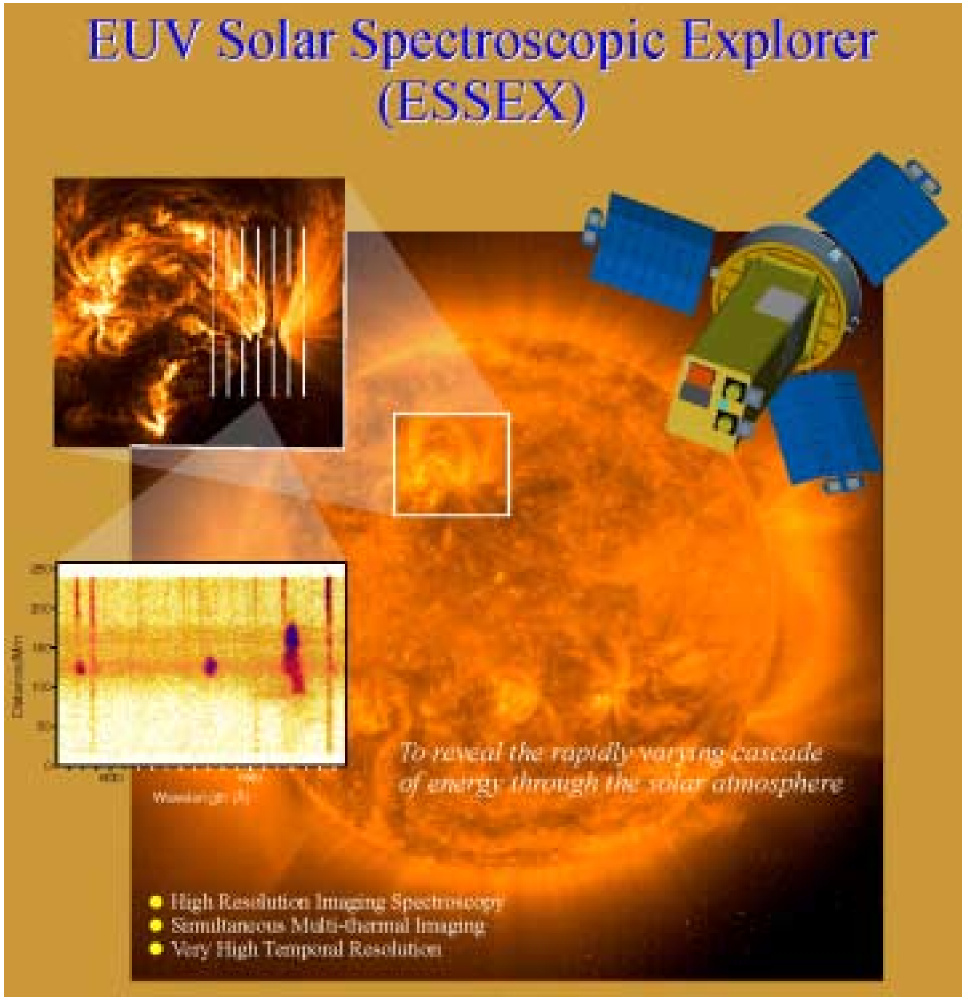
RAM uses a combination of innovative and proven technologies to yield exciting new science:

- **New Technologies**:
  - **Ultra-high precision optics (0.25m pathfinder mirror under development with partners ROSI and Bauer, Assoc.).**
  - **Cryogenic bolometers for soft x-ray spectroscopy.**
- **Heritage technologies:**
  - **Extendable Optical Bench: RAM re-uses the SRTM deployable mast to reduce cost, reduce risk, & improve reliability.**
  - **Image stabilization techniques: RAM extends techniques from TRACE and SOHO/MDI missions.**
  - **Multilayers based on TRACE heritage**

Extendable Optical Bench Prototype

Future Capability 2:

High time resolution Imaging Spectroscopy



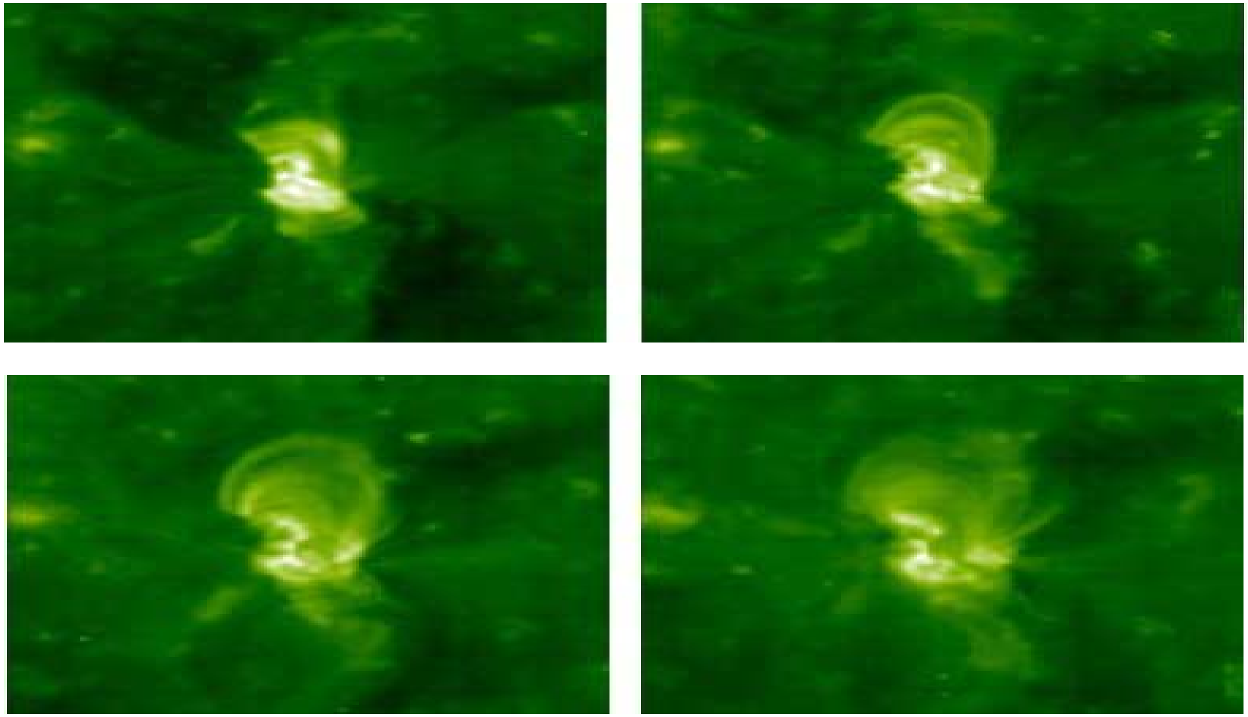
EUV Solar Spectroscopic Explorer
(ESSEX)

To reveal the rapidly varying cascade of energy through the solar atmosphere

- High Resolution Imaging Spectroscopy
- Simultaneous Multi-thermal Imaging
- Very High Temporal Resolution

Limitations of Imaging

Significant ambiguities between **bulk motion** and **successive illumination** of adjacent features in any image sequence; between **density** and **temperature variations** in sequences from a single narrow spectral band; and between **temperature effects** and **temporal changes** in multi-wavelength image sets without strictly simultaneous exposures.



- **Figure 2:** Expansion of post-flare loops observed with EIT: Does the motion in the image plane correspond to genuine mass motion, or to successive illumination of nested loops? Imaging alone cannot discern the difference, while time/space resolved spectroscopy can measure directly the motion of the loops.

Imaging alone can't resolve total time derivatives.

This non-solar example image shows the difficulty in resolving the causes of motions observed in image sequences. Only partial time derivatives are truly measured, causing the visual confusion in this cloudscape.

Coronal phenomena such as wave propagation, simultaneous motion and heating or cooling of plasma, smooth acceleration, and unresolved differentiation all confound imaging measurements, and are all resolvable with spectroscopic measurements.

*Craig DeForest, “Decadal Survey Presentation”, 17 April 2001.

Outstanding Questions and Morphology of the Solar Transition Region

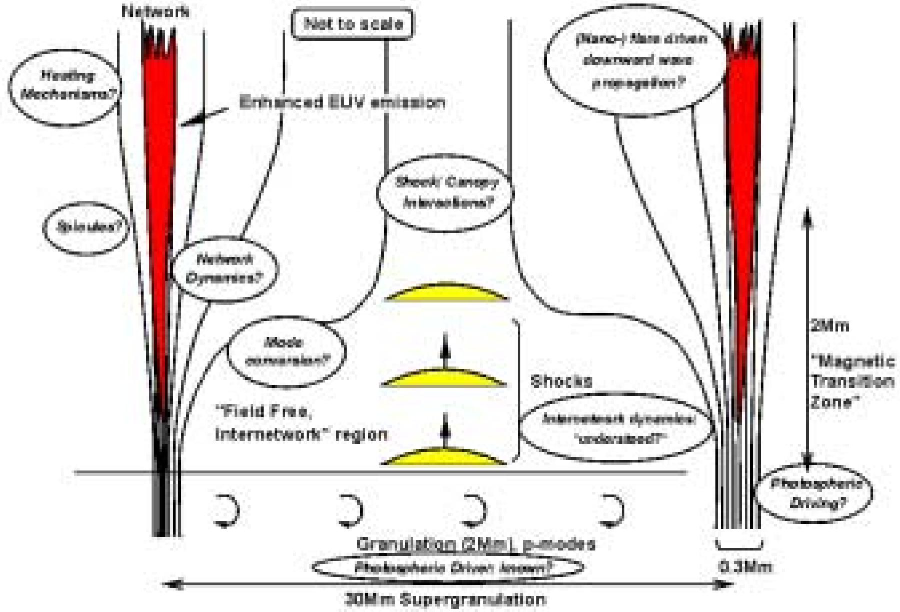


Figure 1 Cartoon depicting the general morphology of the solar magnetic field through the crucial magnetic transition zone. In the deep photosphere, turbulent plasma flows control the dynamics of the embedded field lines. In the corona, the field entrains the gas and guides its motion. In the intervening "magnetic transition zone," the field dominates where it is strong and gas motions dominate where their amplitudes are large (or the field is weak), thus the influence of one over the other is spatially mixed. Given the relatively large densities, and large amplitudes of unresolved motions in the low chromosphere, energy transfer to the higher layers is magnified.

Current SUMER-style Spectroheliograms

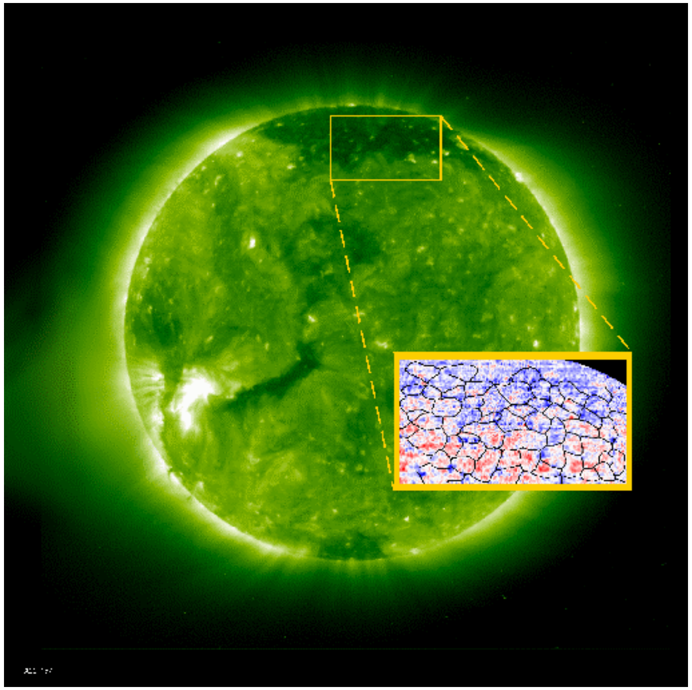


Figure X: SOHO/SUMER Doppler velocity map in Ne VIII 770 Å (0.8 MK) at the base of the corona superposed on a SOHO/EIT Fe XII 195 Å image formed at 1.5 MK. Blue regions are outflows within the polar coronal hole. Superposed is the Si II 1533 Å chromospheric network boundary pattern.

The Importance of Joint Imaging and Spectroscopy

Joint observations by EUV telescopes and spectrometers can encompass the best of both worlds: the rapid cadence of the imaging and diagnostic data from the spectrometer.

Even sparsely sampled raster scans, such as the one shown here, can resolve ambiguities in image data -- provided that the spectrometer's spatial resolution is high enough to match the imager.

Extremely high cadence, high resolution measurements of line profiles are needed to resolve individual reconnection events and the acceleration and wave motion that they engender.

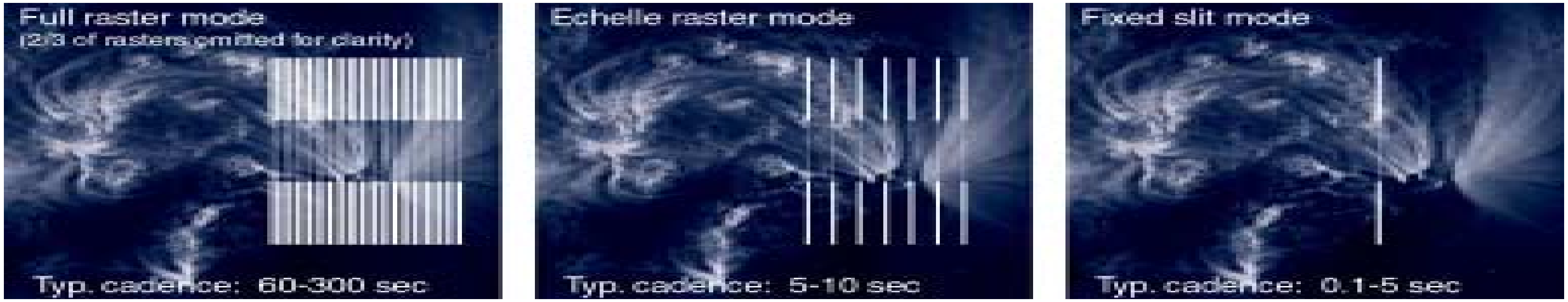


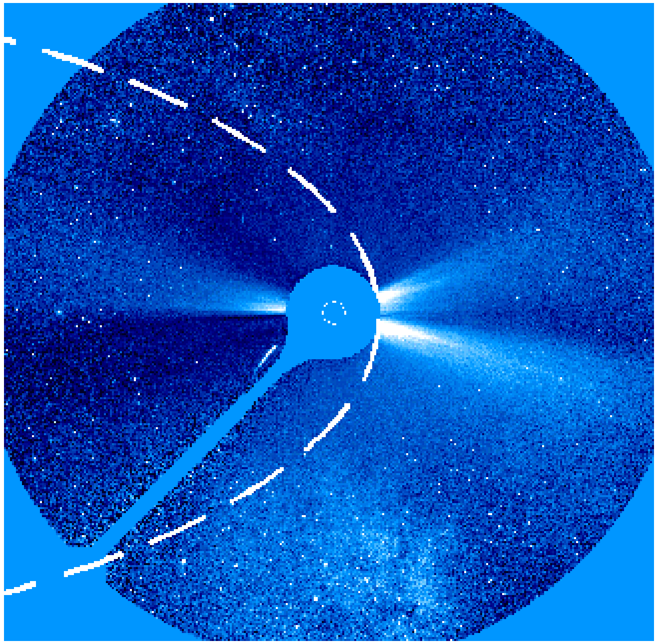
Figure 3: EUV Spectrometer Observing modes. Slit positions for the three principal observing modes are depicted, to scale, on a TRACE 171Å 200x200 arcsec^2 image showing coronal “moss” under an active region. Cadences are given for typical line selections and exposure times for each mode. Slit exposure times are typically 1-2 seconds for bright lines (used in the echelle scan); 1-5 seconds for a broader line selection (in the full scan).

High Resolution Imaging AND Spectroscopy

- Understanding the microscale processes that occur in all magnetized astrophysical plasmas requires BOTH:
  - High resolution/throughput imagers
  - High time resolution imaging spectrometers

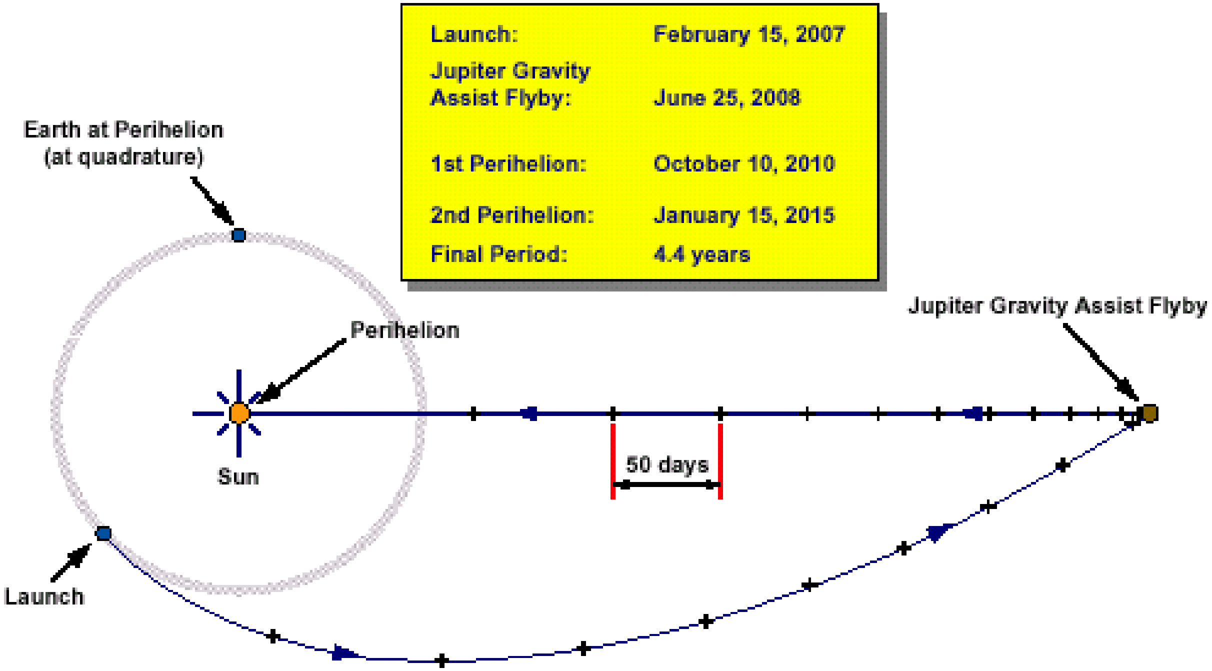
Future Capability 3: Go to the Sun!

Solar Probe: a mission of discovery - NOT incremental science!



- Directly sample the corona and the inner heliosphere, where the solar wind is born!
- ONLY way to determine uniquely what heats the corona and accelerates the solar wind.
- First view of the Sun’s Poles!
- Polar magnetograms and sub-surface velocity maps will solve fundamental mysteries related to the solar dynamo and the origins of the solar cycle.

Jupiter Gravity Assist Trajectory

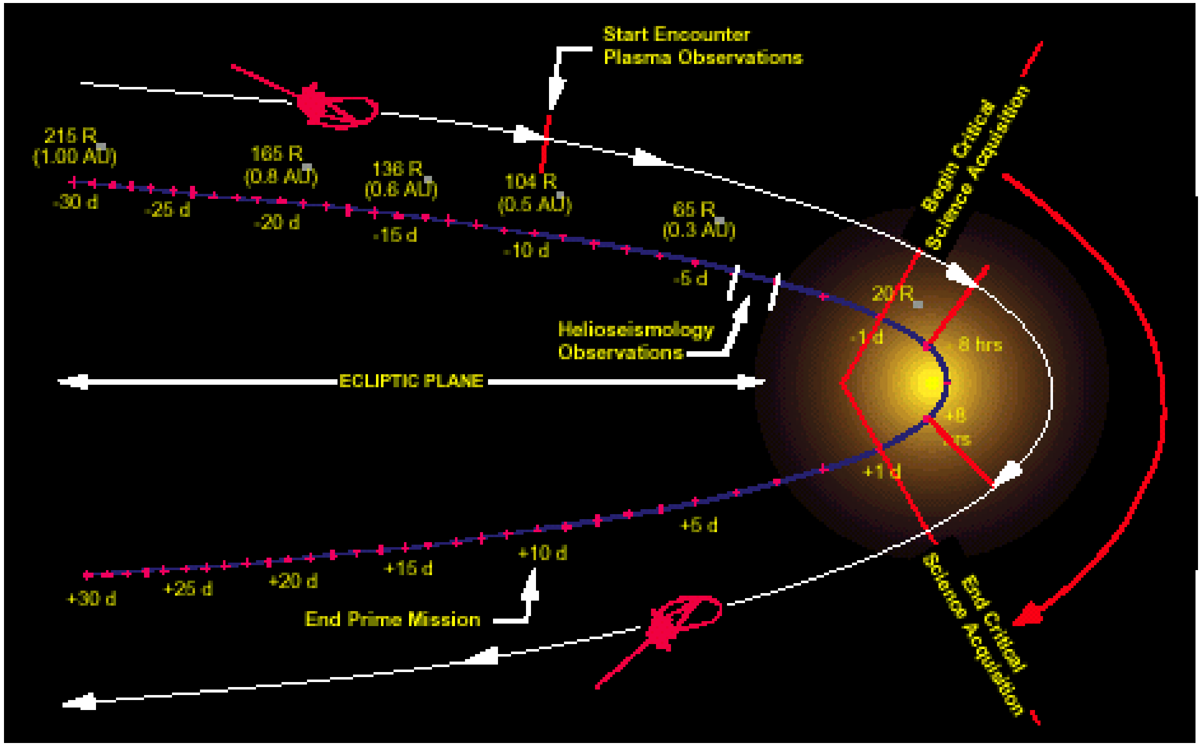


Launch:	February 15, 2007
Jupiter Gravity Assist Flyby:	June 25, 2008
1st Perihelion:	October 10, 2010
2nd Perihelion:	January 15, 2015
Final Period:	4.4 years

The planned trajectory for Solar Probe will take it from launch at Earth out to Jupiter, where the planet will be used for a gravity assist. This will alter the spacecraft trajectory to a highly elliptical orbit with a perihelion of 4 R_S and an aphelion of 5 AU. The mission duration is approximately 3.7 years from launch to first solar perihelion, and up to 8.1 years from launch to second perihelion.

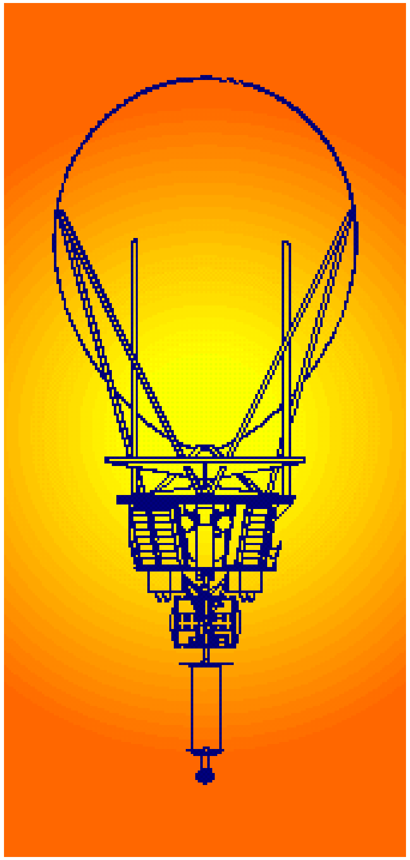
Solar Probe Mission Profile

(view from Earth)



As shown above, encounter measurements will start on approach to the Sun at 10 days prior to perihelion and will continue to 10 days after perihelion. During this time (within 0.5 AU), the inner heliosphere and the corona will be observed in-situ for the first time. Helioseismology measurements will begin at 4 days before perihelion (0.2 AU). The most intense observation period will take place during the two days centered on closest approach (the critical science acquisition period indicated in the figure).

Solar Probe Science Payload

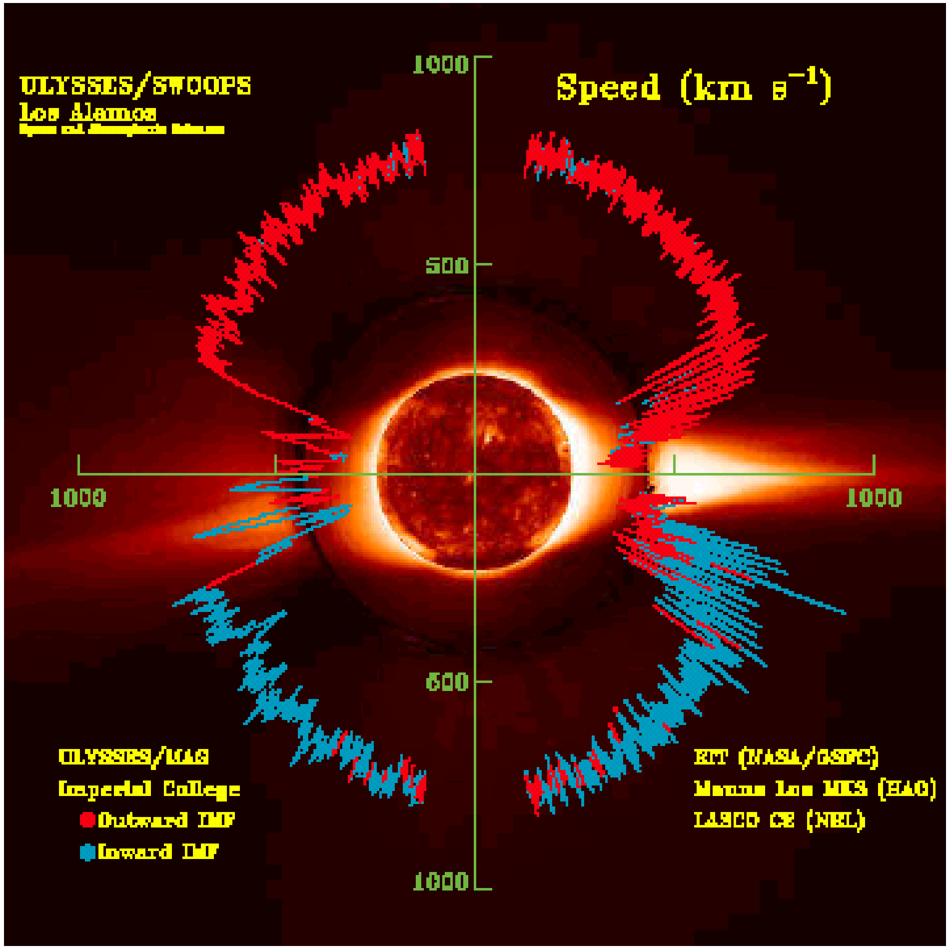


Remote Sensing Instruments
Visible Magnetograph/Helioseismograph
EUV Imager
All-sky, 3-D Coronagraph Imager

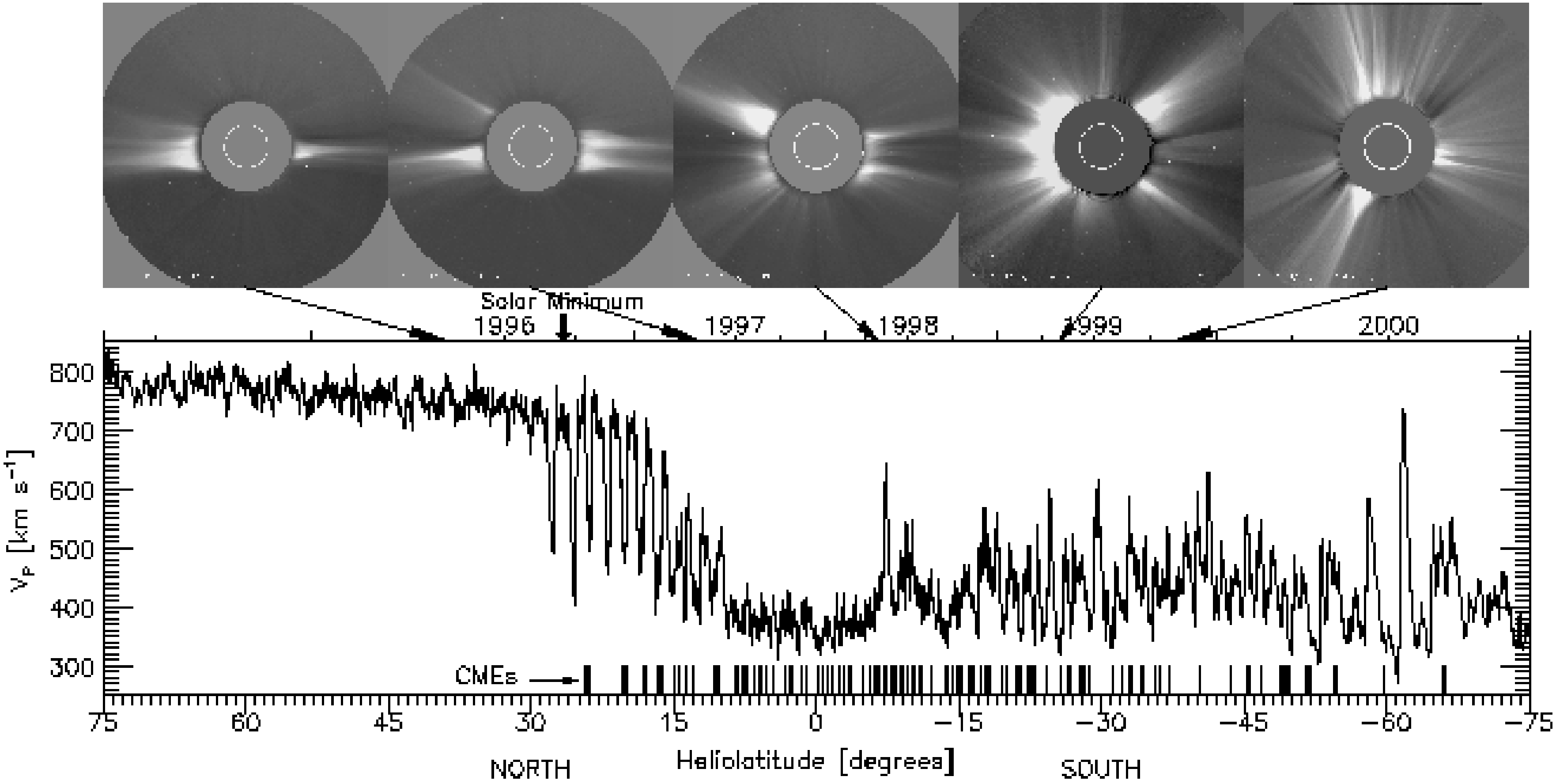
In-situ Instruments
Magnetometer (with boom cables)
Solar Wind Ion Composition and Electron Spectrometer
Energetic Particle Composition Spectrometer
Plasma Wave Sensor (with boom cables)
Fast Solar Wind Ion Detector

Total	21 kg	15 W

Ulysses Solar Wind Speed Observations



Measurements of the solar wind from the Ulysses mission show that solar wind velocities are 750-800 km/s over the Sun's polar regions and about 400 km/s over the equatorial regions (slow solar wind region). There are spatial variations in the latter region because Ulysses was moving into and out of high speed streams.

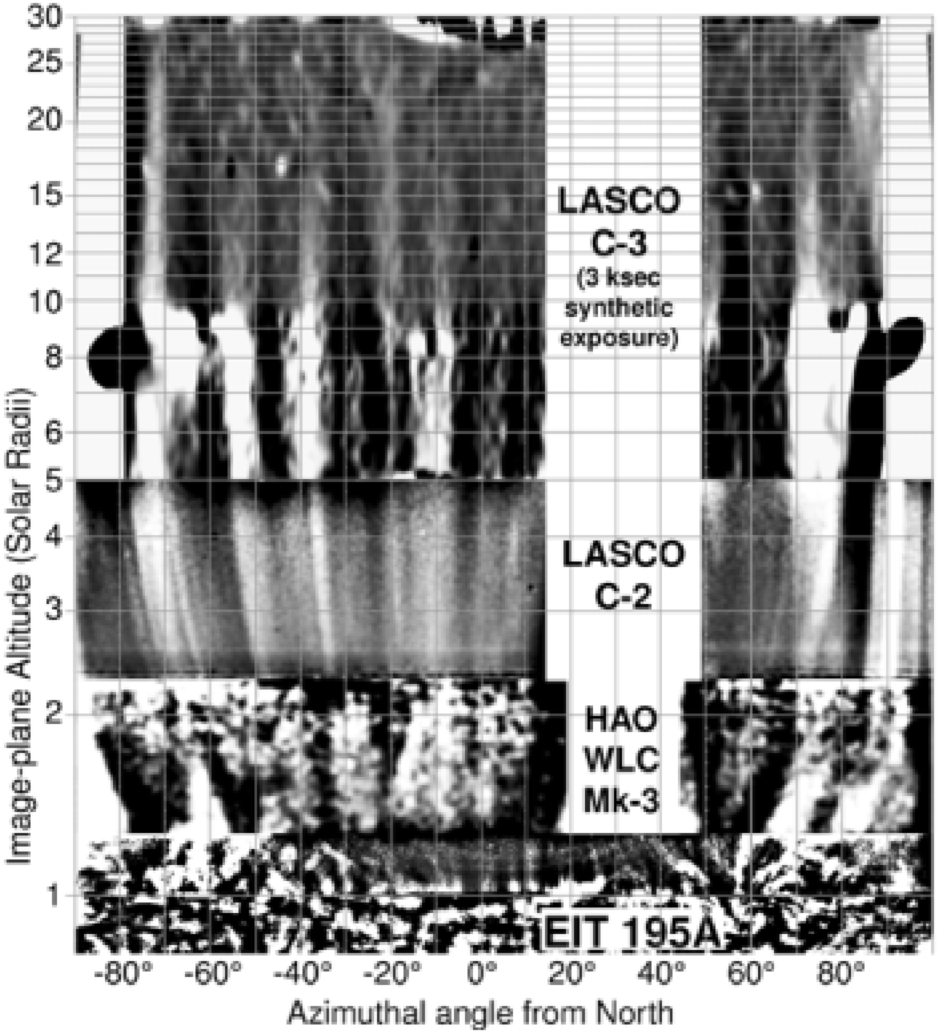

Solar Minimum
1996
1997
1998
1999
2000
V_P [km s^-1]
800
700
600
500
400
300
CMEs
75
60
45
30
15
0
−15
−30
−45
−60
−75
NORTH
Heliolatitude [degrees]
SOUTH

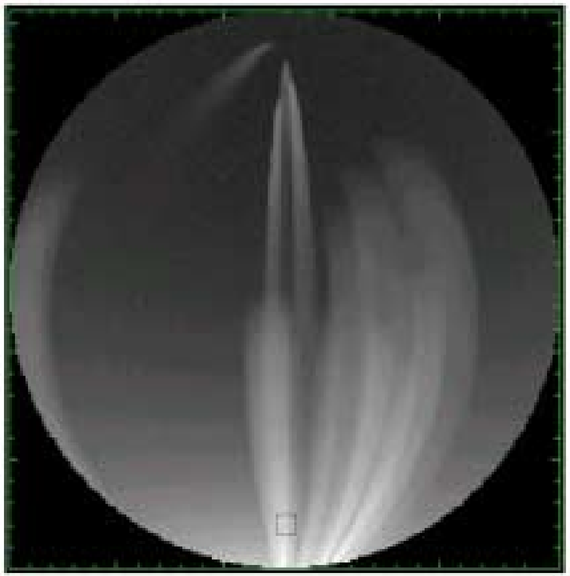
In-Situ Measurements

High time resolution, synchronized plasma, energetic particle, and field measurements, including mass resolved ion distribution functions, will resolve:

- solar wind heating and acceleration
- macroscopic coronal structure and composition
- fine scale spatial structures
  - plasma and magnetic structures in the helmet streamer belt
  - plume/interplume structure

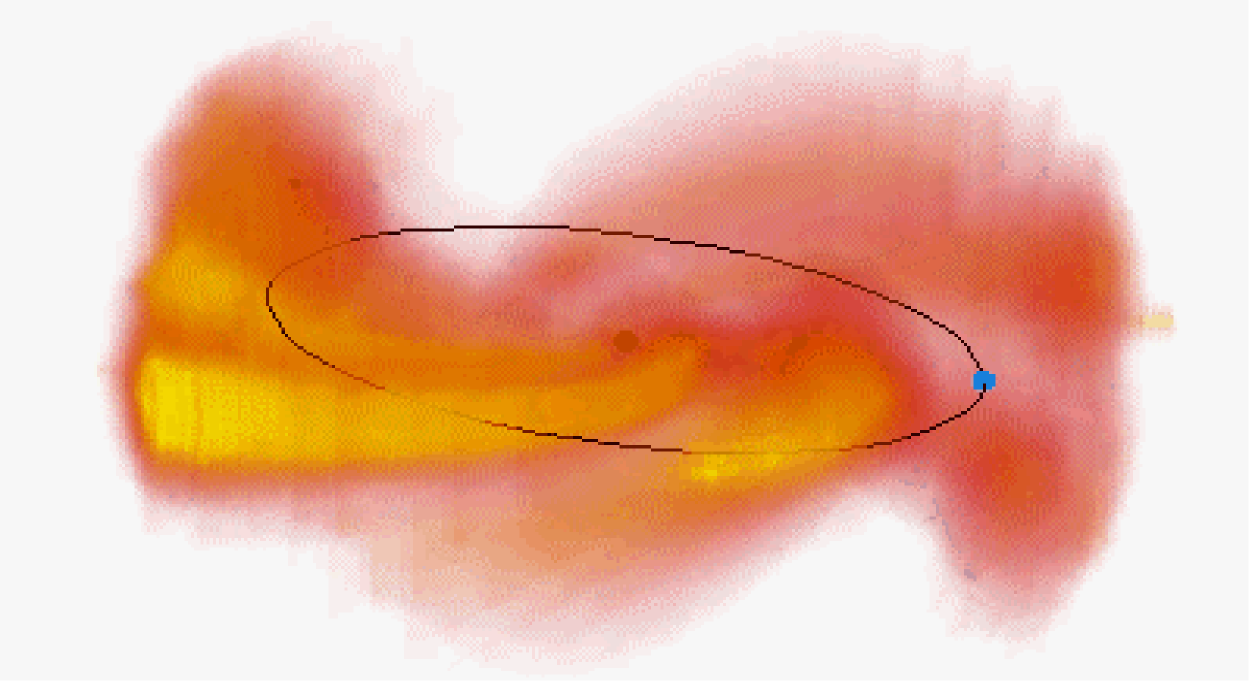
Simultaneous imaging of coronal structures (e.g. polar plumes) as the spacecraft flies through the corona is required to resolve inherent ambiguities in the interpretation of spatial and temporal changes seen in the *In-situ* measurements.





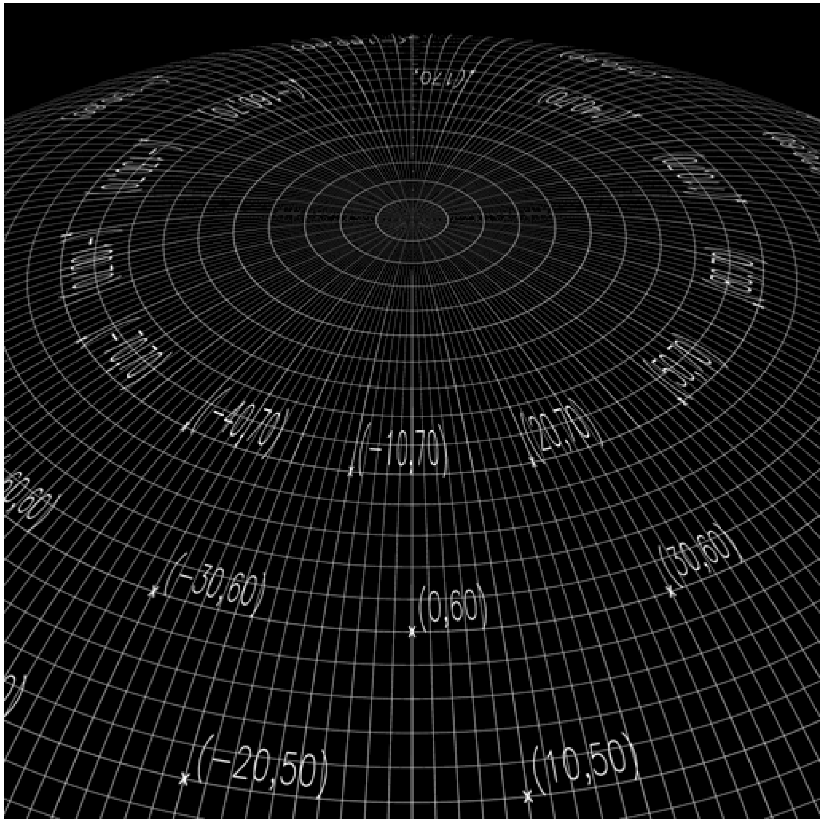
A coronal fly-through is the ONLY way to reconstruct the 3-D coronal structure!

The Hemispheric Imager’s 180 deg. FOV permits true tomographic reconstruction of 3-D coronal structure and context for the in-situ package



Reconstructed image of the heliosphere out to 1.5 AU, derived by tomographic reconstruction from HELIOS photometer data. Solar Probe will permit reconstruction of the corona and inner heliosphere with 1,000 times better spatial resolution.

Solar Probe will provide an unprecidented view of the both of the Sun’s Poles during both Solar Minimum and Solar Maximum!



Perspective view of Sun’s Pole from Solar Probe three days before Perihelion.

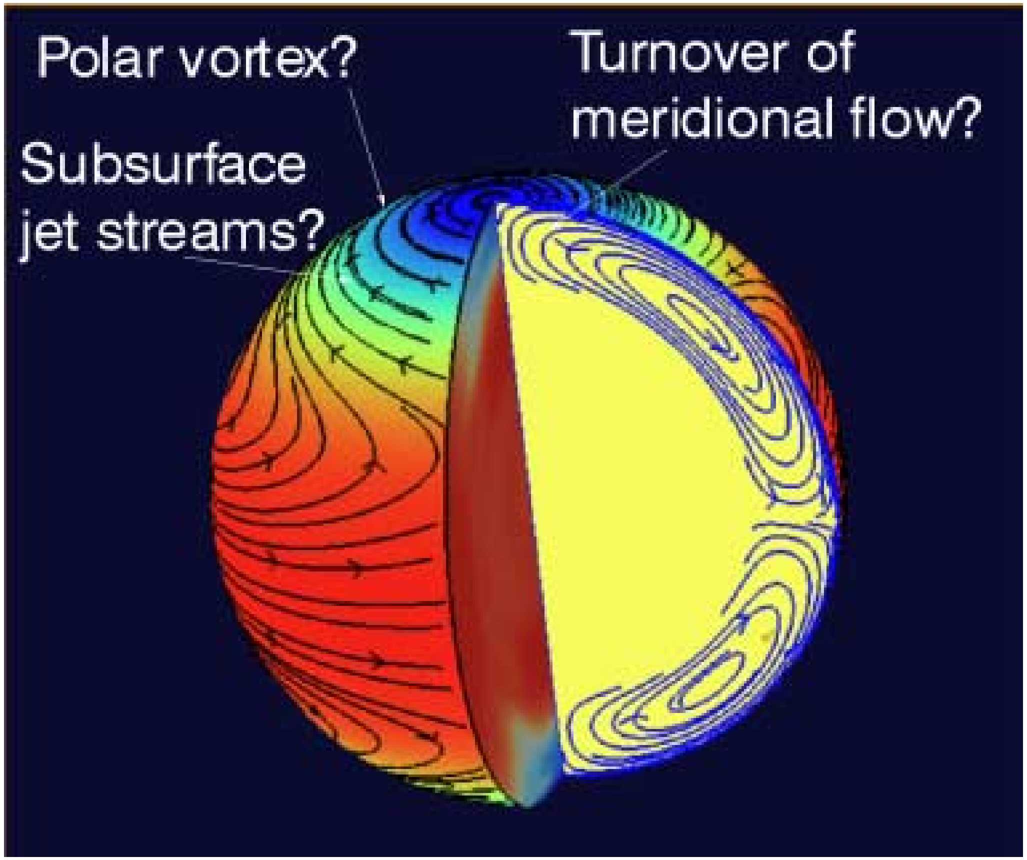
Observations of the Sun’s Poles: Polar Magnetic Field

- The Solar Probe magnetograph will provide the first high resolution maps and time series evolution studies of the *polar* magnetic field.
- Solar Probe magnetograms will be the highest resolution magnetograms of the photosphere ever obtained.

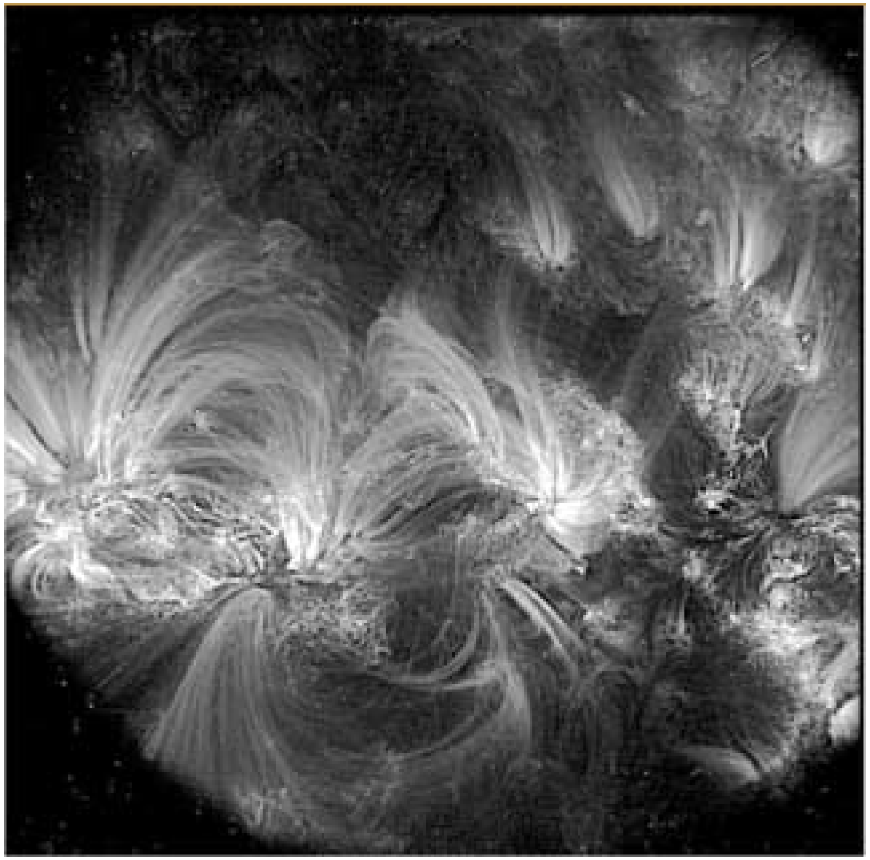
Solar Probe magnetograms will provide important constraints on theories of the Solar Dynamo

- The poloidal component of the magnetic field, a key ingredient to the dynamo mechanism, is predicted to be strongest at the poles.
- Models suggest that transport of magnetic flux by meridional circulation is crucial for the solar cycle and the operation of the dynamo, because it couples toroidal and poloidal field components, and links the surface field to the shear layer at the base of the convection zone.

Solar Probe helioseismology will provide maps of the polar sub-surface velocity flow patterns, solving fundamental mysteries related to the sub-surface origins of the solar cycle.



Ultra-high (35 km) resolution images of the corona and solar surface, including the poles!



Solar Probe will provide EUV imaging of the corona and solar surface with a resolution 10 times higher than TRACE.

Summary

- Moderate time cadence, simultaneous, multi-thermal synoptic imaging and imaging spectroscopy (Solar Dynamics Observatory-SDO).
- Very high time and spatial (10-100 km) resolution imaging (RAM).
- Simultaneous, high time and spatial resolution imaging spectroscopy (spectral images) (ESSEX).
- Polar observations (to constrain theories of the Solar Dynamo and the Solar Cycle) (Solar Probe).
- *In-situ* direct measurements of the corona (Solar Probe).