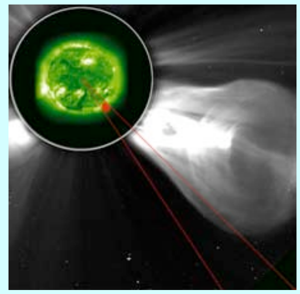
Advances in Solar Coronagraphy

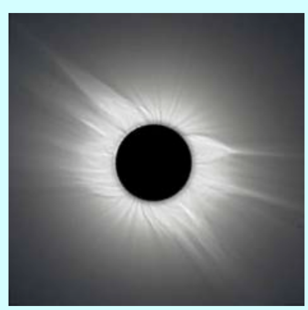


D. Rabin, J. Davila, and O. C. St. Cyr
Solar Physics Laboratory
NASA Goddard Space Flight Center

Special thanks to the STEREO/SECCHI team for sharing graphics and movies and to H. Lin and J. Kuhn for sharing material relating to the measurement of coronal magnetic fields

The First Coronagraph

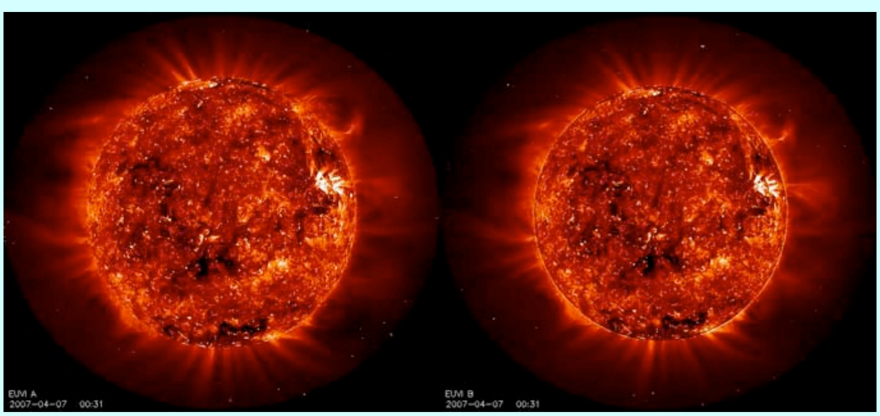
Movie by F. Espanak



Photograph by Olgarde
(Libya, 2006)

A Recent Partial Eclipse

The Corona Without a Coronagraph



Wavelet-enhanced images from STEREO A and B in Fe IX/X 171 Å (4 April 2007)

Why do we (still) study the solar corona?

- Physical structure and heating
- Evolution
- Dynamics
- $\vec{B}$
- $\vec{B}$
- $\vec{B}$!

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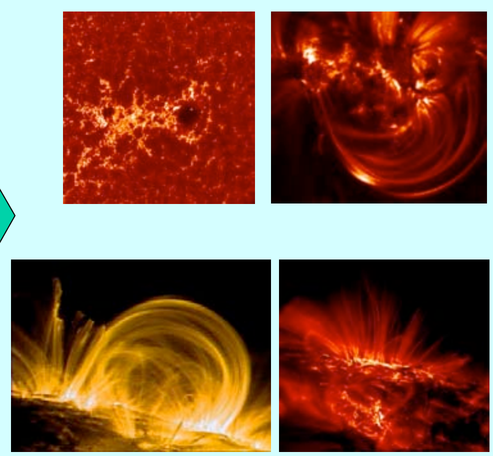
Physical Structure and Heating

One-dimensional, time-independent models



Images courtesy of TRACE (trace.lmsal.com)

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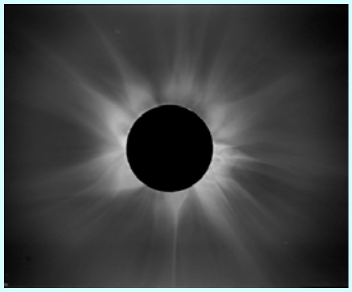
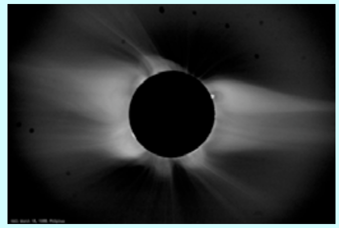
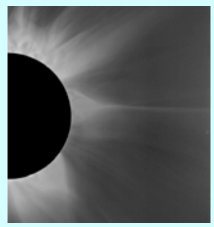
Evolution



Total Eclipse of 16 February 1980; Palem, India
Courtesy High Altitude Observatory



Total Eclipse of 18 March 1988; Phillipines
Courtesy High Altitude Observatory



Helmet Streamer

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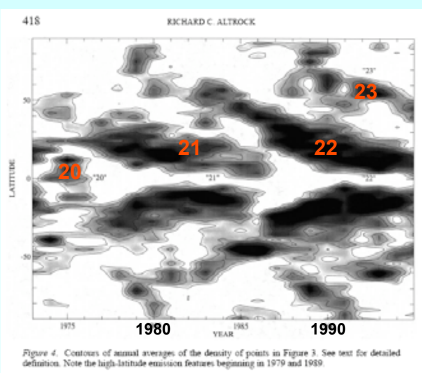
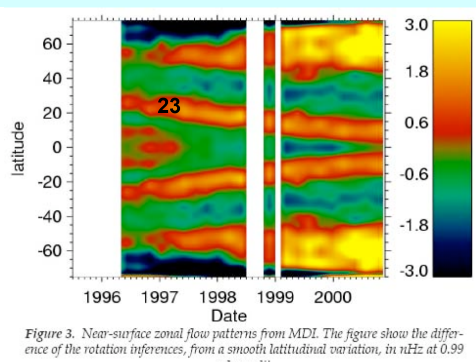
Evolution

Fe XIV Corona



Contours of annual averages of local intensity maxima in Fe XIV 530.3 nm at 1.15 Rs (National Solar Observatory).

Subsurface Rotation



Contours of zonal flows (departures from smooth differential rotation) at 0.99 Rs inferred from helioseismic data (SOHO/MDI).

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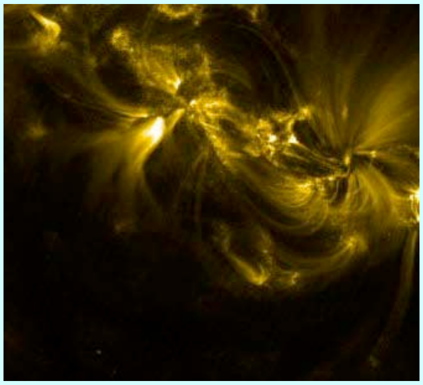
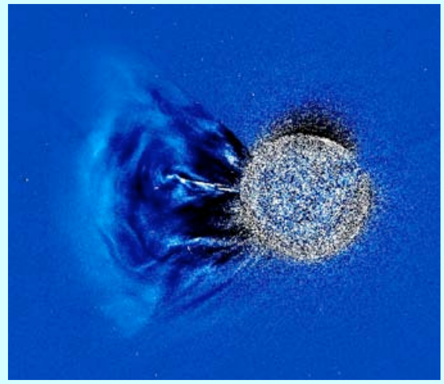
Dynamics

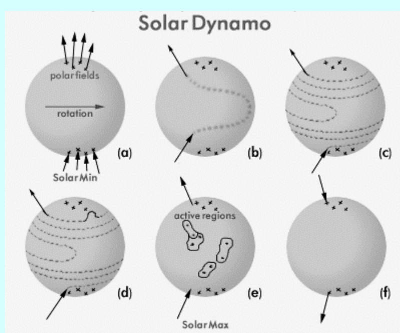


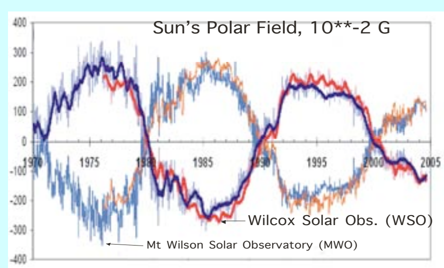
Movie in Fe IX/X 171 Å from TRACE

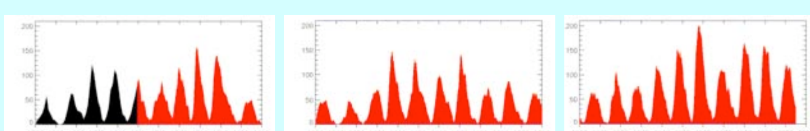


STEREO COR1 (24 January 2007)

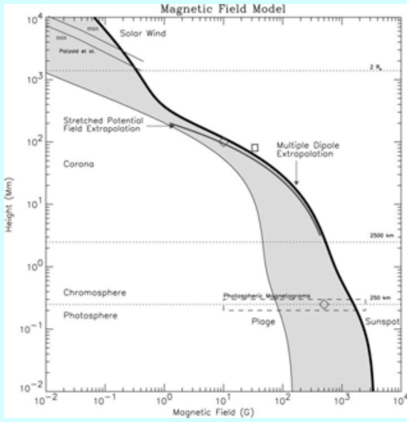
The Magnetic Field Controls the Solar Cycle

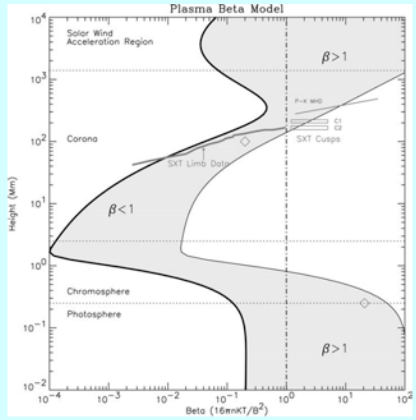






… and the Inner Corona





Diagrams by A. Gary

"Were it not for its magnetic field, the Sun would be as uninteresting as most astronomers think it is." R. B. Leighton

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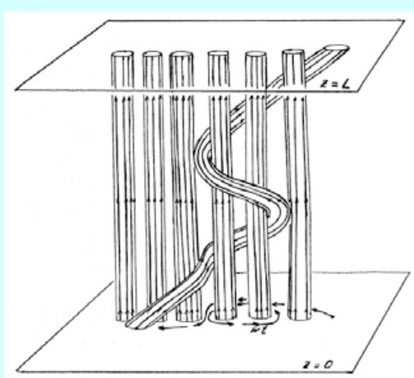
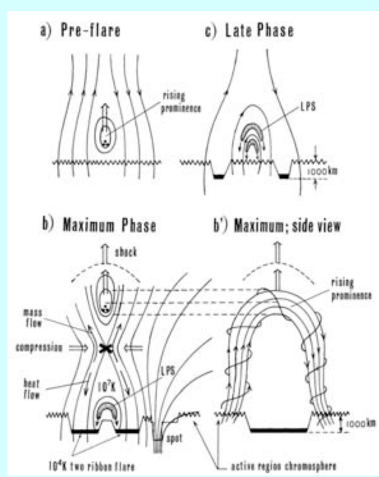
Many Cartoons, Few Measurements



Parker 1983



Hirayama 1974

solarmuri.ssl.berkeley.edu/~hhudson/cartoons/

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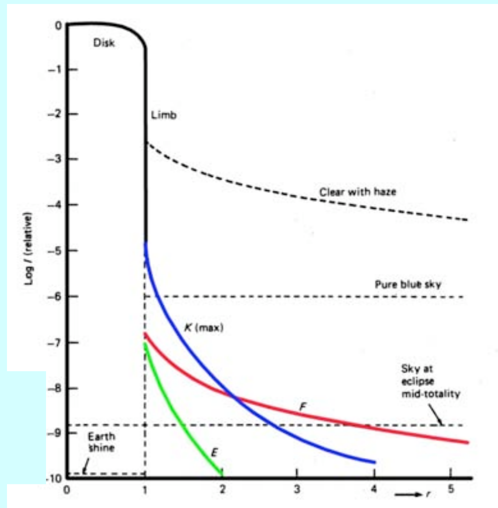
Components of the Solar Corona

- k-corona: The “true” corona, arising from Thomson scattering of photospheric radiation by electrons (highly polarized)
- F-corona: Caused by scattering due to dust between the observer and the Sun (unpolarized near the Sun)
- E-corona: Emission-line corona, much fainter than k- or F-, seen as discrete features at select wavelengths
- Often, use polarization and/or color techniques to separate the F- and k-coronae and to remove stray light.



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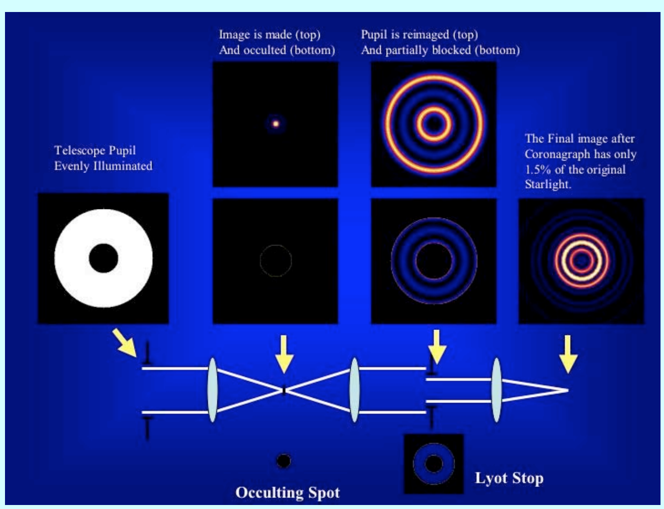
Internally Occulted (Lyot) Coronagraph



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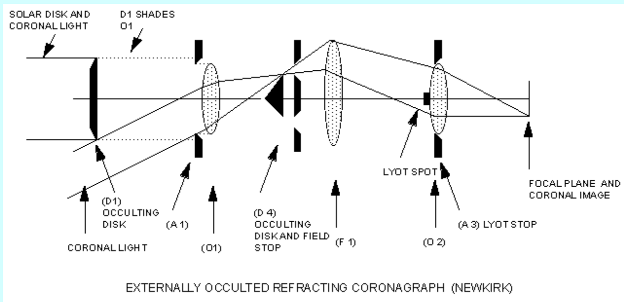
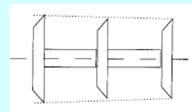
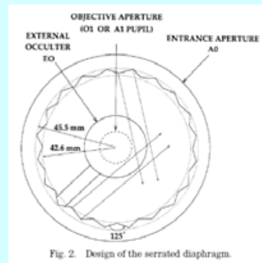
Externally Occulted Coronagraph





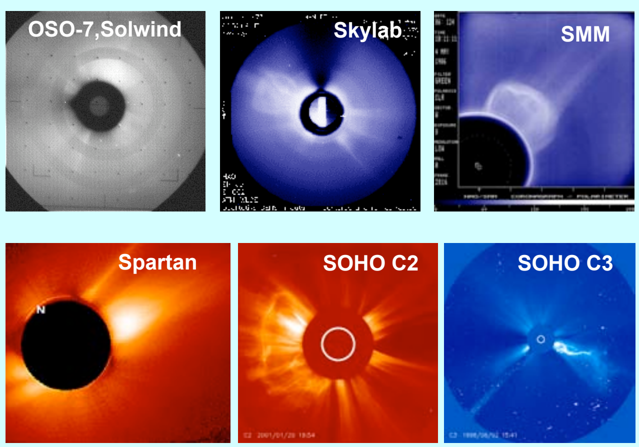
Triple disk occulter

Newkirk & MacQueen (HAO) and Tousey & Koomen (NRL) began experimenting with externally-occulted instruments in the 1960s, and these were adapted for balloons, airplanes, and spaceflight.



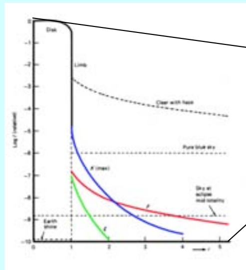
Serrated external diaphragm for LASCO C2

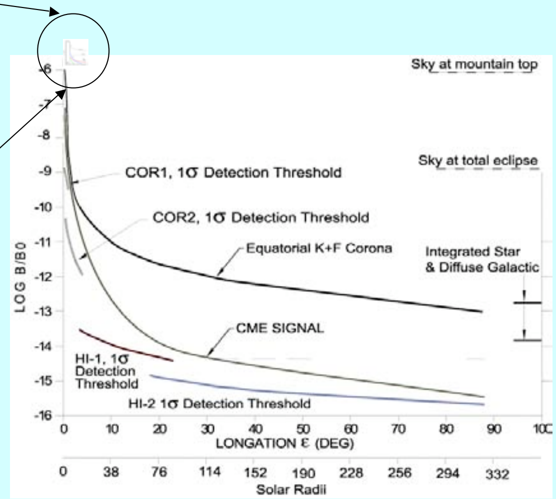
Most Solar Coronagraphs are in Space



Spaceborne coronagraphs, 1970−1995. All externally occulted.

Why Multiple Coronagraphs?

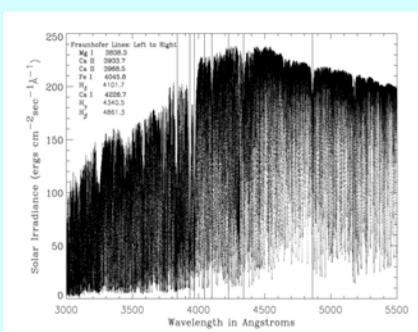




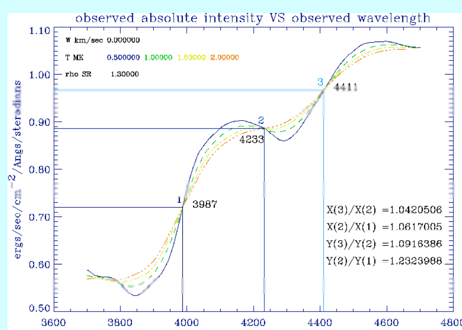
- Each coronagraph is designed to operate in a small height regime.
- This makes the problem of observing the corona over many orders of magnitude tractable.
- Shown are the 1 sigma CME detection threshold compared to the coronal brightness.

We Still Learn from Solar Eclipses (1)

Temperature and Flow Speed from Thomson Scattered Coronal Emission
Davila, Reginald, St. Cyr, Guhathakurta & Hassler (Libya 2006)



Photospheric Spectrum

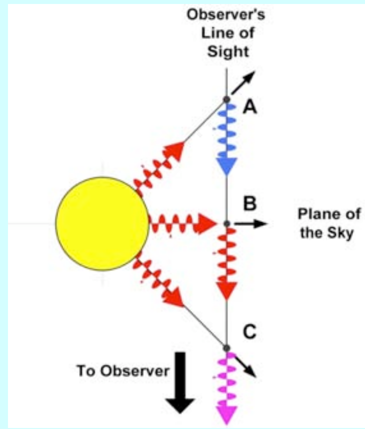


Coronal Model Spectrum

- Hot coronal electron distribution smoothes the photospheric spectrum (Cram 1976).
- The degree of smoothing is proportional to the electron temperature.
- Doppler shift of the entire spectrum is proportional to the flow speed.

Flow Speed from Thomson Scattered Coronal Emission

- Wavelength is conserved in the frame of the moving electron.
- Therefore the Doppler shift of the scattering source is observed in the scattered radiation even if the motion is transverse.
- Integrate over Maxwellian velocity distribution and sum over line of sight.
- Result is a spectral shift of approximately 4 Å per 100 km s^{-1}.



As usual, get electron column density from white-light image: $I_{WL} \propto \int n_e \, d\ell \, ds$

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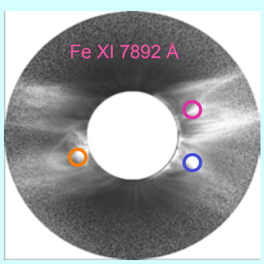
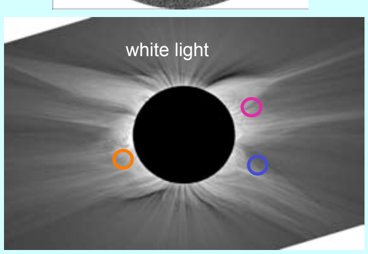
We Still Learn from Solar Eclipses (2)

Heavy Ion Density Enhancements in the Corona

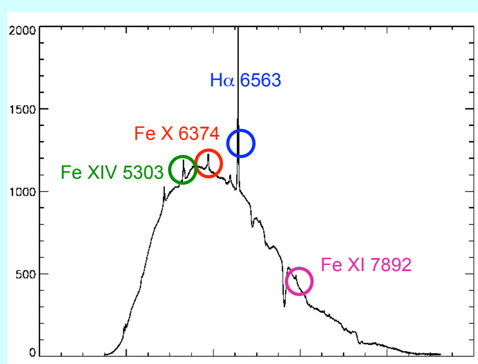
Habal et al. (Libya 2006)





First image of the corona in Fe XI 7892 Å

- Emission seen out to 2 R_ε
- Intensity enhancements not seen in white light



Visible coronal spectrum (Jaeggli et al. 2007)

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Heavy Ion Density Enhancements in the Corona

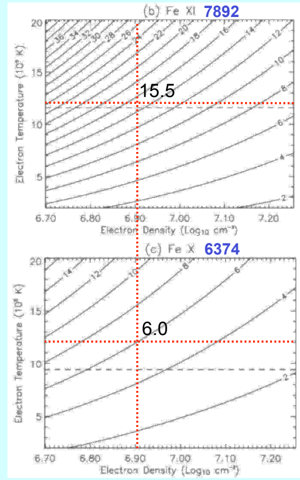
Lie-Svenden & Esser (2005) showed that low heating rates can lead to large coronal abundances of heavy ions in the corona.

- Minor ions are carried at low heights by the outflow of protons.
- At larger heights, ions decouple from protons
- If heating rate is too low, a build-up of ions will occur, leading to a localized increase in abundance.
- Abundance enhancement increases with mass.

➡ Density enhancements may be a diagnostic of energy input to heavy ions.

Other heavy ion diagnostics (for another talk)

- O VI as an indicator of ion-cyclotron resonance heating in the solar wind acceleration region
- The FIP effect



Ratio of resonance to collisional contributions to intensity at observed radius for two iron lines.

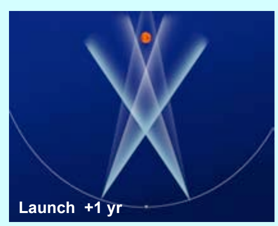
The Forefront of Space-Based Coronagraphy

SECCHI Instrument Package on the STEREO Satellites

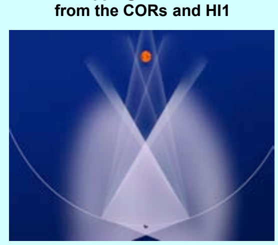
Launched in October 2006, all instruments are now operational.

Inst.	Observable	Wavelength	Field of View
EUVI	He II Intensities	30.4 nm	<1.7 Rs
	Fe X, Fe XII, Fe XV Intensities	17.1, 19.5, 28.4nm	
COR1	Intensity - B, pB, p	650 - 660 nm	1.4 - 4 Rs
COR2	Intensity - B, pB, p	650 - 750 nm	2.5 - 15 Rs
HI-1	Intensity - B	630 - 730 nm	20° (15 - 90 Rs)
HI-2		400 - 1000 nm	70° (70 - 332 Rs)

stereo.gsfc.nasa.gov secchi.nrl.navy.mil

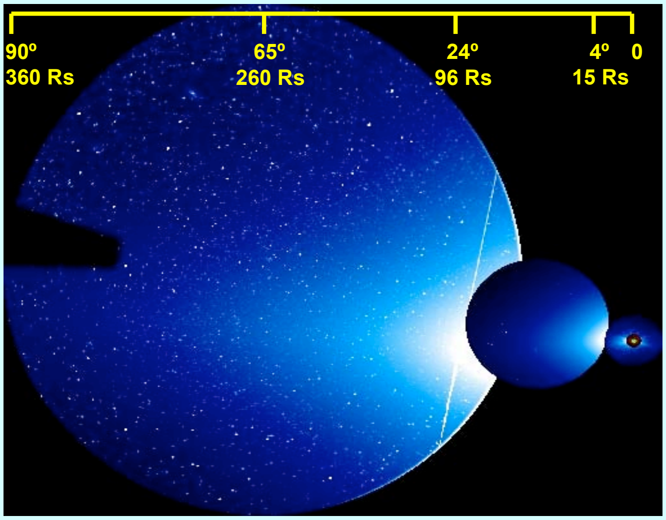


Overlapping fields of view from the CORs and HI1



Overlapping fields of view from HI1 and HI2

The STEREO Panoramic View



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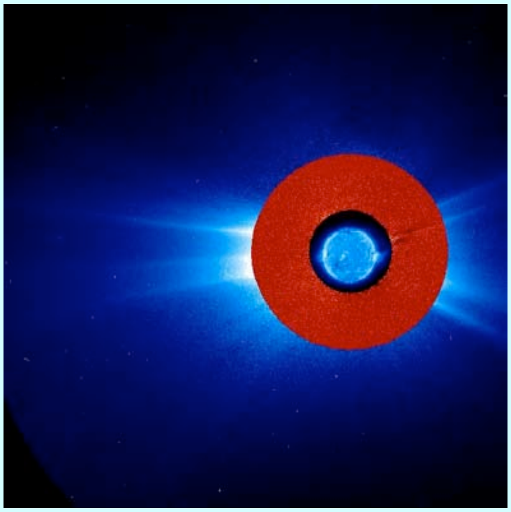
EUVI, COR1 and COR2

9 February 2007

Outer Limit at 15 Rs

Cropped on West limb



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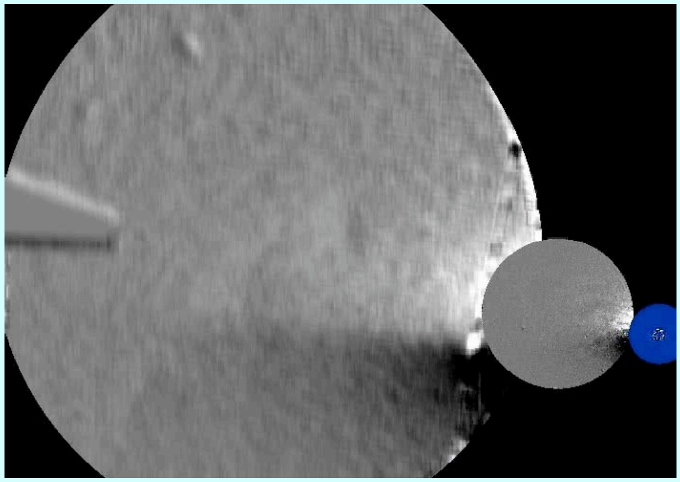
COR2, HI-1 and HI-2

9 February 2007

Running Differences and Median Filtering



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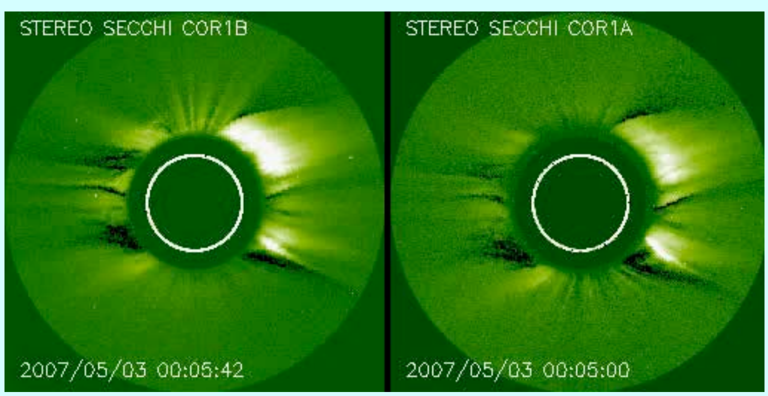
But is it Stereo?



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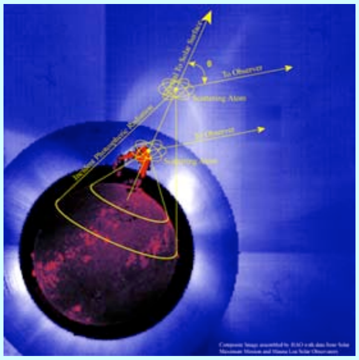
The Forefront of Ground-Based Coronagraphy

Polarization of Forbidden Coronal Emission Lines



Resonant scattering of anisotropic photospheric radiation by atoms and ions in the corona in the presence of a magnetic field.

Linear Polarization – Hanle effect

- Orientation of linear polarization maps orientation of magnetic field projected in the plane of the sky.
- Not sensitive to the magnetic field strength
- 90-degree ambiguity in field direction (Van Vleck effect)

Hard to measure well

Circular Polarization – Zeeman effect

- Circular polarization is proportional to the line-of-sight magnetic field.
- The magnetograph formula is modified by an atomic alignment factor that depends on the inclination angle between ***B*** and the local vertical direction and the anisotropy of the incident radiation field.

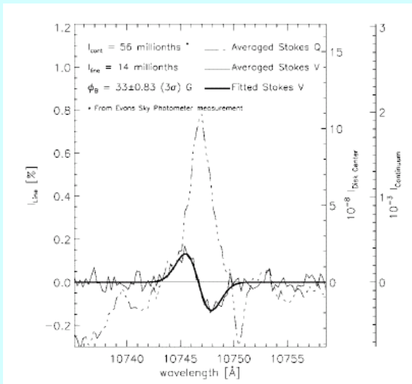
Very hard to measure, period

The Challenge of Coronal Zeeman Effect Measurements

- High temperature (T >10^6 K) and low magnetic field strength (*B* ~ 1–10 G) result in a low circular polarization signal (Stokes V).
  - $V \sim 10^{-3}$ to 10^{-4} I_{line} $\Rightarrow$ *Need > 10^9 photon per measurement*
- *Low photon flux from the emission lines*: $I_{line} \sim 10^{-5}\ I_{\odot}$
  - $V \sim 10^{-8}$ to 10^{-9} $I_{\odot}$
- *Large scattered light background*: $I_{sc} \sim 10^{-5}\ I_{\odot}$
- *Relatively high linear polarization:* $Q, U \sim 0.01–0.1\ I_{line} >> V$
  - Even a small linear-to-circular polarization crosstalk will overwhelm the weak Stokes *V* profiles.
  - $Q,U \rightarrow V$ crosstalk must be calibrated to better than 10^{-3}.
- Long history of measurement attempts with only upper limits
- Fe XIII 1075 nm is the most favorable line (Judge et al. 2001)

First Definitive Coronal Zeeman Effect Measurement

Lin, Penn & Tomczyk (2000)



Fe XIII 1075 nm

- 40 cm coronagraph (National Solar Observatory Evans Facility)
- 240 arcsec^2 FOV (summed over the entire length of the slit)
- 2560 seconds (44 minutes) integration time (*Q* & *V*)
- Careful telescope and instrumental polarization cross-talk control

Bravo! But …

- Need 2d coverage
- Need spatial resolution
- Need time resolution

Therefore …

- Need more glass

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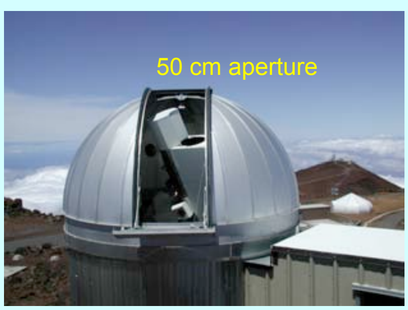
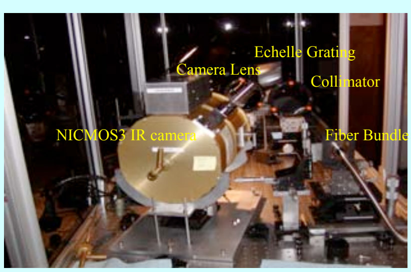
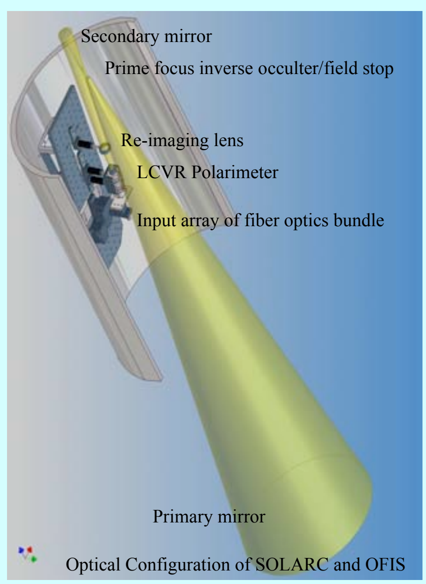
SOLARC on Haleakala, Maui







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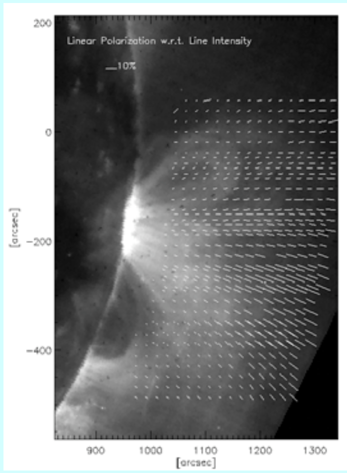
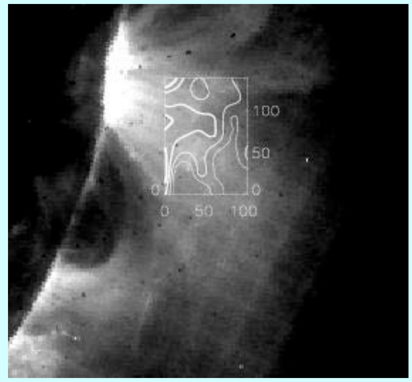
First 'Vector' Coronal Magnetogram

Lin, Kuhn & Coulter 2004

Transverse field orientation



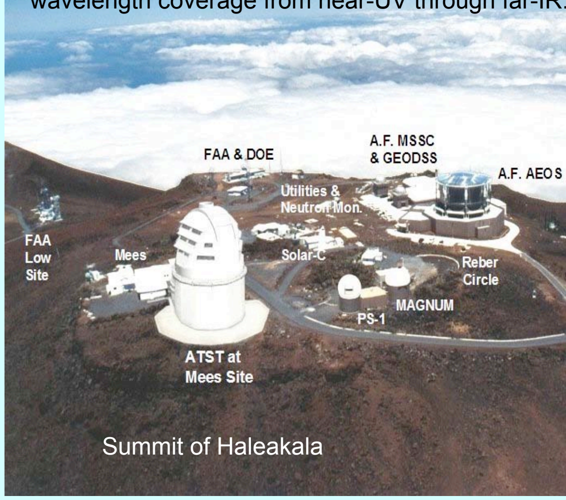
Longitudinal Field Strength

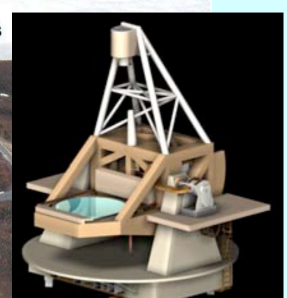


Contours of line-of-sight field strength plotted over SOHO/EIT FeXVI 284 Å image. The contours are 5G, 3G, and 1G.

Advanced Technology Solar Telescope

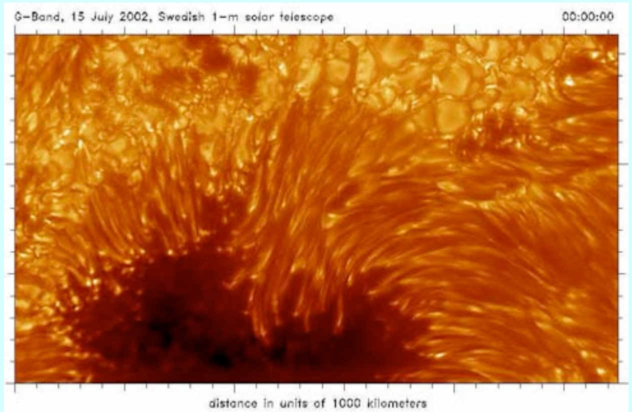
ATST will be a 4-m decentered coronagraphic telescope designed from the ground up for precision polarimetry with wavelength coverage from near-UV through far-IR.





Advanced Technology Solar Telescope

3d MHD model of a magnetic flux tube



In addition to coronagraphy and infrared spectroscopy, ATST will carry out high-resolution imaging at visible wavelengths using high-order adaptive optics. The movie above represents the current state of the art for ground-based observations using AO (1-m Swedish Solar Telescope)

Prospectus

- Solar coronagraphy has made great strides since Lyot's pioneering instruments and studies.
- In space, the frontier is three-dimensional imaging of coronal mass ejections and the solar wind throughout the heliosphere.
- On the ground, the frontier is spatially and temporally resolved measurements of the magnetic field in the lower corona.
- … except for the frontiers we haven't yet discovered.