Advances in Solar Coronagraphy

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The First Coronagraph

Movie by F. Espanak

Photograph by Olgarde
(Libya, 2006)
A Recent Partial Eclipse

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

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
- $\vec{B}$
- $\vec{B}$
- $\vec{B}$!

Physical Structure and Heating

Images courtesy of TRACE (trace.lmsal.com)

One-dimensional, time-independent models
Evolution

Total Eclipse of 16 February 1986; Palem, India
Courtesy High Altitude Observatory

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

Helmet Streamer

Evolution

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

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

Movie in Fe IX/X 171 Å from TRACE

STEREO COR1 (24 January 2007)

The Magnetic Field Controls the Solar Cycle

The Magnetic Field Controls the Solar Cycle

4 June 2007  Spirit of Lyot Conference
… and the Inner Corona

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

Many Cartoons, Few Measurements

solarmuri.ssl.berkeley.edu/~hhudson/cartoons/  Hirayama 1974

Parker 1983
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.

Internally Occulted (Lyot) Coronagraph

- Image is made (top) and occulted (bottom)
- Pupil is reimaged (top) and partially blocked (bottom)
- The final image after Coronagraph has only 1.5% of the original stray light.
Externally Occulted Coronagraph

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.

Most Solar Coronagraphs are in Space

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)

- Hot coronal electron distribution smooths 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: \[ I_{WL} \propto \int n_e \, dl \, ds \]

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 \( R_e \)
- Intensity enhancements not seen in white light
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.

<table>
<thead>
<tr>
<th>Inst.</th>
<th>Observable</th>
<th>Wavelength</th>
<th>Field of View</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUVI</td>
<td>He II Intensities</td>
<td>30.4 nm</td>
<td>&lt;1.7 Rs</td>
</tr>
<tr>
<td></td>
<td>Fe X, Fe XII, Fe XV Intensities</td>
<td>17.1, 19.5, 28.4 nm</td>
<td></td>
</tr>
<tr>
<td>COR1</td>
<td>Intensity - B, pB, p</td>
<td>650 - 666 nm</td>
<td>1.4 - 4 Rs</td>
</tr>
<tr>
<td>COR2</td>
<td>Intensity - B, pB, p</td>
<td>650 - 750 nm</td>
<td>2.5 - 15 Rs</td>
</tr>
<tr>
<td>HI-1</td>
<td>Intensity - B</td>
<td>630 - 730 nm</td>
<td>20° (15 - 90 Rs)</td>
</tr>
<tr>
<td>HI-2</td>
<td>Intensity - B</td>
<td>400 - 1000 nm</td>
<td>70° (70 - 332 Rs)</td>
</tr>
</tbody>
</table>

Overlapping fields of view from the CORs and HI1

Overlapping fields of view from HI1 and HI2

stereo.gsfc.nasa.gov  secchi.nrl.navy.mil
The STEREO Panoramic View

EUVI, COR1 and COR2

Outer Limit at 15 Rs
Cropped on West limb
COR2, HI-1 and HI-2
9 February 2007
Running Differences and Median Filtering

But is it Stereo?

4 June 2007
Spirit of Lyot Conference
The Forefront of Ground-Based Coronagraphy

**Polarization of Forbidden Coronal Emission Lines**

**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]

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The Challenge of Coronal Zeeman Effect Measurements

- High temperature ($T > 10^6$ K) and low magnetic field strength ($B \sim 1$–10 G) result in a low circular polarization signal (Stokes $V$).
  - $V \sim 10^{-3}$ to $10^{-4} I_{\text{line}} \Rightarrow$ Need $> 10^9$ photon per measurement
  - Low photon flux from the emission lines: $I_{\text{line}} \sim 10^{-5} I_{\odot}$
  - $V \sim 10^{-8}$ to $10^{-9} I_{\odot}$
- Large scattered light background: $I_{\text{sc}} \sim 10^{-5} I_{\odot}$
- Relatively high linear polarization: $Q, U \sim 0.01$–$0.1 I_{\text{line}} >> V$
  - 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)

- 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

SOLARC on Haleakala, Maui

- 50 cm aperture
- Primary focus inverse occulter/field stop
- Re-imaging lens
- LCVR Polarimeter
- Input array of fiber optics bundle

**Optical Configuration of SOLARC and OFIS**
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.
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.