UVCS Observations of the Solar Wind and its Modeling

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UVCS Observations of the Solar Wind and its Modeling

Outline:

• Background & spectroscopic diagnostics

• Results:
  Coronal holes (fast wind)
  Streamers (slow wind)
  CMEs (SEP source regions!)
The need for both solar-disk & coronagraph observations

- On-disk measurements help reveal basal coronal heating & lower boundary conditions for solar wind.

- Off-limb measurements (in solar wind "acceleration region") allow dynamic non-equilibrium plasma states to be followed as the asymptotic conditions at 1 AU are gradually established.

  Occultation is required because extended corona is 5 to 10 orders of magnitude less bright than the disk!

  Spectroscopy provides detailed plasma diagnostics that imaging alone cannot.
**UVCS / SOHO**

- **1979–1995:** Rocket flights and Shuttle-deployed Spartan 201 laid groundwork.

- **1996–present:** Solar and Heliospheric Observatory (SOHO), with 12 instruments probing solar interior to outer heliosphere.

- The Ultraviolet Coronagraph Spectrometer (UVCS) measures plasma properties of coronal protons, ions, and electrons between 1.5 and 10 solar radii.

- **6th Solar-B Science Meeting**
  Kyoto, Japan, November 8–11, 2005

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**slit field of view:**

- Mirror motions select height
- Instrument rolls indep. of spacecraft
- 2 UV channels: LYA & OVI
- 1 white-light polarimetry channel
Several rotations of UVCS + EIT
Spectroscopic diagnostics

- Off-limb photons formed by both collisional excitation/de-excitation and resonant scattering of solar-disk photons.

- **Profile width** depends on **line-of-sight** component of velocity distribution (i.e., perp. temperature and projected component of wind flow speed).

- **Total intensity** depends on the **radial** component of velocity distribution (parallel temperature and main component of wind flow speed), as well as density.

- If atoms are flow in the same direction as incoming disk photons, “**Doppler dimming/pumping**” occurs.
UVCS results: solar minimum (1996-1997)

- Ultraviolet spectroscopy probes properties of ions in the wind’s acceleration region.
- In June 1996, the first measurements of heavy ion (e.g., O$^{+5}$) line emission in the extended corona revealed surprisingly wide line profiles . . .

On-disk profiles: $T = 1$–$3$ million K

Off-limb profiles: $T > 200$ million K !
Coronal holes: the impact of UVCS

UVCS/SOHO has led to new views of the acceleration regions of the solar wind. Key results include:

- The fast solar wind becomes **supersonic** much closer to the Sun (~2 \( R_s \)) than previously believed.
- In coronal holes, heavy ions (e.g., O\(^{+5}\)) both flow **faster** and are **heated** hundreds of times more strongly than protons and electrons, and have **anisotropic temperatures**. (e.g., Kohl et al. 1997, 1998)

\[
\begin{align*}
T_{\text{ion}} & \gg T_p > T_e \\
(T_{\text{ion}}/T_p) & > (m_{\text{ion}}/m_p) \\
T_{\perp} & \gg T_{||} \\
\bar{u}_{\text{ion}} & > \bar{u}_p
\end{align*}
\]

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Coronal holes: over the solar cycle

- Even though large coronal holes have similar outflow speeds at 1 AU (>600 km/s), their acceleration (in O⁺5) in the corona is different! (Miralles et al. 2001)

Solar minimum:

Solar maximum:

POLAR (1996)

EQUATORIAL (1999)
Coronal holes: over the solar cycle

- For many large coronal holes, the heavy ions show a strong correlation between perpendicular heating and wind speed:

\[ r = 2.5 R_{\text{sun}}, \, \text{O}^{5+} \]

**Ion cyclotron waves in the corona?**

- UVCS observations have **rekindled theoretical efforts** to understand heating and acceleration of the plasma in the (collisionless?) acceleration region of the wind.

- Ion cyclotron waves (10 to 10,000 Hz) suggested as a natural energy source that can be tapped to preferentially heat & accelerate heavy ions.

- Dissipation of these waves produces **diffusion** in velocity space along contours of ~constant energy in the frame moving with wave phase speed:

  Alfven wave’s oscillating E and B fields

  ion’s Larmor motion around radial B-field

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MHD turbulence

- It is highly likely that somewhere in the outer solar atmosphere the fluctuations become turbulent and cascade from large to small scales:

\[ E_{\text{out}} = \rho \frac{v_{\text{edd}}^3}{L_{\text{edd}}} \quad \sim \quad \sim \quad \sim \quad Q_{\text{heat}} \approx E_{\text{out}} \]

- With a strong background field, it is easier to mix field lines (perp. to \( B \)) than it is to bend them (parallel to \( B \)).

- Also, the energy transport along the field is far from isotropic:

\[ Q_{\text{heat}} = \rho \frac{\langle Z_- \rangle^2 \langle Z_+ \rangle + \langle Z_+ \rangle^2 \langle Z_- \rangle}{4 L_\perp} \]

(e.g., Dmitruk et al. 2002)

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**But does turbulence generate cyclotron waves?**

- Preliminary models say **“probably not”** in the extended corona. (At least not in a straightforward way!)

**How then are the ions heated & accelerated?**

- Impulsive plasma **micro-instabilities** that locally generate high-freq. waves (Markovskii 2004)?
- Non-linear/non-adiabatic KAW-particle effects (Voitenko & Goossens 2004)?
- Larmor “spinup” in dissipation-scale **current sheets** (Dmitruk et al. 2004)?
- KAW damping leads to electron beams, further (Langmuir) turbulence, and Debye-scale **electron phase space holes**, which heat ions perpendicularly via “collisions” (Ergun et al. 1999; Cranmer & van Ballegooijen 2003)?

MHD turbulence ➞ something else? ➞ cyclotron resonance-like phenomena
Streamers: open and/or closed?

- **High-speed wind:** strong connections to the largest coronal holes

- **Low-speed wind:** still no agreement on the full range of coronal sources:
  - hole/streamer boundary (streamer “edge”)
  - streamer plasma sheet (“cusp/stalk”)
  - small coronal holes
  - active regions (some with streamer cusps)
Streamers viewed “edge-on” look different in H⁰ and O⁺5

- Ion abundance depletion in “core” due to grav. settling?

- Brightest “legs” show negligible outflow, but abundances consistent with in situ slow wind.

- Higher latitudes and upper “stalk” show definite flows (Strachan et al. 2002).

- Stalk also has preferential ion heating & anisotropy, like coronal holes! (Frazin et al. 2003)
Why is the fast/slow wind fast/slow?

- Several ideas exist; one powerful one relates flux tube expansion to wind speed (Wang & Sheeley 1990). Physically, the geometry determines location of Parker critical point, which determines how the “available” heating affects the plasma:

  - MHD turbulence heating rates give temperatures consistent with UVCS & in situ.
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Coronal mass ejections (CMEs) are an efficient way for the Sun to shed twisted magnetic fields (and net helicity?) and generated solar energetic particles (SEPs).

Coronagraph images contain much information, but **spectroscopy** also provides:

- Heating rates and energy budget (DEM)
- 3D velocity field & chirality; twisting/unwinding rates
- conditions in **shocks** (preferential ion accel.)
- conditions in **current sheets** (reconnection rates)
UVCS CME results: Doppler shifts

Feb. 12, 2000

LASCO
UVCS
H I Lyα

Intensity Width Shift
(Lyman alpha) April 18, 2000

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UVCS CME results: Shock physics

- Passage of a shock through the UVCS slit is identifiable (unambiguously!):
  - “Hot” ion intensities increase & broad components appear
  - “Cooler” lines rapidly Doppler dim
  - Immediate change in $T$ equilibration!

Shock strengths derived by:
(1) Type II radio burst band-splitting
(2) Ly-alpha adiabatic compression
(3) Ion heating (Lee & Wu 2000)
are all consistent with one another!
UVCS CME results: Reconnection physics

- On several occasions, narrow brightening in Fe XVIII ($T_e \sim 6$ MK) appears in the probable location of a current sheet.
- Lin et al. (2005) also saw Lyman alpha “closing down” in the sheet: one can measure reconnection rate ($V_{in} / V_{out}$)

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Conclusions

- Ultraviolet coronagraph spectroscopy has led to fundamentally new views of the acceleration regions of the solar wind and CMEs.

- The surprisingly extreme plasma conditions in coronal holes (e.g., $T_{\text{ion}} \gg T_p > T_e$) have guided theorists to discard some candidate processes, further investigate others, and have cross-fertilized other areas of plasma physics.

- Upcoming missions like Solar-B will help build a more complete picture, but it won’t be complete without a next-generation “UVCS-B” and “LASCO-B” . . . !

For more information: http://cfa-www.harvard.edu/uvcs/