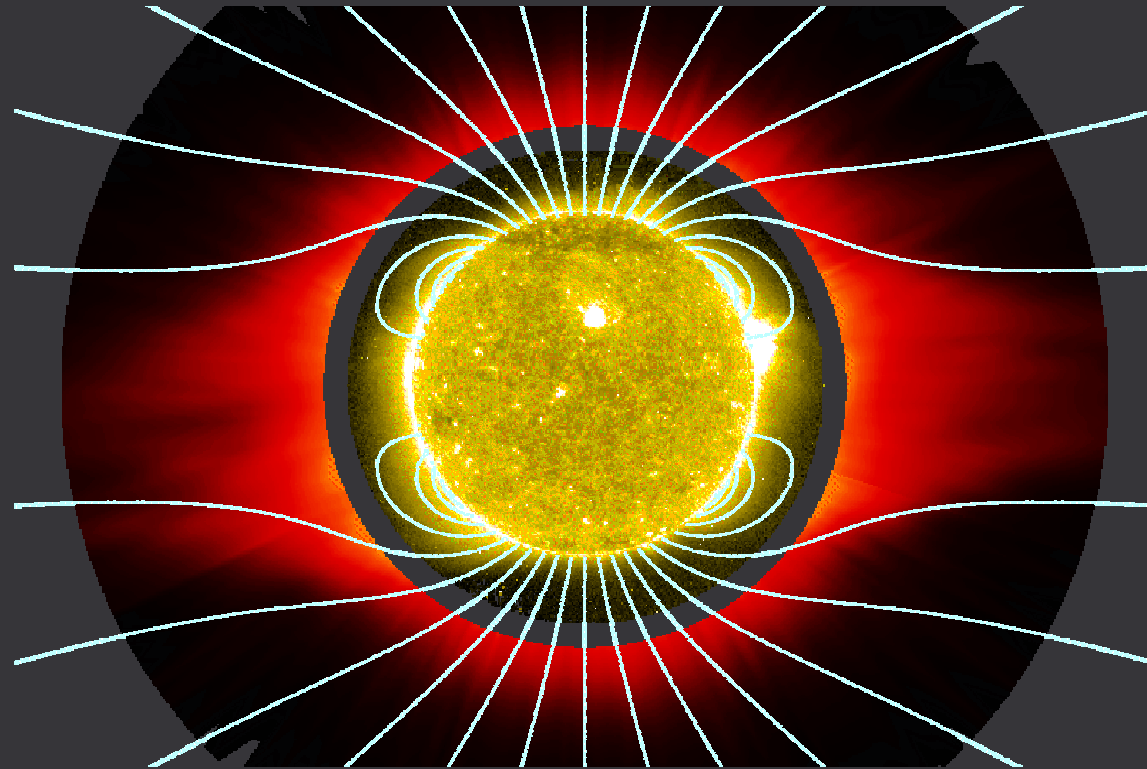


UVCS Observations of the Solar Wind and its Modeling



Steven R. Cranmer and the UVCS/SOHO Team

Harvard-Smithsonian Center for Astrophysics



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!)

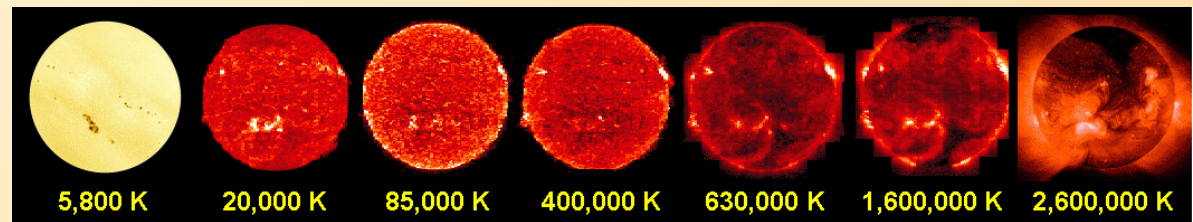


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The need for both solar-disk & coronagraph observations

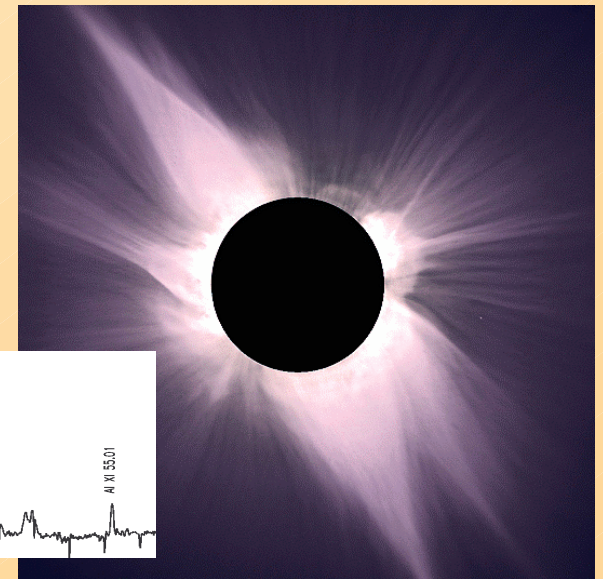
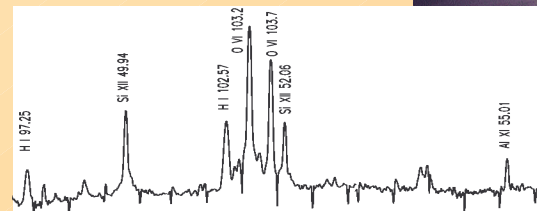
- On-disk measurements help reveal **basal** coronal heating & lower boundary conditions for solar wind.



- 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.

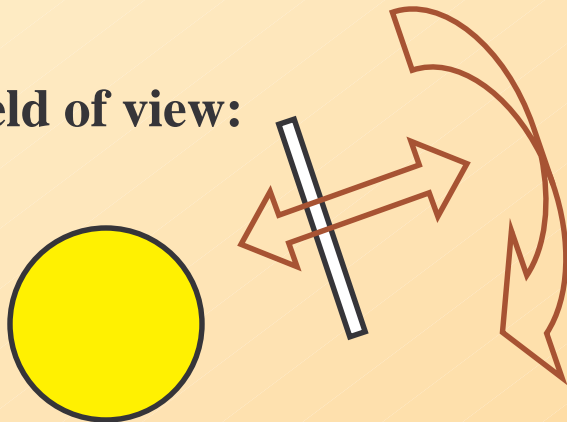


UVCS / SOHO

- **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.



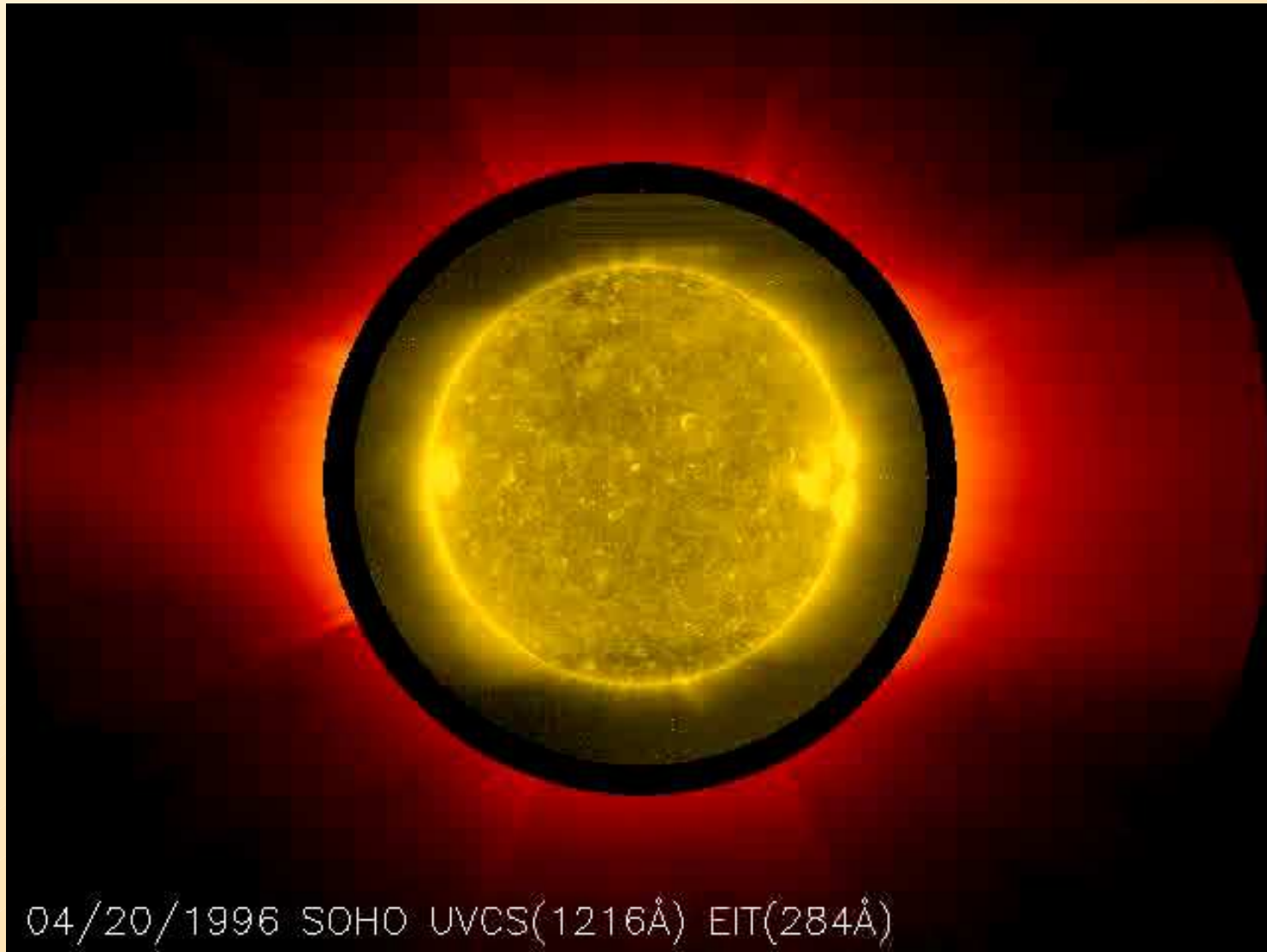
slit field of view:



- Mirror motions select height
- Instrument rolls indep. of spacecraft
- 2 UV channels: LYA & OVI
- 1 white-light polarimetry channel



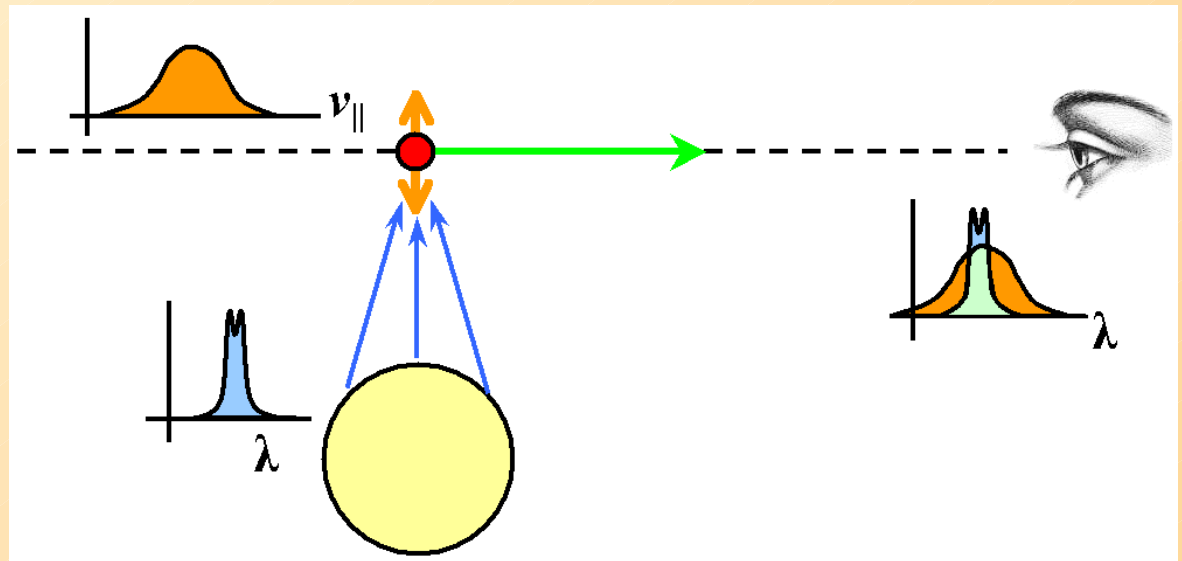
Several rotations of UVCS + EIT



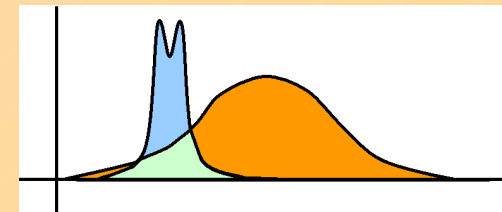
Spectroscopic diagnostics

- 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.

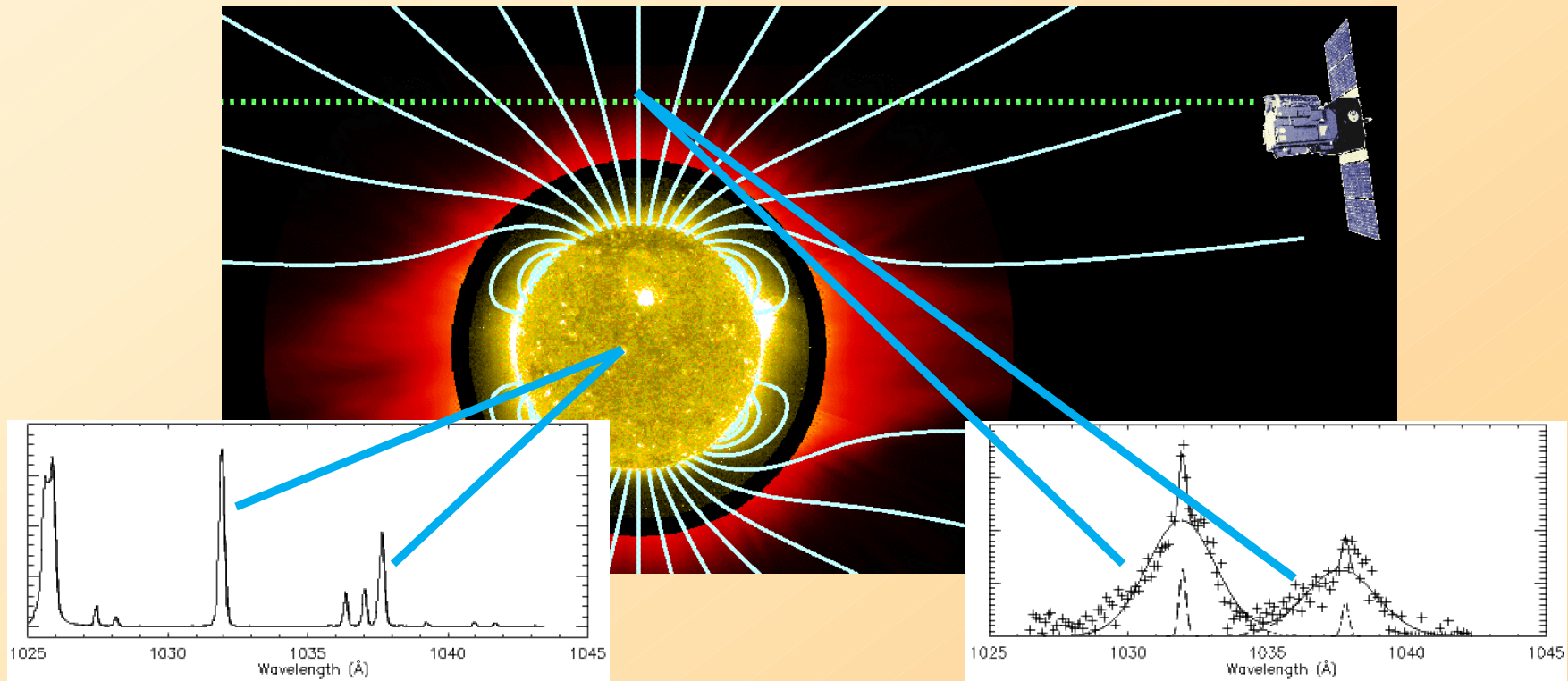


- If atoms flow in the same direction as incoming disk photons, “**Doppler dimming/pumping**” occurs.



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: $T = 1\text{--}3$ million K

Off-limb profiles: **$T > 200$ million K !**

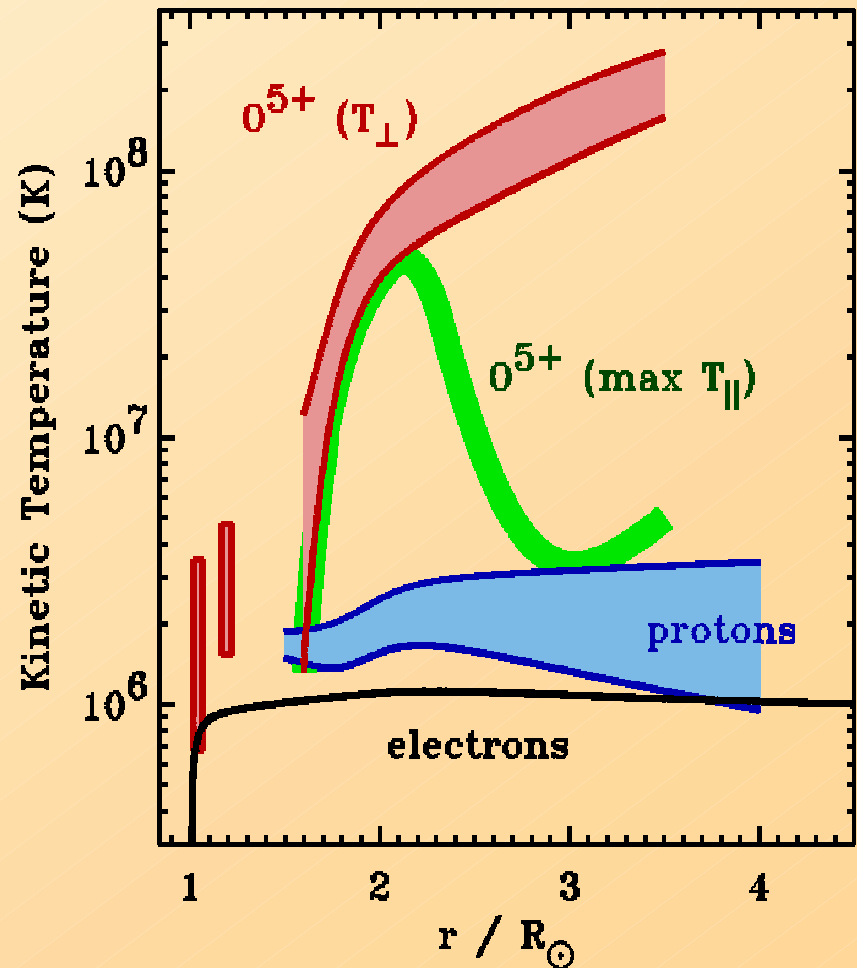


Coronal holes: the impact of UVCS

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 ($\sim 2 R_s$) 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)

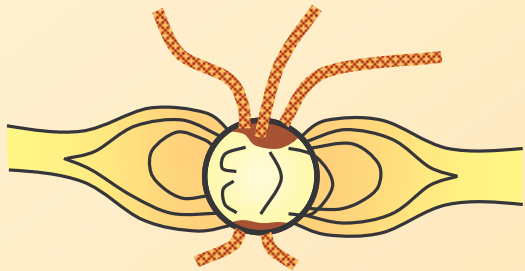
$$\left\{ \begin{array}{l} T_{\text{ion}} \gg T_p > T_e \\ (T_{\text{ion}}/T_p) > (m_{\text{ion}}/m_p) \\ T_{\perp} \gg T_{\parallel} \\ u_{\text{ion}} > u_p \end{array} \right\}$$



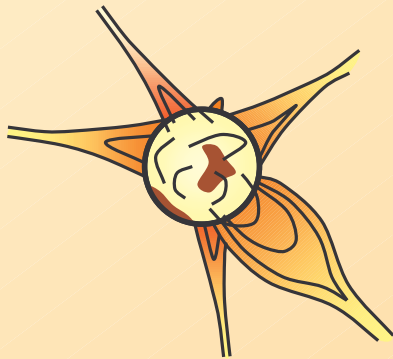
Coronal holes: over the solar cycle

- 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)

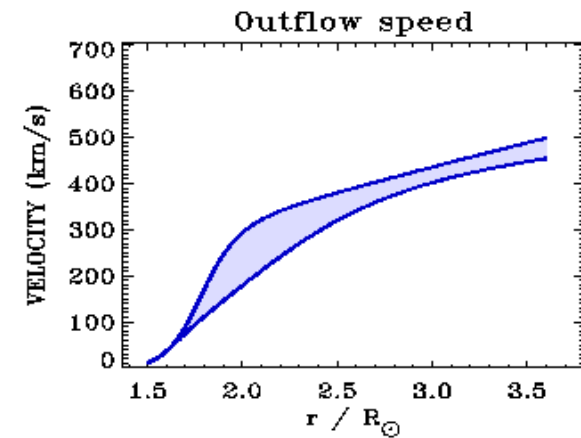
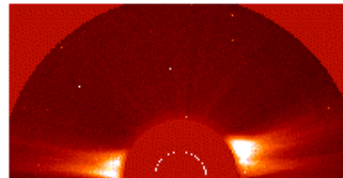
Solar minimum:



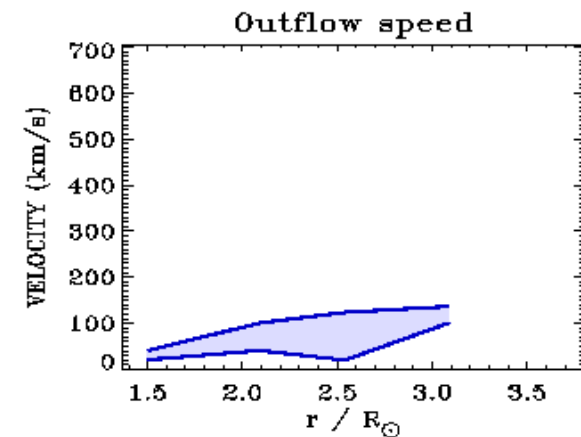
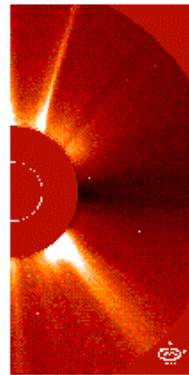
Solar maximum:



POLAR (1996)

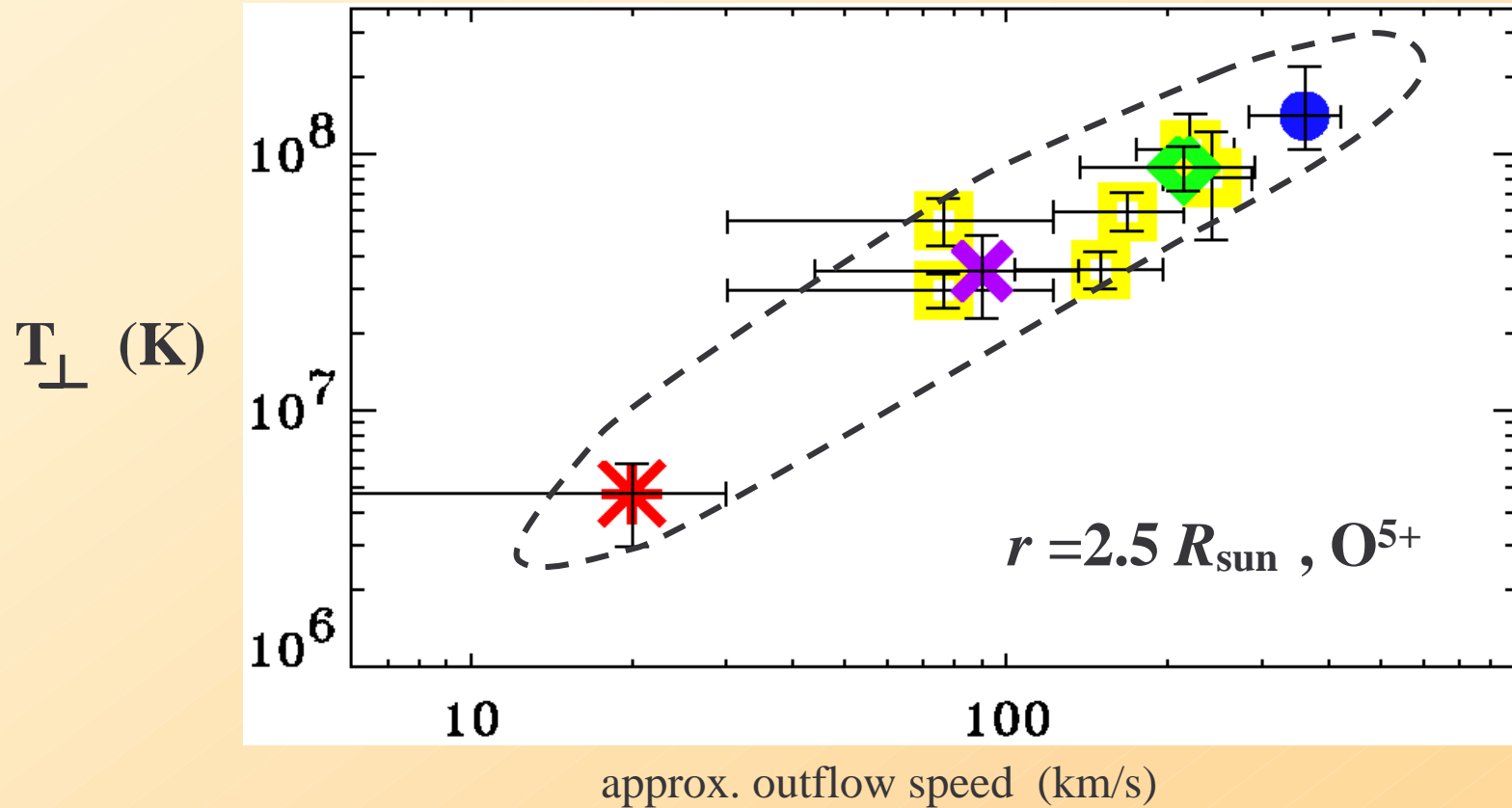


EQUATORIAL (1999)



Coronal holes: over the solar cycle

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

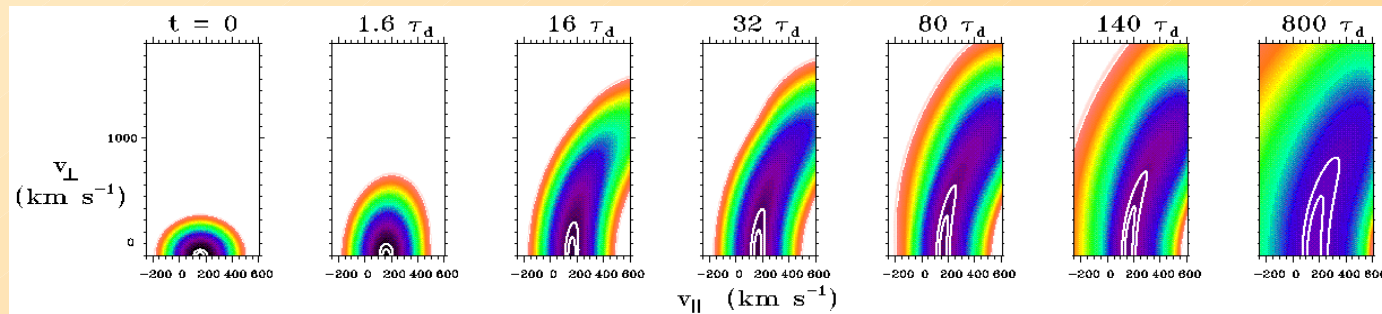
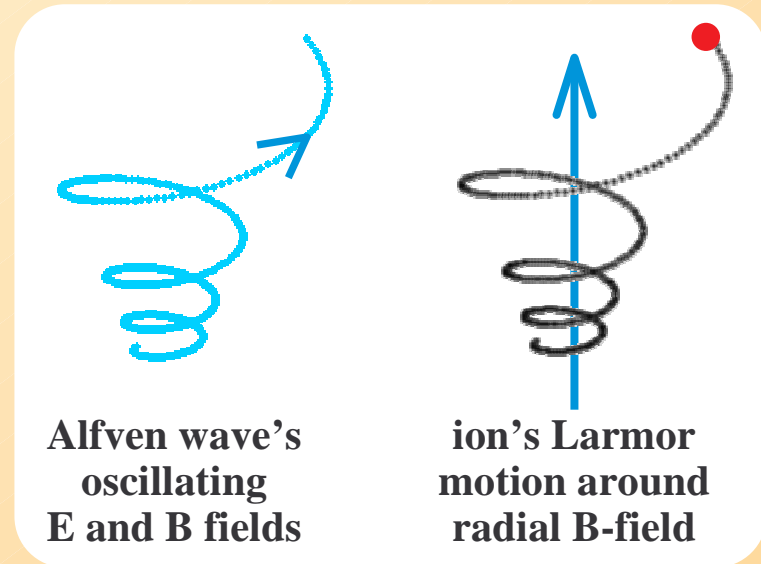


Key: **streamer legs**, **polar CH** (1996), **high-latitude CH** (2001), **equatorial CH** (1999), **mid-latitude CHs** (1999-2002)



Ion cyclotron waves in the corona?

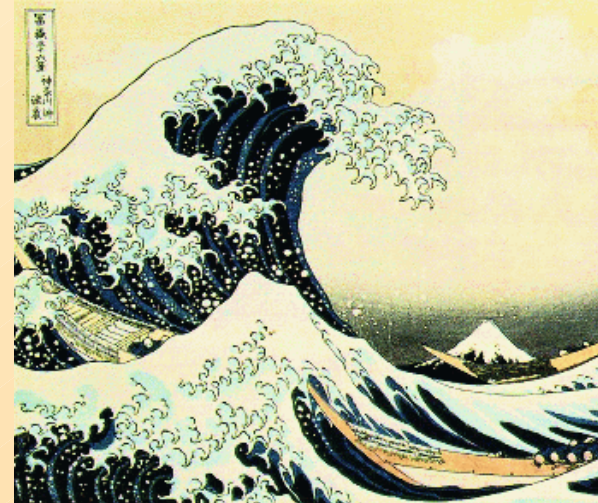
- UVCS observations have **rekindled theoretical efforts** to understand heating and acceleration of the plasma in the (collisionless?) acceleration region of the wind.
- Ion cyclotron waves (10 to 10,000 Hz) suggested as a natural energy source that can be tapped to preferentially heat & accelerate heavy ions.
- Dissipation of these waves produces **diffusion** in velocity space along contours of \sim constant energy in the frame moving with wave phase speed:



MHD turbulence

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

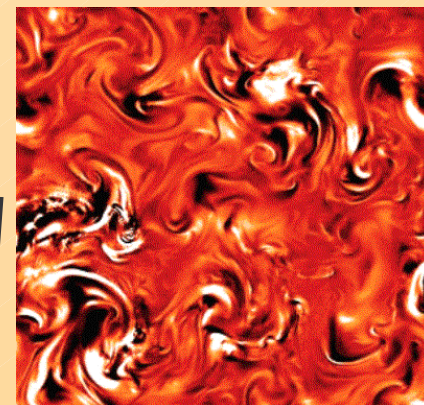
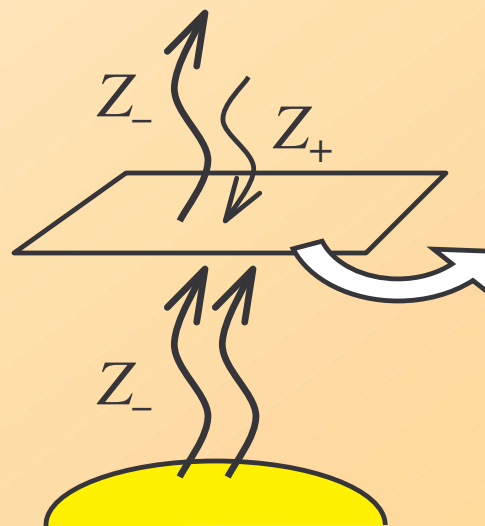
$$\mathcal{E}_{\text{out}} = \frac{\rho v_{\text{eddy}}^3}{l_{\text{eddy}}} \rightsquigarrow \rightsquigarrow \rightsquigarrow Q_{\text{heat}} \approx \mathcal{E}_{\text{out}}$$



- With a strong background field, it is easier to **mix** field lines (perp. to \mathbf{B}) than it is to **bend** them (parallel to \mathbf{B}).
- Also, the energy transport along the field is far from isotropic:

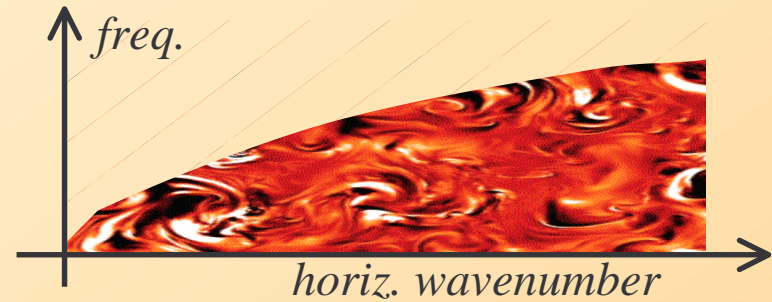
$$Q_{\text{heat}} = \rho \frac{\langle Z_- \rangle^2 \langle Z_+ \rangle + \langle Z_+ \rangle^2 \langle Z_- \rangle}{4L_{\perp}}$$

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



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)?

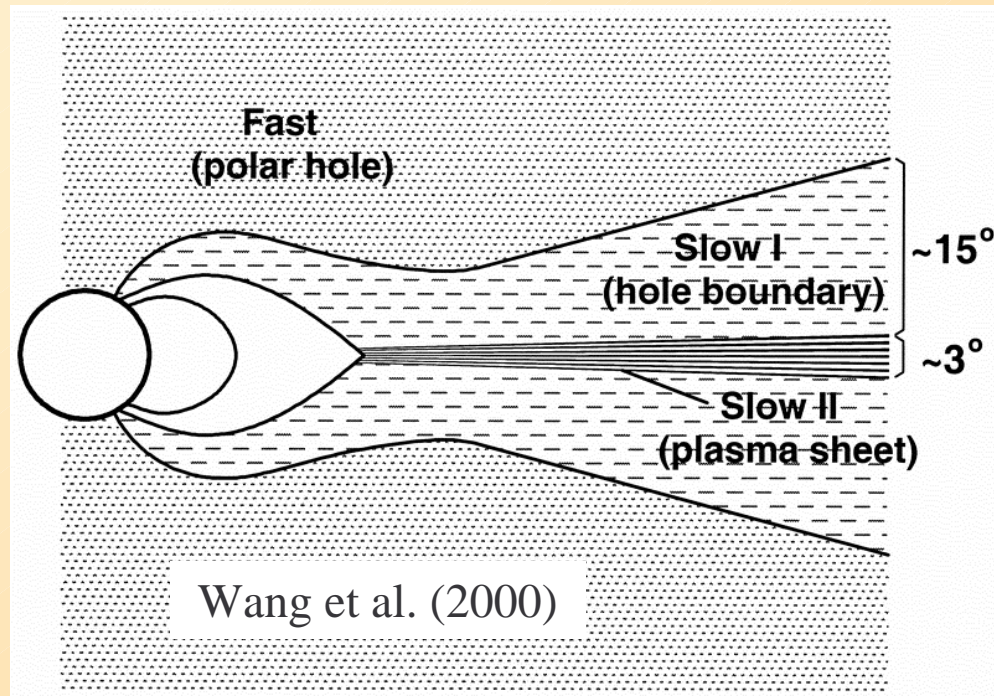
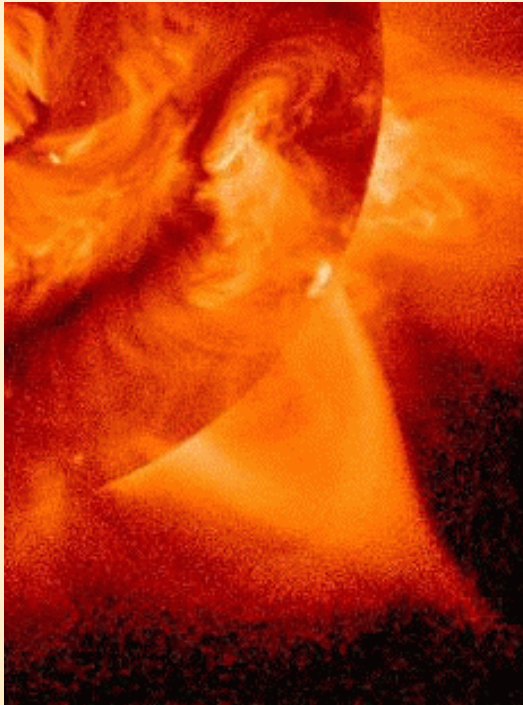
MHD turbulence



cyclotron resonance-like phenomena



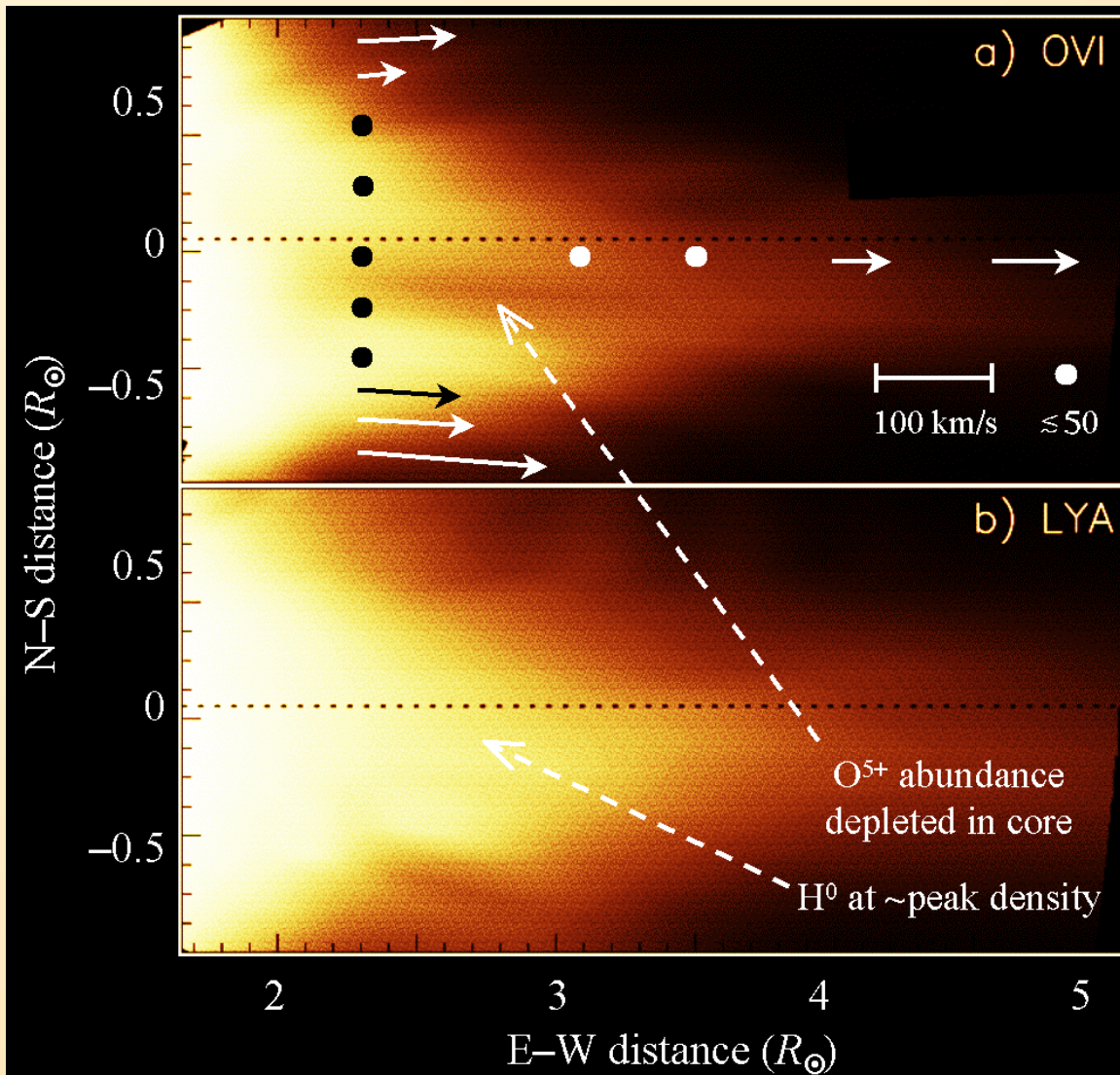
Streamers: open and/or closed?



- **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 with UVCS

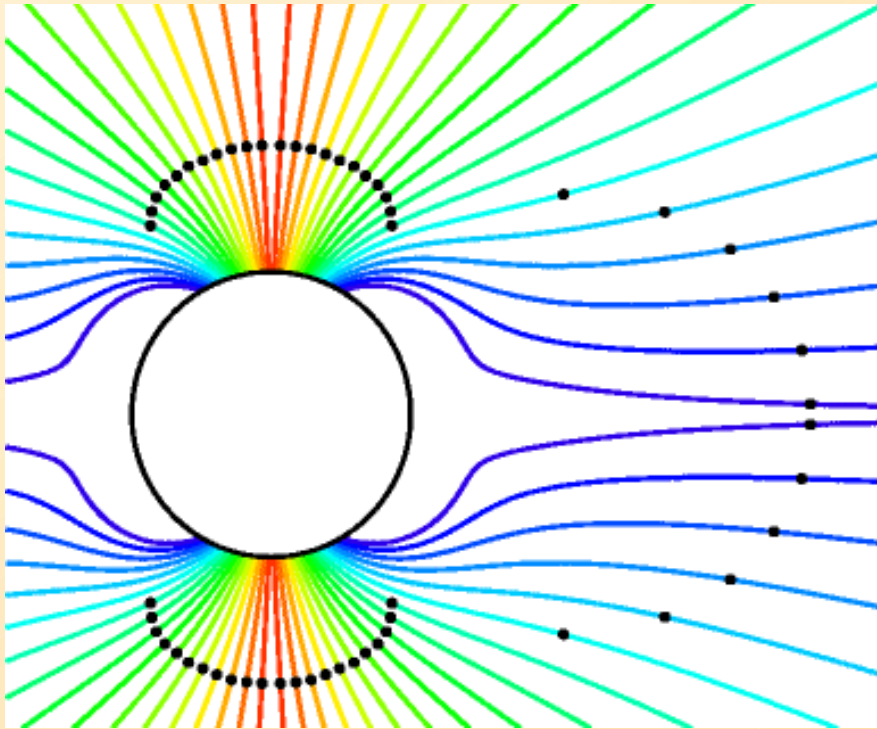


- Streamers viewed “edge-on” look different in H^0 and O^{5+}
- Ion abundance depletion in “**core**” due to grav. settling?
- Brightest “**legs**” show negligible outflow, but abundances consistent with *in situ* slow wind.
- Higher latitudes and upper “**stalk**” show definite flows (Strachan et al. 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:



SUPERSONIC coronal heating:
subsonic region is unaffected.
Energy flux has nowhere else to
go:

$$\dot{M} \text{ same, } u \uparrow$$

VS.

SUBSONIC coronal heating:
“puffs up” scale height, draws
more particles into wind:

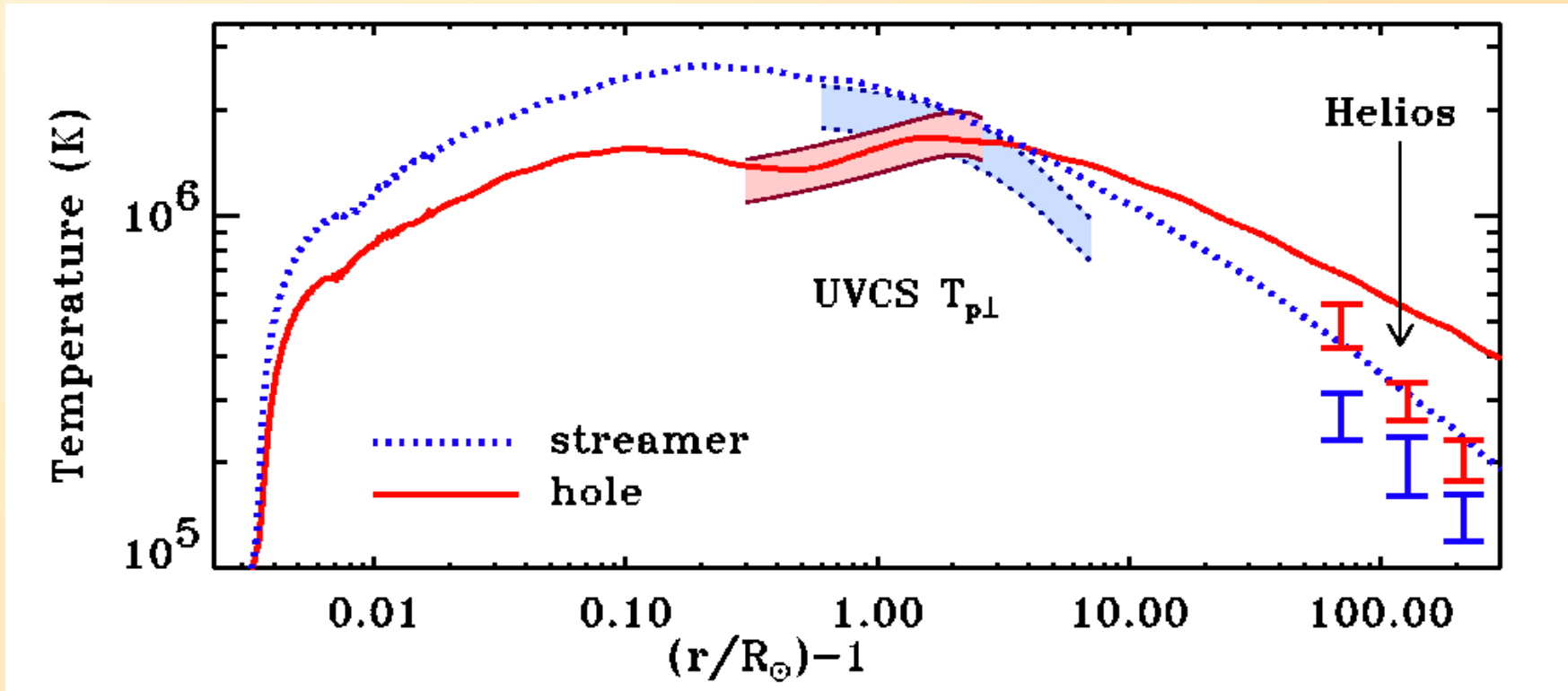
$$\dot{M} \uparrow \quad u \downarrow$$

- MHD turbulence heating rates give temperatures consistent with UVCS & *in situ*.



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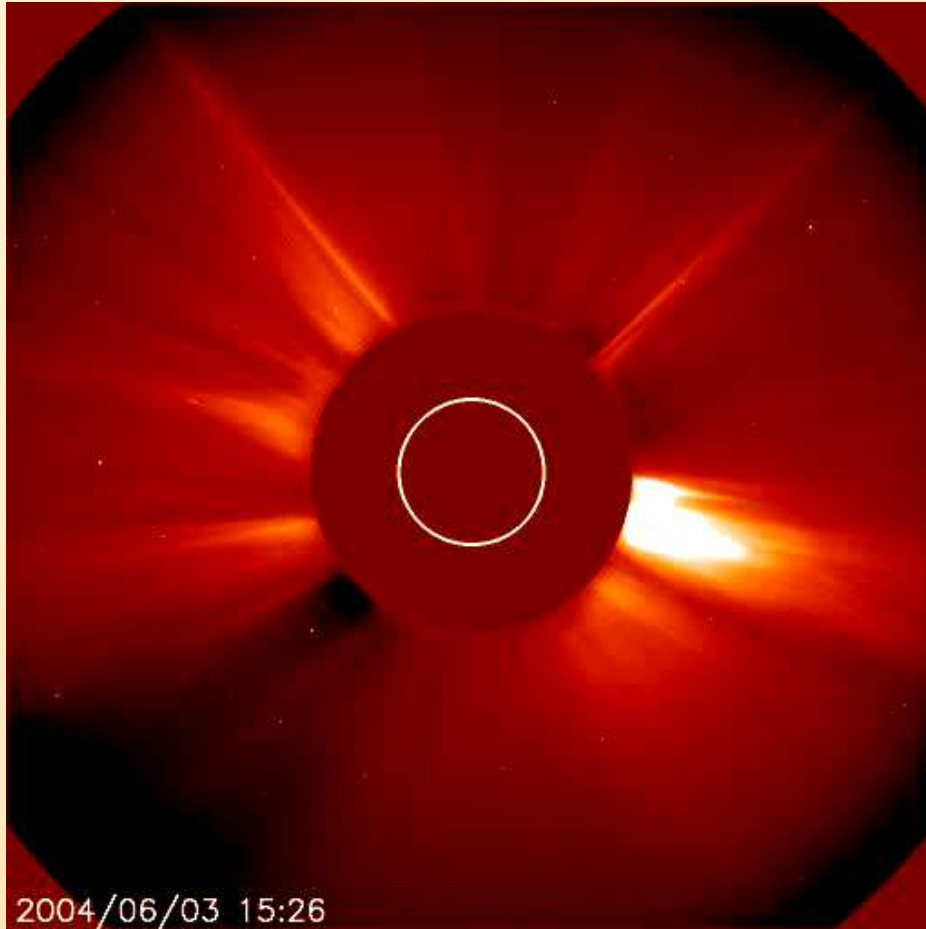


- MHD turbulence heating rates give temperatures consistent with UVCS & *in situ*.



CMEs

- 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).

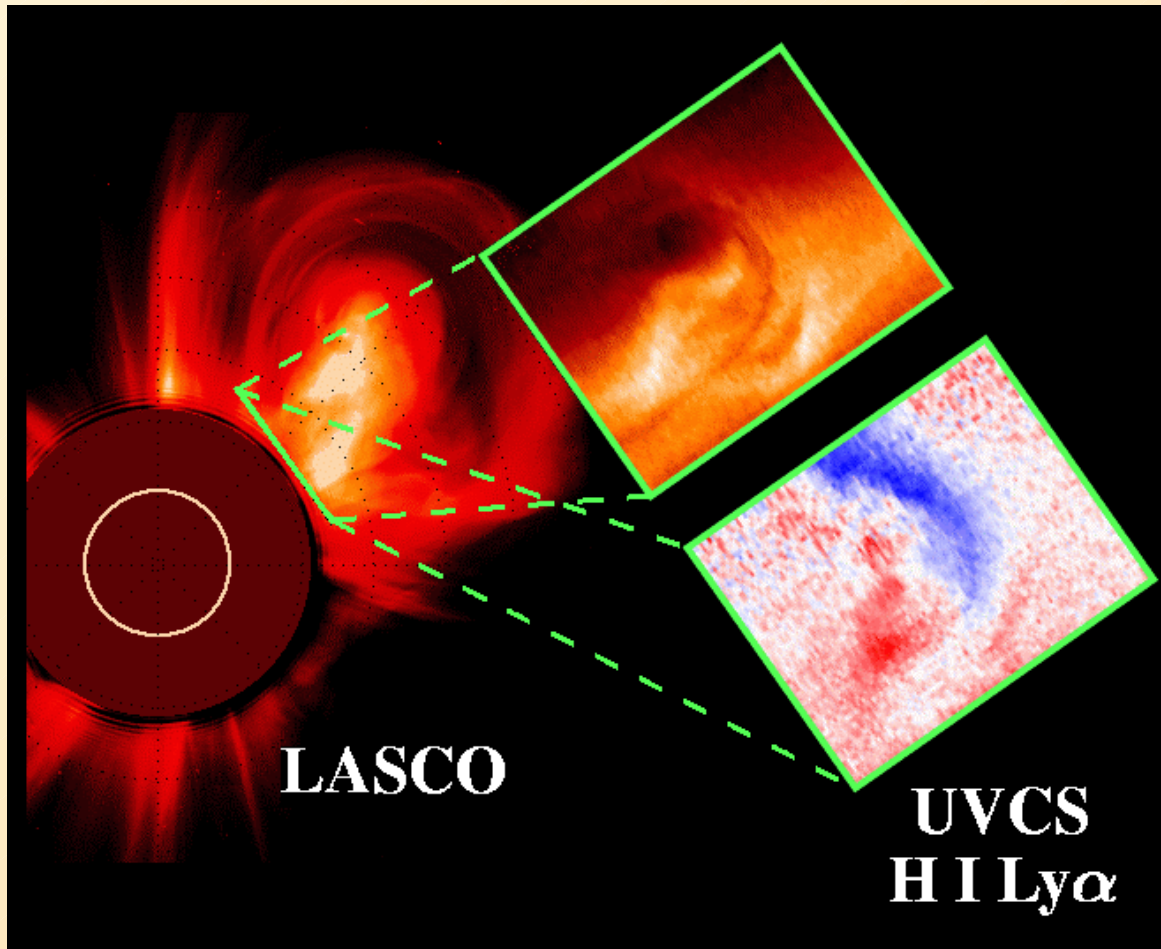


Coronagraph images contain much information, but **spectroscopy** also provides:

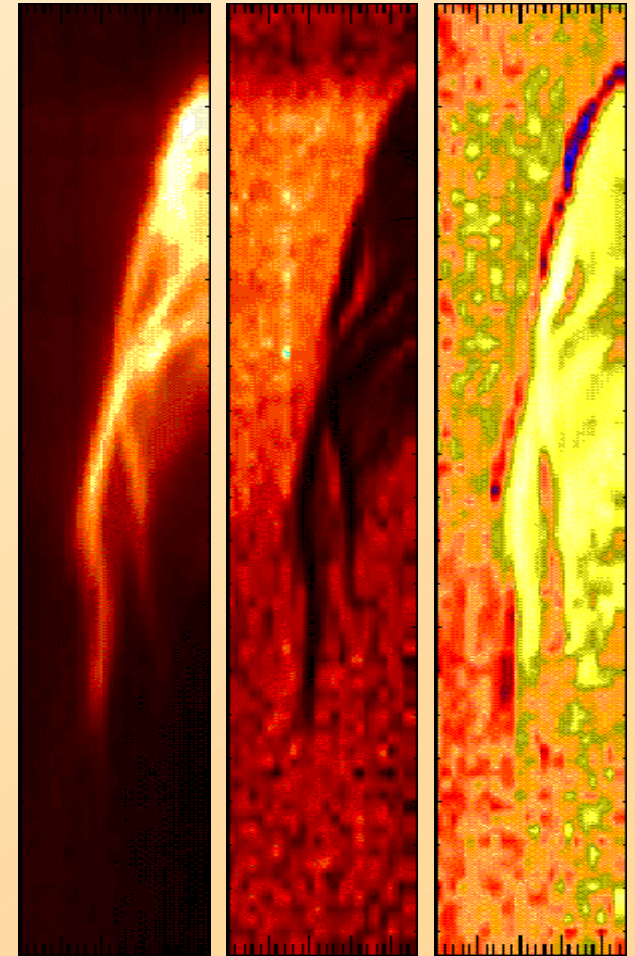
- Heating rates and energy budget (DEM)
- 3D velocity field & chirality; twisting/unwisting rates
- conditions in **shocks** (preferential ion accel.)
- conditions in **current sheets** (reconnection rates)



UVCS CME results: Doppler shifts



Feb. 12, 2000



Intensity **Width** **Shift**
(Lyman alpha) **April 18, 2000**

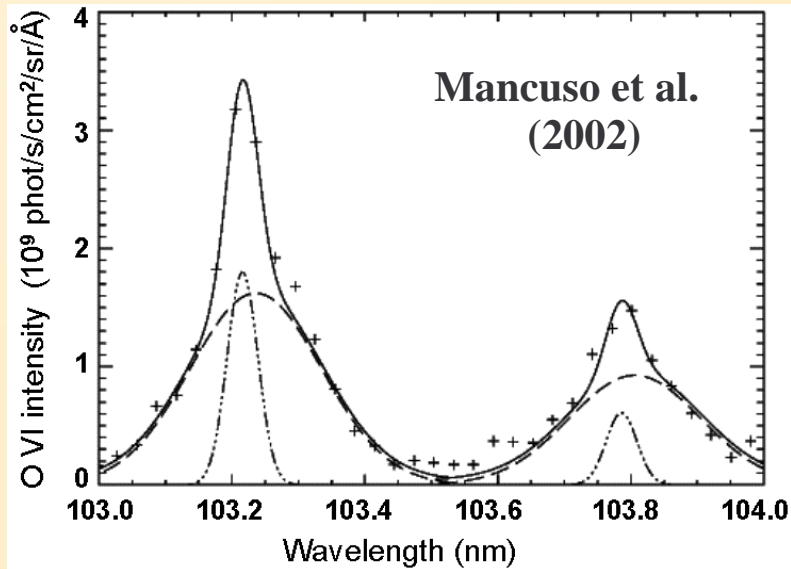


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6th Solar-B Science Meeting
Kyoto, Japan, November 8–11, 2005

UVCS CME results: Shock physics

- Passage of a shock through the UVCS slit is identifiable (unambiguously!):

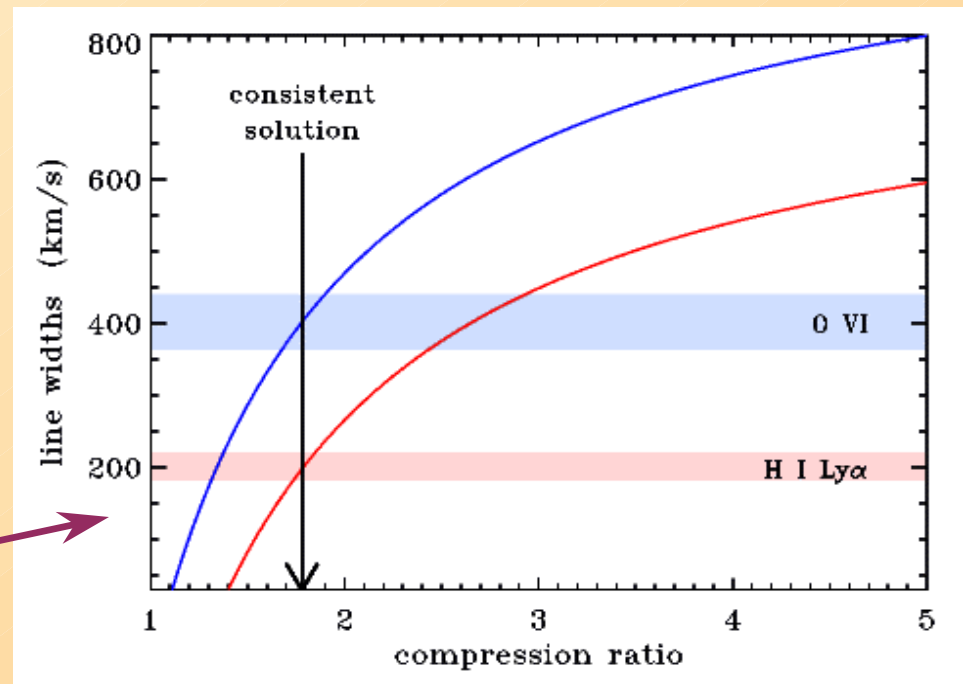


- “Hot” ion intensities increase & broad components appear
- “Cooler” lines rapidly Doppler dim
- Immediate change in T equilibration!

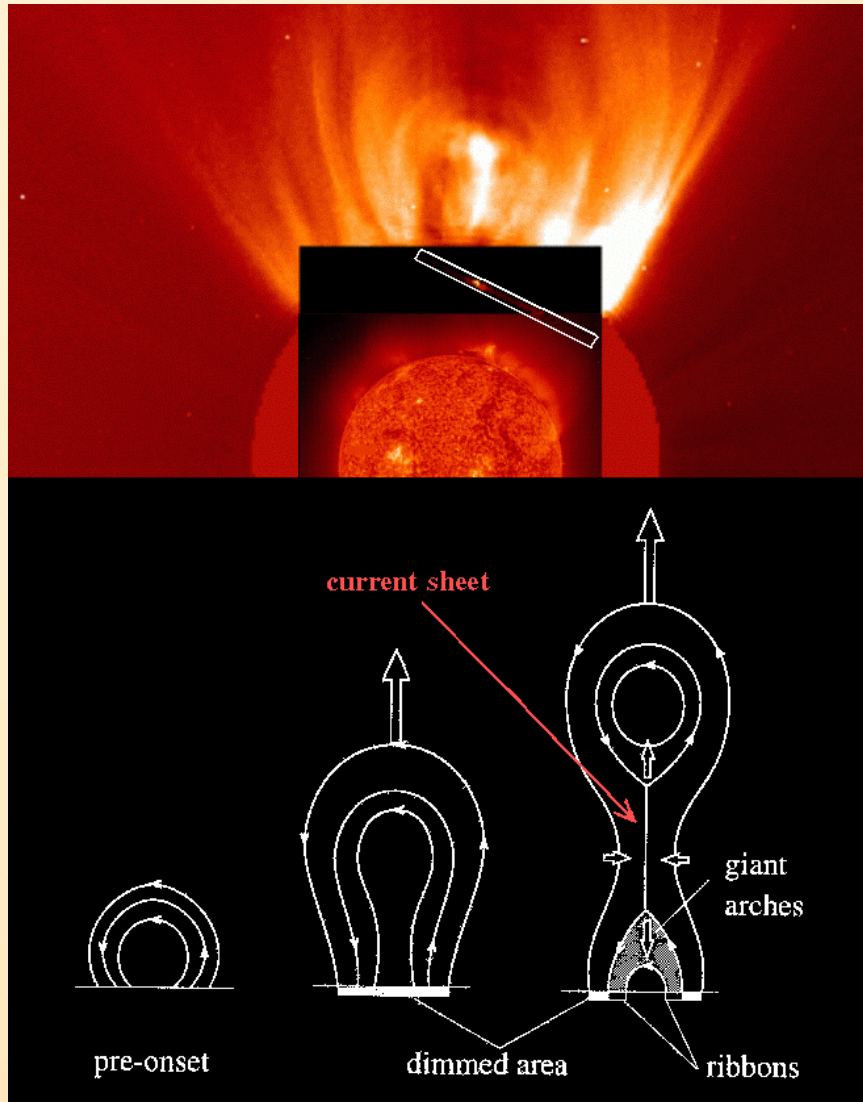
Shock strengths derived by:

- (1) Type II radio burst band-splitting
- (2) Ly-alpha adiabatic compression
- (3) Ion heating (Lee & Wu 2000)

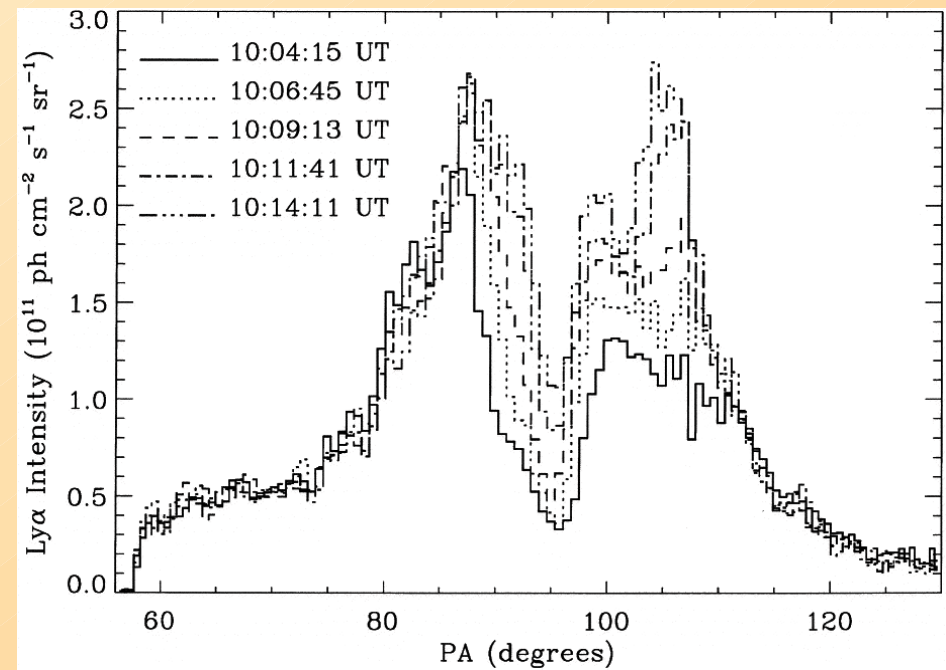
are all consistent with one another!



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})



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., $T_{\text{ion}} \gg T_{\text{p}} > T_{\text{e}}$) 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” . . . !**

More plasma diagnostics



Better understanding!



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

