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Next Generation Ultraviolet Spectroscopy of the Extended Solar Corona: Plasma Diagnostics & Physical Processes

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- Background: history, top-level goals
- Next-generation instrumentation ⟶ diagnostics
- New constraints on physics:
  - ⟶ **high-speed wind** (proton driving)
  - ⟶ **low-speed wind** (flux tube origins)
  - ⟶ **CMEs** (current sheet reconnection)

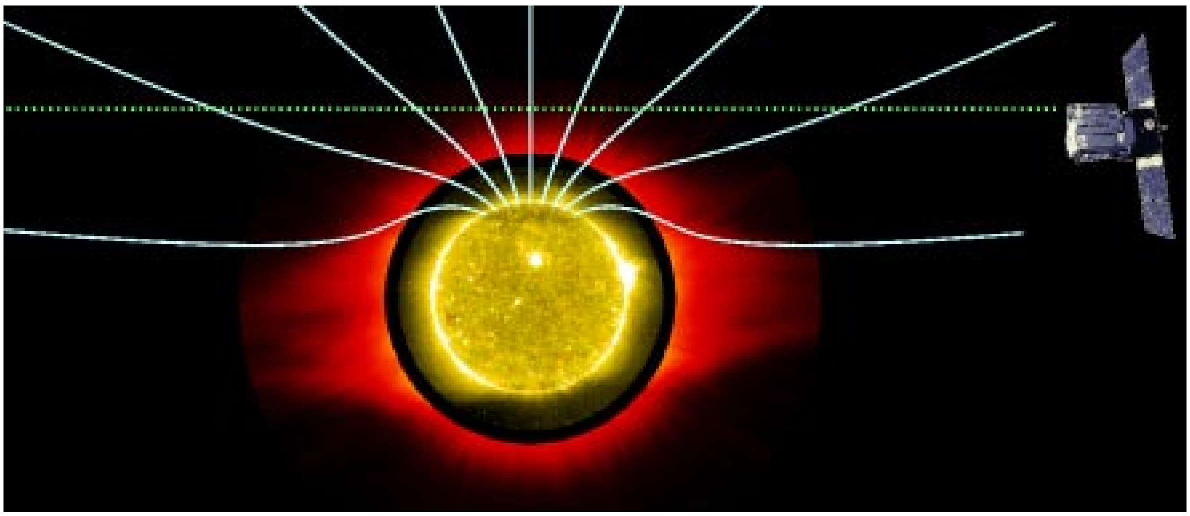
This presentation is on the Web at:

http://cfa–www.harvard.edu/∼scranmer/cssp_cranmer.html

Ultraviolet Coronagraph Spectroscopy

⋆ **Motivation:** measure the plasma properties of protons, electrons, and ions in the **acceleration region** of the solar wind.

1979–1995: H I Lyα measured with rockets, Spartan 201
1996–present: dozens of lines measured with UVCS/SOHO



The energy for coronal heating and wind acceleration all comes from the coronal **base,** *but:*

⇒ per particle, the proton heating at 2–4 $R_\odot$ is of the same order of magnitude as that just above the transition region;

⇒ only the deposition in the extended corona determines the *local* plasma properties and whether the wind will be fast or slow;

⇒ the properties in interplanetary space depend crucially on what happens in the acceleration region.

⋆ Occultation of the solar disk is required because the extended corona is **6** to **10** orders of magnitude less bright than the disk.

Plasma Diagnostics in the Extended Corona

collisionally excited line intensities (ratios)	• abundances, ionization state • electron density & temperature
resonantly scattered line intensities (ratios)	• velocity distributions in sunward direction ($T_{\parallel}$, $u_{\parallel}$)
spectral line shapes	• proton, ion, electron velocity distributions along line of sight ($T_{\perp}$) • departures from Maxwellians
Doppler shifts	• bulk motions along line of sight • chirality of helical flux tubes
visible polarimetry	• electron density, morphology
EUV spectropolarimetry	• velocity distribution anisotropies & flux tube orientation • magnetic field strength

Summary of UVCS/SOHO Results

Fast solar wind:

★ Heavy ions are far from thermal equilibrium, and are probably heated and accelerated by dissipation of ion cyclotron waves.

$$\left\{ \begin{array}{c} T_{\rm ion} \gg T_p > T_e \\ T_\perp > T_\parallel \\ u_{\rm ion} > u_p \end{array} \right\}$$

Slow solar wind:

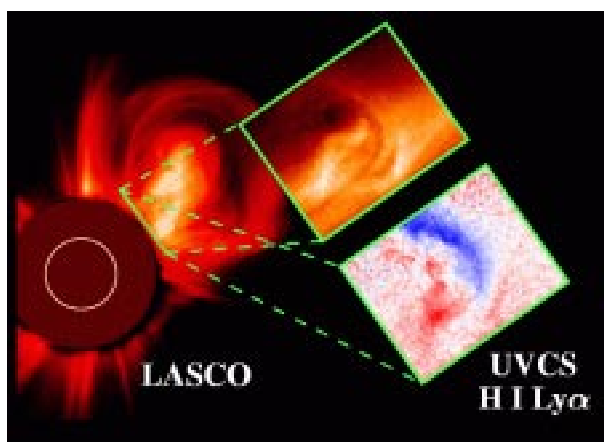
★ Ion abundances along **edges** of streamers agree with *in situ* slow wind values. Streamer **cores** are depleted, probably by gravitational settling.

★ Streamer plasma $\beta \gtrsim 1$, but at solar minimum streamers are ∼stable over several month time scales.

Coronal mass ejections (CMEs):

★ UVCS has identified ∼200 CMEs since 1996. Measured properties include:

- → thermal energy content
- → untwisting rates, chirality
- → shock front properties
- → current sheet temperatures
- → abundances and ionization
- → morphology differences as $T_e = 10^5 \rightarrow 10^7$ K



Top-level Scientific Goal

To achieve a fundamental understanding of the physical processes that

- **heat the corona (base $\longrightarrow$ extended)**
- **accelerate the solar wind**
- **produce CMEs**

Spectroscopy and polarimetry provide a **detailed empirical description** of the plasma that is required to identify the physical processes.

Major Science Questions

Fast solar wind:

- ★ **Do ion cyclotron waves heat and accelerate protons and helium?**
- ★ **Which wave modes are generated and damped (where & how)?**

Slow solar wind:

- ★ **What is the relative contribution from: (1) coronal hole boundary flow, and (2) transient closed-field eruptions?**
- ★ **What are the roles of high & low frequency waves?**

Coronal mass ejections (CMEs):

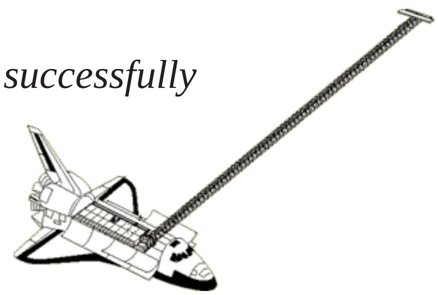
- ★ **What processes convert stored magnetic energy into heating and acceleration in the extended corona?**
- ★ **Does the chirality and geometry measured by spectroscopy determine the helicity and geoeffectiveness near the Earth?**
- ★ **Is the helicity removed from the Sun by CMEs consistent with the rate of helicity generation by the solar dynamo?**

Next Generation Instrumentation

Two key improvements over UVCS/SOHO can be made:

⋆ **Remote external occulter:** reduces stray light from the solar disk and increases the illuminated mirror area. Sensitivity increases by 1–2 orders of magnitude.

A 60 meter deployable boom was tested successfully in February 2000 on STS–99:



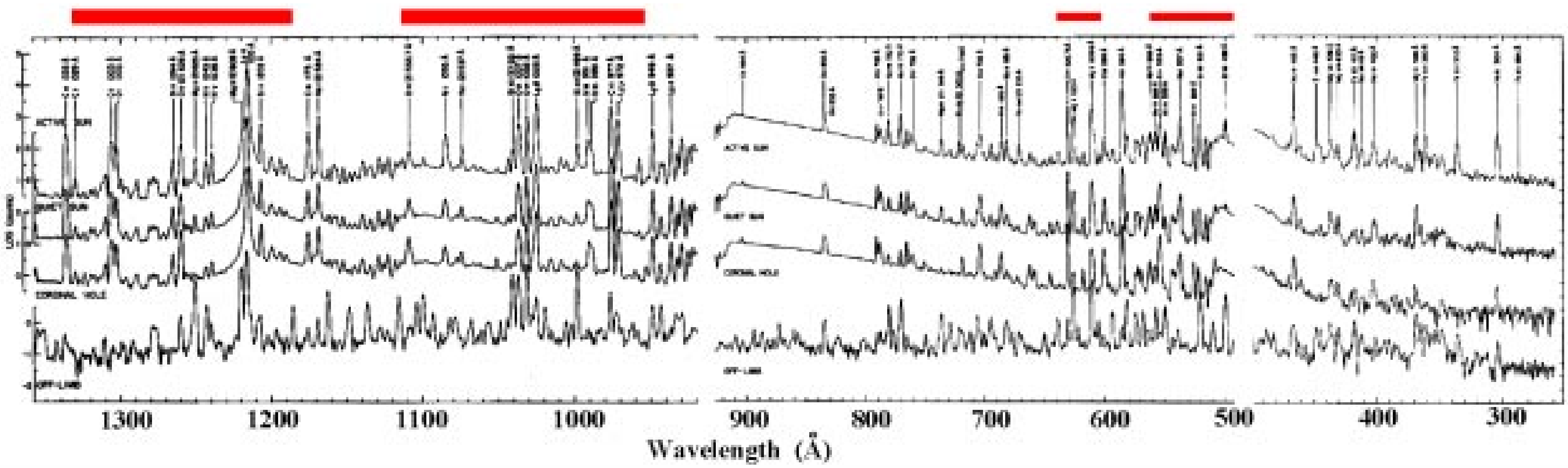
⋆ **Extended wavelength range:** (downward in λ by a factor of two from UVCS) adds dozens more lines of ion species never observed in the extended corona.

⇒ He II 304 Å and He I 584 Å (full range of observable ionization)

⇒ Z/A (charge/mass ratio) range extends to 0.1–1 in coronal holes

Increased Sensitivity $\rightarrow$ More Spectral Lines

UVCS range:



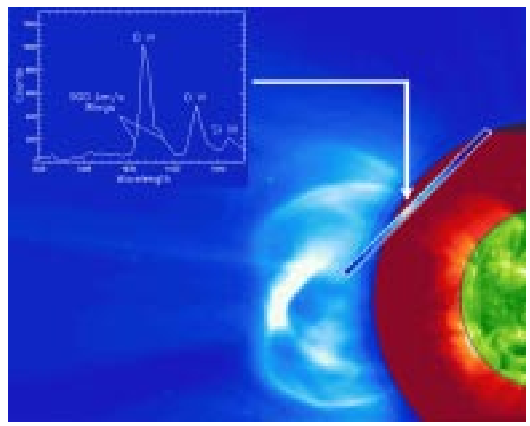
(Vernazza & Reeves 1978)

- ⋆ Ions in the **collisionless** extended corona exhibit unequal outflow speeds, temperatures, and kinetic anisotropies.
- ⋆ CMEs contain plasma with T_e ranging over 2–3 orders of magnitude.

Synergy between UV and Visible Observations

The **combination** of ultraviolet spectroscopy with visible-light imaging, polarimetry, and spectroscopy results in much-improved diagnostic power.

Improvements in UV sensitivity, spatial resolution, and time resolution should be matched by improvements in visible-light capabilities . . .

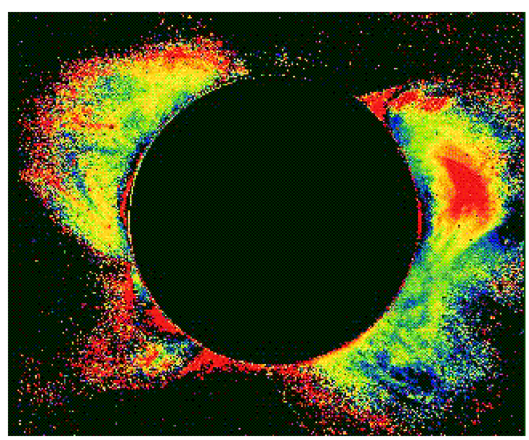


- ⇒ Imaging provides crucial context about the geometry of coronal structures.

  (e.g., shock identification in CMEs)

- ⇒ Imaging also provides the time evolution and large-scale dynamical behavior.

- ⇒ Electron density (line-integrated vs. local; $< n_e^2 > / < n_e >^2$)



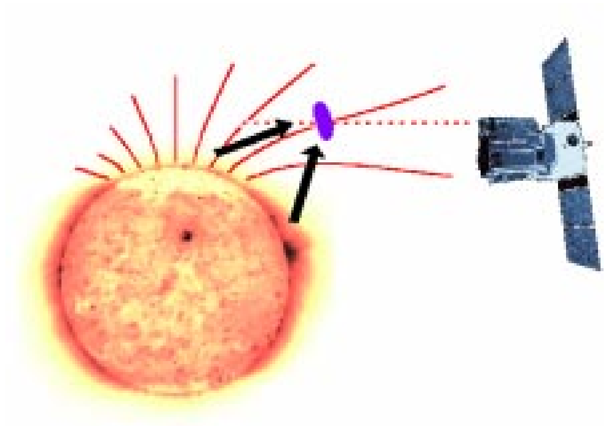
- ⇒ Fabry-Perot spectroscopy provides properties of ions inaccessible in the ultraviolet.

  (e.g., [Fe X], [Fe XIV])

- ⇒ Spectral lines scanned in λ over a large simultaneous field of view.

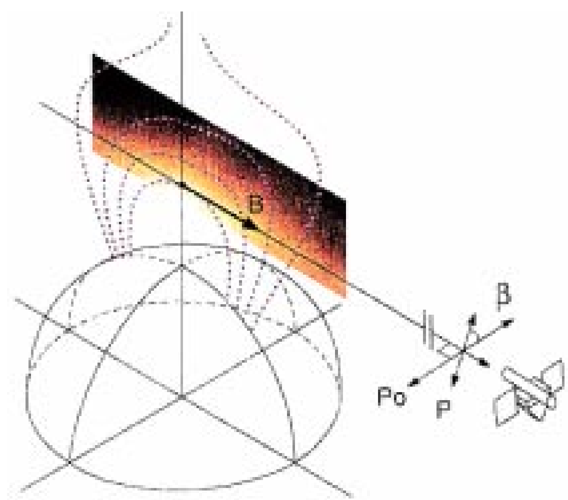
New Diagnostics: EUV Spectropolarimetry

Measuring the **linear polarization** of emission lines in the extended corona provides:



⇒ Constraints on the ion temperature anisotropy and **nonradial** flux tube orientation ($r \lesssim 3\,R_\odot$).

(Fineschi et al. 2001, in prep.)



⇒ Constraints on the **magnetic field** strength ($\gtrsim$ 1 G) and geometry in streamers and pre-CME flux ropes.

(Hanle 1924; Bommier et al. 1994)

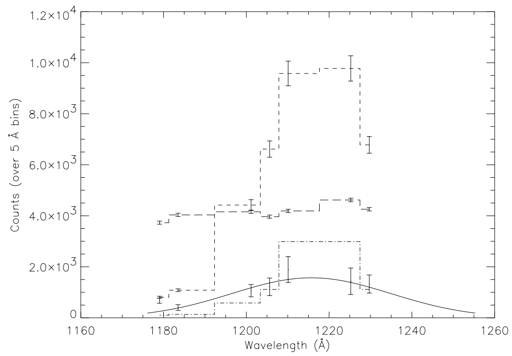
New Diagnostics: Thomson-scattered H I Lyα

- ⋆ The only existing estimates of T_e in coronal holes are indirect determinations from **(1)** line ratios at low heights, **(2)** *Yohkoh* filter ratios, and **(3)** *in situ* charge states mapped back into the corona.

- ⋆ The **electron velocity distribution** (and thus T_e) can be measured more directly from the Thomson-scattered H I Lyα line profile.

- ⋆ This emission is $\sim$1000 times less intense than resonantly scattered H I Lyα, and is spread over a $\sqrt{m_p/m_e} \approx 43$ larger range of wavelength.

- ⋆ UVCS/SOHO observed Thomson-scattered Lyα in a bright streamer at 2.7 $R_\odot$ (Fineschi et al. 1998), but low sensitivity and high grating stray light made this measurement extremely difficult.

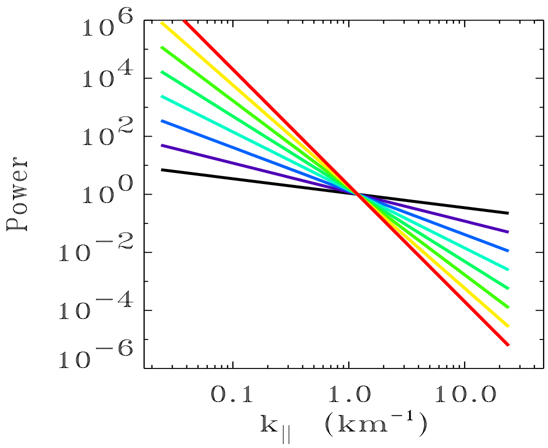


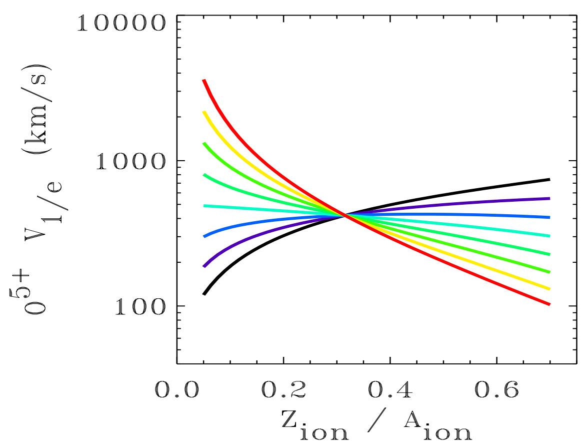
A dedicated double-pass spectrometer can improve the sensitivity to the Thomson-scattered H I Lyα profile by a factor of at least 100, thus making routine measurements possible in coronal holes, streamers, and CMEs.

- ⋆ Accurate electron velocity distributions can be compared with:
  - ⇒ ion velocity distributions — *(probes preferential ion heating; Coulomb collision efficiency)*
  - ⇒ *in situ* freeze-in temperatures — *(probes departures from ionization equilibrium & Maxwellians)*

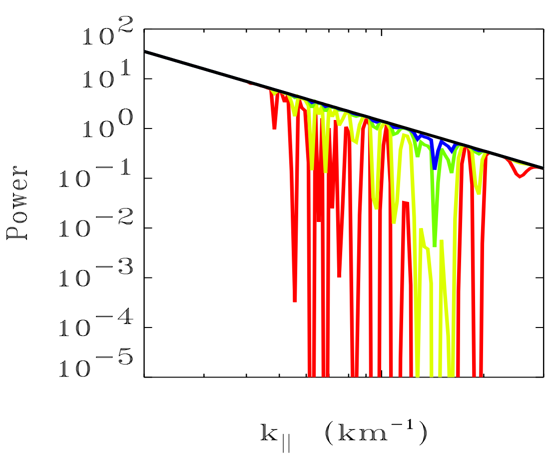
Science Goals: Fast Solar Wind

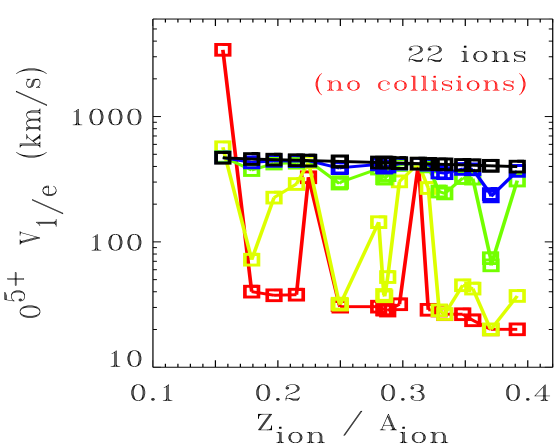
- **Which wave modes are generated and damped (where & how)?**
- UVCS/SOHO provided line widths for H^0, O^{5+}, & Mg^{9+} in coronal holes, with $V_{1/e}(Mg^{9+}) < V_{1/e}(O^{5+})$.
- Measuring the widths of lines of **more ions** can put constraints on how wave damping competes with existing wave generation mechanism(s).
- Fixed power law spectra:





- Vary the amount of heavy ion resonant damping:



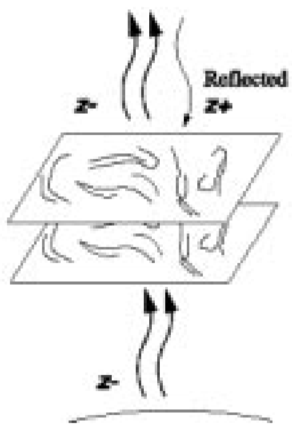


Science Goals: Fast Solar Wind

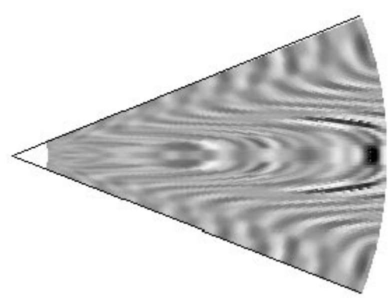
- ⋆ **Do ion cyclotron waves heat and accelerate protons and helium?**
- ⋆ Minor ion observations lead to a derivation of the **high-frequency** wave power spectrum $P(k_{\|})$.
  - ⇒ The proton and He^{2+} heating that must result from this *empirical* $P(k_{\|})$ can be computed and compared to required values.
  - ⇒ Is it enough?
- ⋆ If not, there may be enough wave energy in **other modes** that could be responsible for heating the bulk plasma:

(1) MHD turbulence, $P(k_{\perp})$ dissipate by Landau damping

(2) Low-freq. nonlinear waves that do work on the wind



(Matthaeus et al. 1999)



(Ofman & Davila 1997)

- ⋆ Proton and **electron** velocity distributions will be crucial constraints on models of non-cyclotron wave dissipation in the low–β coronal hole plasma *(e.g., Landau damping also should heat electrons).*

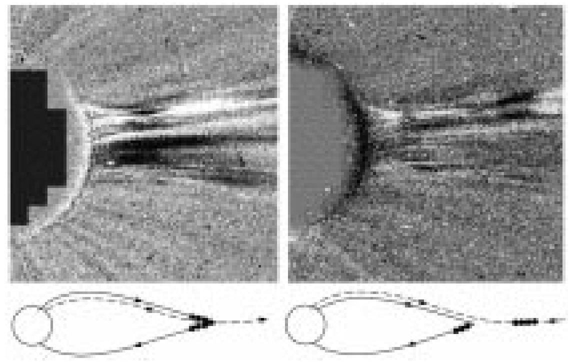
Science Goals: Slow Solar Wind

- ⋆ **What is the relative contribution from: (1) coronal hole boundary flow, and (2) transient closed-field eruptions?**

- ⋆ A "census" of mass and energy flux in pressure-driven eruptions can be taken by comparing, e.g.,

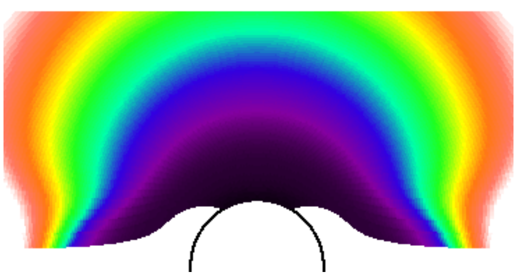
  n_e (local & line-integrated)

  T_e (Thomson & ioniz. balance)

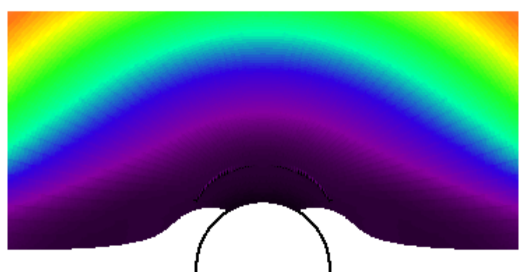


- ⋆ **What are the roles of high & low frequency waves?**

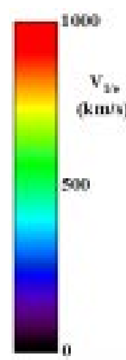
- ⋆ Coronal hole models can be extended in **latitude** down to the "last open field lines." Straw-man predictions for O VI widths:



Ion cyclotron waves with equal power in equal-diameter tubes; obeying WKB wave action conservation.



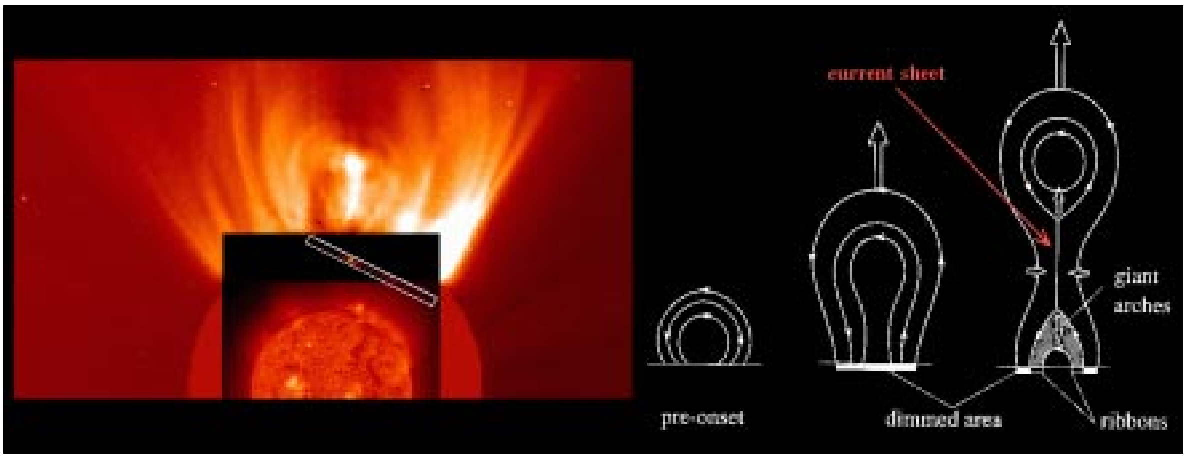
Ion cyclotron waves, with damping rate $\propto \nabla V_A$; inspired by MHD turbulence driven by wave reflection.



Science Goals: CMEs

- ⋆ **What processes convert stored magnetic energy into heating and acceleration?**

- ⋆ UVCS observed hot ($>$ 6 million K) plasma at the expected location of a **current sheet** in a flux-rope CME model (Lin & Forbes 2000).



- ⋆ Improved diagnostics (n_e, T_e, T_{ion}) in current sheets will lead to quantitative determinations of the energy budget and the efficiency of magnetic reconnection in CMEs.

- ⋆ Simultaneous He II 304 Å and He I 584 Å measurements can determine what fractions of the CME plasma are **heated** prominence material and **cooled** pre-existing coronal material.

Conclusions

- ⋆ Next generation spectroscopy and polarimetry of the extended corona is ideally suited to provide us with **detailed empirical descriptions** of the plasma in the acceleration region of the solar wind and CMEs.

- ⋆ With these quantitative descriptions in hand, we can identify and characterize the physical processes responsible for:

  - ⇒ **the primary plasma components (protons and helium) and the minor ions in the high-speed wind**
  - ⇒ **the steady-state and transient components of the slow-speed wind**
  - ⇒ **the driving, non-equilibrium heating, and helicity evolution of CMEs.**

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