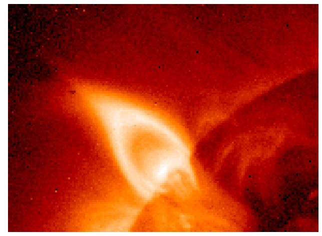
Multi-wavelength Observations of Coronal Structure and Dynamics: Yohkoh 10th Anniversary Meeting, Kailua-Kona, Hawaii, 21–24 January 2002



Coronal Holes and the Solar Wind

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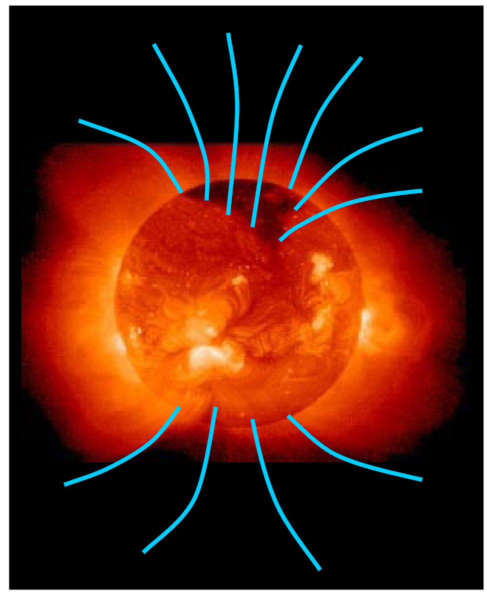
- **Background**
  - ⟶ definitions
  - ⟶ major unanswered questions
- **Observations**
  - ⟶ coronal base *(Yohkoh, EIT, CDS, SUMER)*
  - ⟶ extended corona *(UVCS, LASCO)*
- **Proposed heating and acceleration processes**

Coronal Holes: Definitions

- ★ Dark features first identified by Max Waldmeier (1950s) in 5303 Å green-line coronagraph images as **“Löcher”** *(holes)*, **“Rinne”** *(grooves)*, and **“Kanal”** *(channels)*.



- ★ Coronal holes conjectured to be regions of open magnetic field by Wilcox (1968).

- ★ Confirmed as sources of high-speed solar wind streams by Krieger, Timothy, and Roelof (1973).

- ★ The term “coronal hole” is currently applied to dark regions **both** on the solar disk and in off-limb coronagraph/eclipse images.

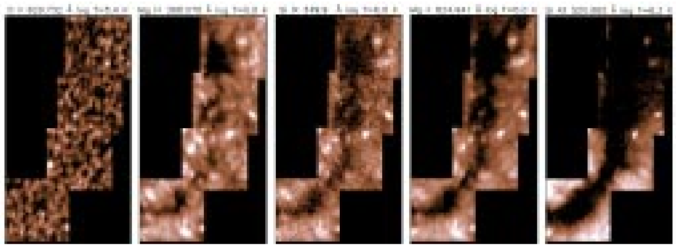
- ★ Connectivity to the wind . . . .

solar disk feature		extended corona feature		solar wind type
coronal holes	→	**coronal holes**	→	**fast (v > 500 km/s)**
quiet regions **active regions**	} →	**streamers**	→	**slow (v < 500 km/s)**

?

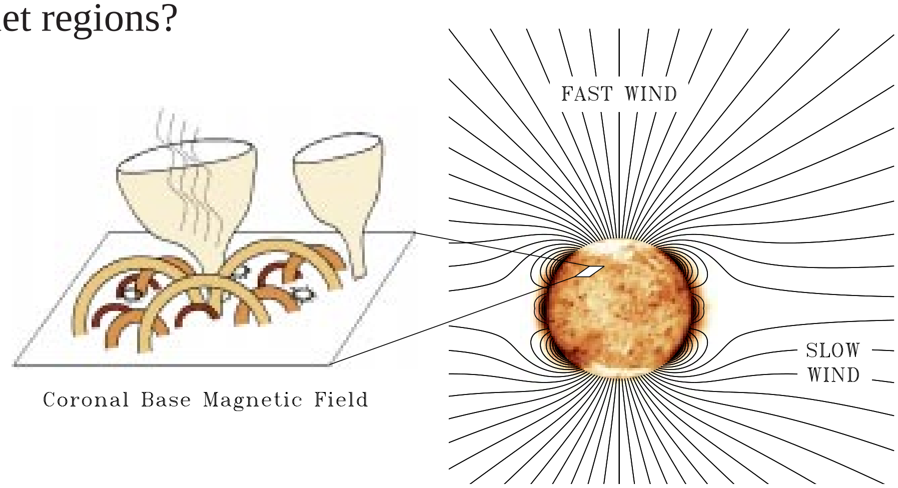
Unanswered Questions: Coronal Base

★ Why are coronal hole **boundaries** as sharp as they appear to be?



(e.g., Bromage et al. 2000)

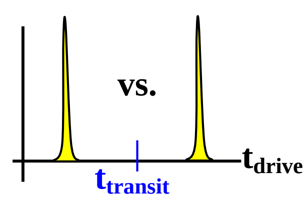
★ Is the establishment of a coronal hole only a matter of closed vs. open flux **filling factor,** or are heating rates intrinsically different between holes and quiet regions?

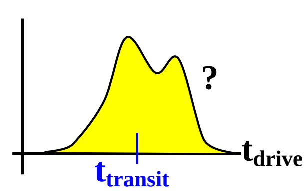


★ “AC vs. DC” coronal heating?

⇒ What is the **time scale distribution** of the driving motions (e.g., turbulence, flux tube emergence, reconnection, wave excitation)?

⇒ How do “microscale” kinetic processes transfer magnetic and kinetic energy into heat?

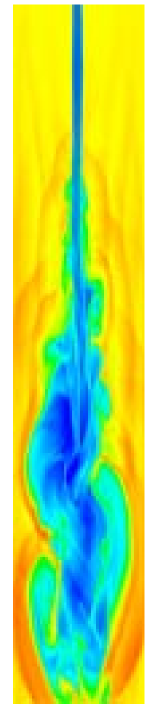




★ How is the **mass flux** of the high-speed wind determined and regulated?

Unanswered Questions: Extended Corona

- How much of the solar wind comes from coronal holes?



- What are the **physical processes** responsible for heating and accelerating the fast solar wind?

  ⇒ How and where are **fluctuations** (waves, turbulence, or shocks) generated and damped?

  (e.g., how important is ion cyclotron resonance?)

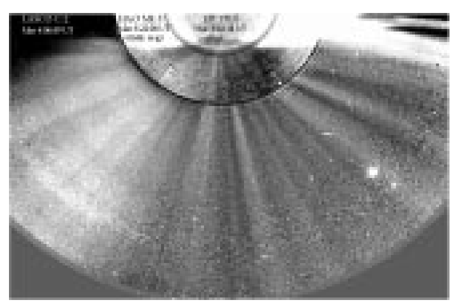
  ⇒ What is the relative contribution from each fluctuation mode (Alfvén, fast, slow) and what propagation angles are most important?

  ⇒ Is "velocity filtration" of suprathermal particles important in the collisionless extended corona?

- How important are filamentary inhomogeneities?

  ⇒ To what degree to **polar plumes** contribute to the mass, momentum, and energy budget of the fast wind?

  ⇒ Is even the "zero-order" mean state an adequate description of the dominant physics?



(e.g., DeForest et al. 1997)

To answer these questions, we need measurements of the **plasma properties . . .**

⇒ **number densities (abundances, ioniz. fractions)**

⇒ **flow speeds**

⇒ **temperatures**

constraints on anisotropic and non-Maxwellian velocity distributions!

for electrons, protons, and minor ions, both at the base and in the acceleration region of the fast wind (1–10 $R_\odot$), as well as . . .

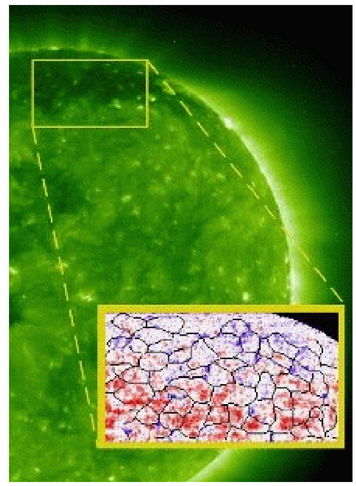
⇒ **power spectra of MHD fluctuations!**

Observations: Coronal Base

On disk: ρ and T lower than in quiet & active regions

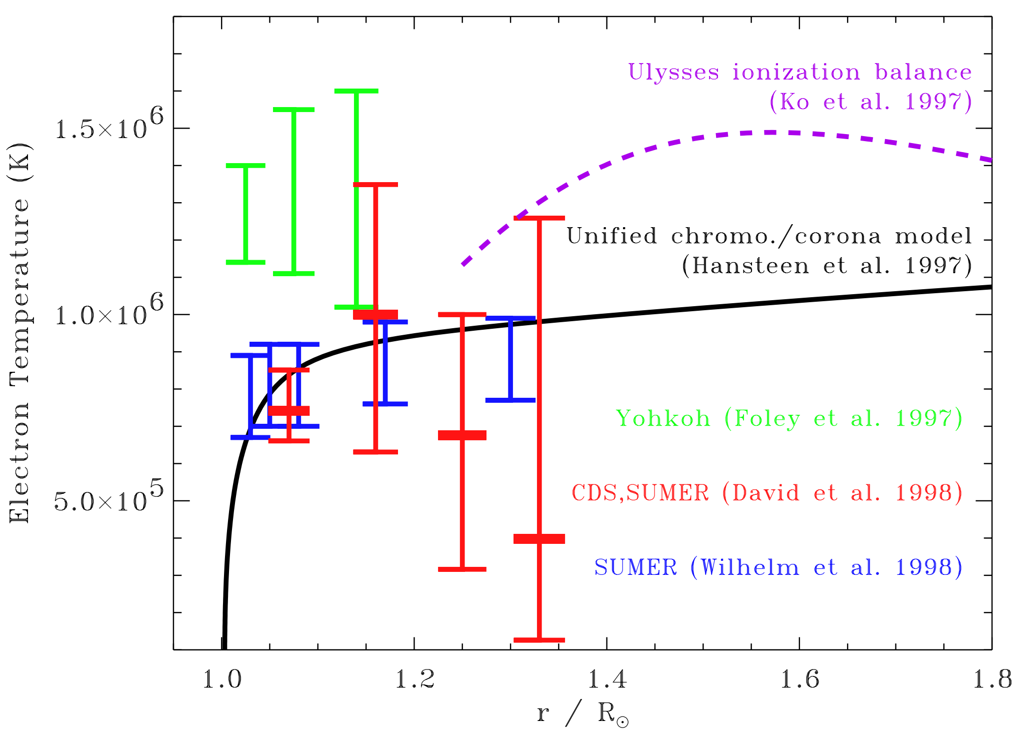
Off-limb: $T_e < T_p < T_{ion}$

SUMER/SOHO spectroscopy:



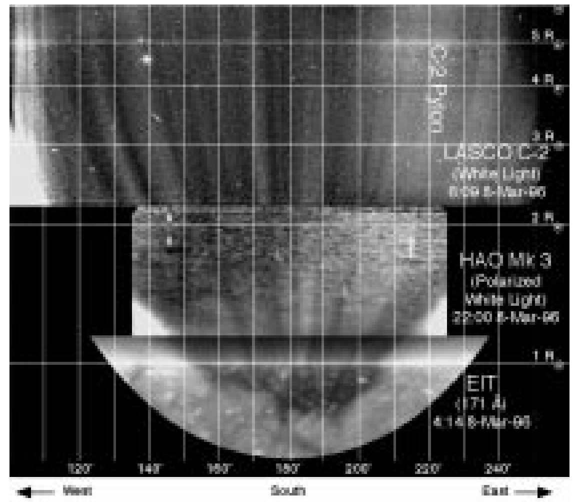
- ★ Blueshifted emission lines at the coronal base map out launching points of the high-speed wind (e.g., Hassler et al. 1999).
- ★ T_{ion} exceeds T_e at very low heights, and depends on ion **charge-to-mass ratio** (Seely et al. 1997; Tu et al. 1998).

Electron temperature controversy . . .



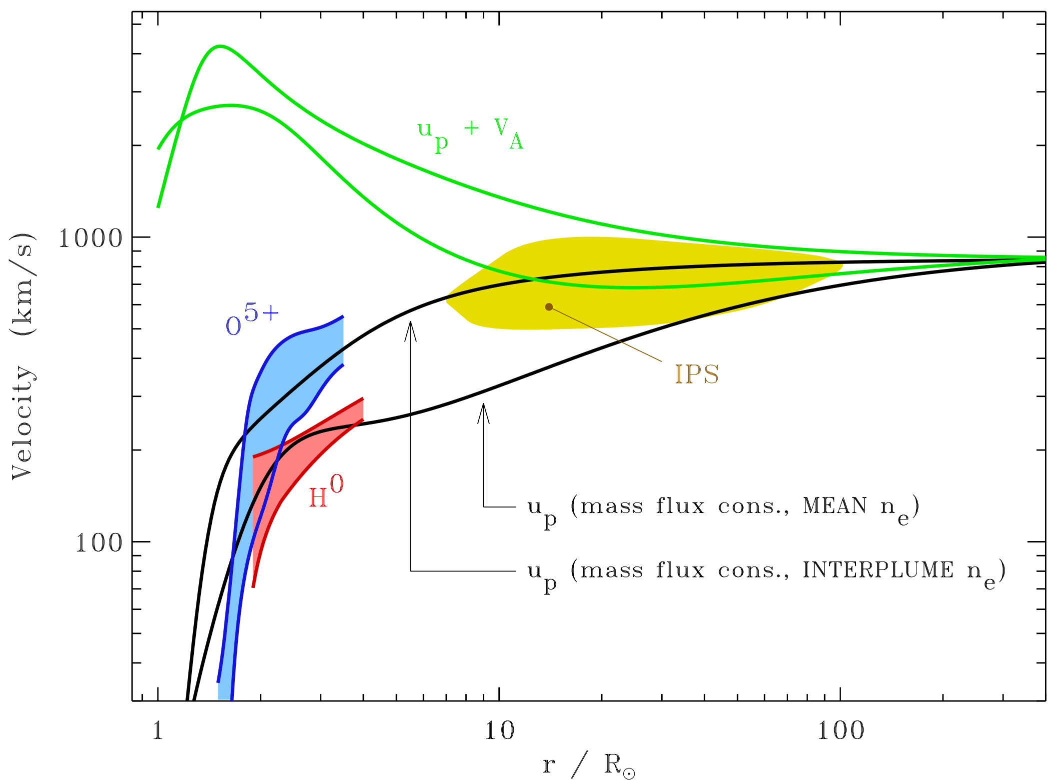
Observations: Extended Corona

- ⋆ Visible-light **coronagraphs** that observe the linearly polarized (Thomson-scattered) K-corona provide a direct diagnostic of the electron density from $\sim$1.1 to $\sim$30 $R_\odot$.



- ⋆ **Polar plumes** trace the superradial divergence of the magnetic field in polar coronal holes (e.g., DeForest et al. 1997, 2001).

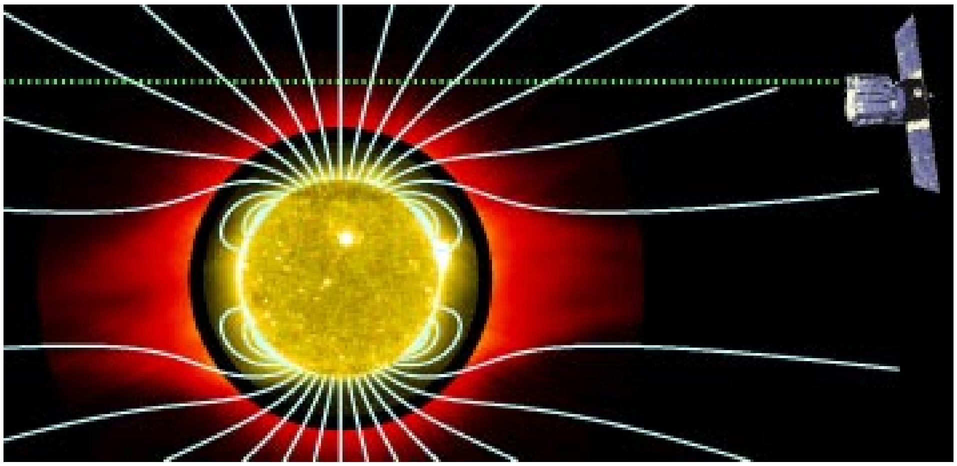
- ⋆ Assuming steady state flow, **mass flux conservation** provides the bulk (proton-electron plasma) outflow speed . . .



Mass flux conservation from n_e (*upper:* Fisher & Guhathakurta 1995; *lower:* Guhathakurta & Holzer 1994) and flux tube area (Banaszkiewicz et al. 1998). **Range of IPS speeds** from Grall et al. (1996); **H^0** and **O^{5+}** speeds from Cranmer et al. (1999b).

Observations: Extended Corona

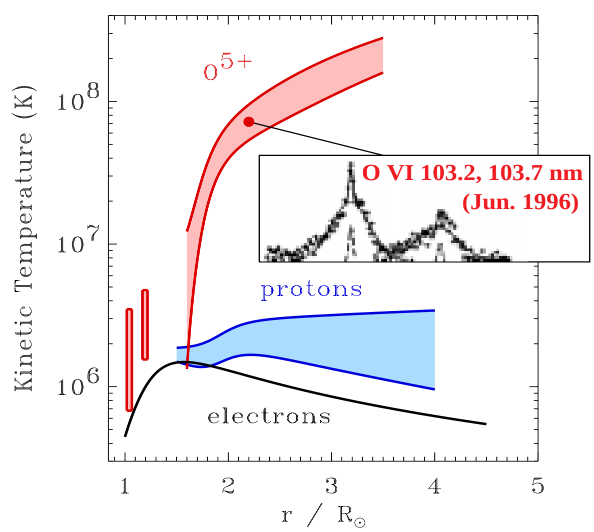
★ UVCS/SOHO has measured the properties of protons and minor ions in the wind's acceleration region:



Polar coronal holes at solar minimum:

★ Detailed analysis of line profiles and intensities allows us to deduce that H^0 and O^{5+} have **anisotropic** distributions between 1.5 and 4 $R_\odot$ in coronal holes (Kohl et al. 1997). For O^{5+}, $T_\perp / T_\parallel \approx$ 10–100.

★ For O^{5+}, $T_\perp$ approaches **200 million K** at 3 $R_\odot$. The kinetic temperatures of O^{5+} and Mg^{9+} are much greater than mass-proportional when compared with hydrogen (Kohl et al. 1998, 1999; Cranmer et al. 1999b; Esser et al. 1999).



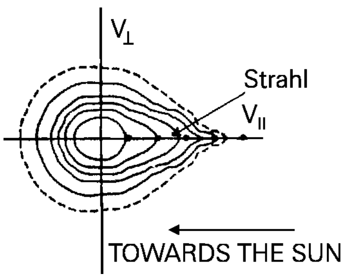
★ Doppler dimmed line intensities are consistent with the **outflow speed** for O^{5+} being larger than the outflow speed for H^0 by as much as a factor of **two** (Li et al. 1998; Cranmer et al. 1999b).

Observations: Interplanetary space

★ Similar departures from thermal equilibrium have been observed at $r > 0.3$ AU for decades:

$$\left\{ \begin{array}{rcl} \boldsymbol{T_\perp} & > & \boldsymbol{T_\parallel} \\ (\boldsymbol{T_{\rm ion}/T_p}) & > & (\boldsymbol{m_{\rm ion}/m_p}) \\ \boldsymbol{u_{\rm ion}} & > & \boldsymbol{u_p} \end{array} \right\}$$

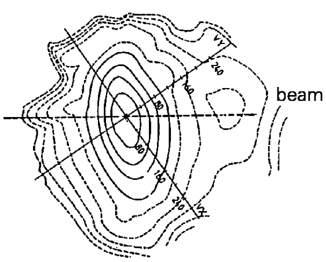
★ In high-speed wind streams (correlated with coronal holes),



Electrons: thermal "core" + beamed "halo"

★ suprathermals conserve $\boldsymbol{\mu = (T_\perp/B)}$

(see, e.g., Marsch 1999, Space Sci Rev., 87, 1)



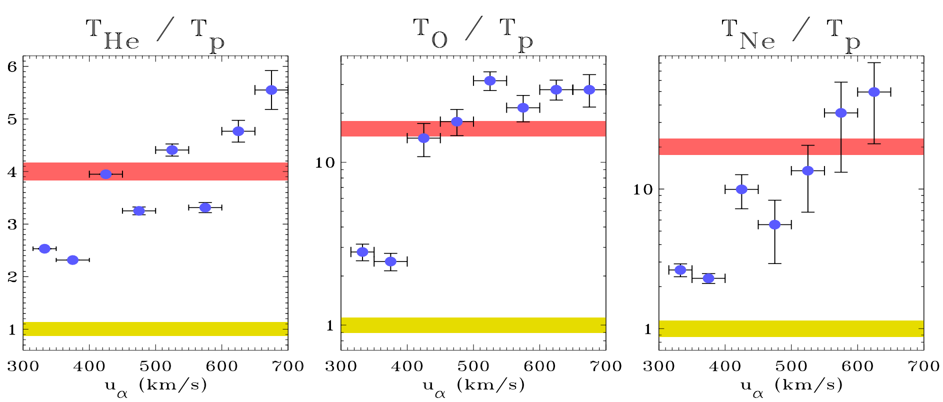
Protons: thermal core exhibits $\boldsymbol{T_\perp > T_\parallel}$

★ $\boldsymbol{\mu}$ grows ∼linearly with distance (0.3–1 AU)

★ beam flows ahead of core at $\boldsymbol{\Delta V \approx V_A}$

Heavy ions: flow faster than protons $(\boldsymbol{\Delta V \approx V_A})$

★ $(\boldsymbol{T_{\rm ion}/T_{\rm p}}) \gtrsim (\boldsymbol{m_{\rm ion}/m_{\rm p}})$



(Collier et al. 1996, Geophys. Res. Letters, 23, 1191)

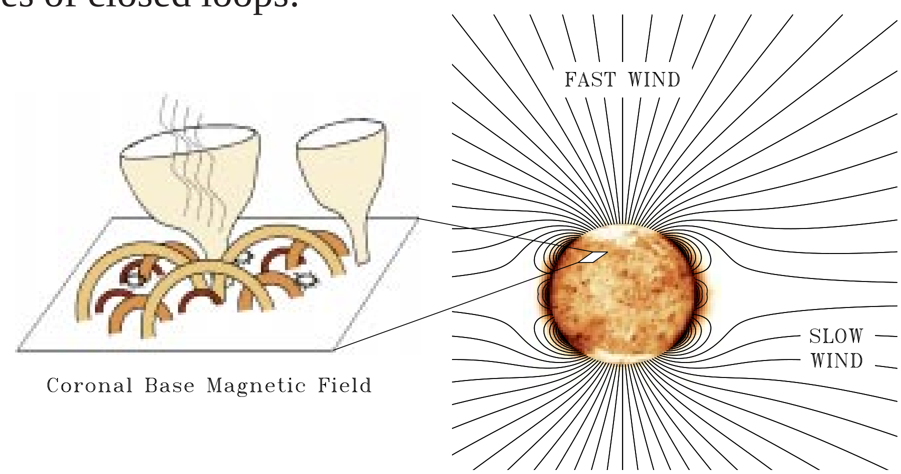
Heating the Extended Corona → Solar Wind

Additional heating is required above 2 $R_\odot$ . . .

- ★ The observed *in situ* $T(r)$ gradient is shallower than if dominated by adiabatic expansion ($T \propto r^{-4/3}$).
- ★ Classical electron heat conduction (Chapman 1954) cannot be responsible for this supra-adiabaticity in *collisionless* plasma.
- ★ Magnetic moment ($T_\perp / B$) increases between 0.3 and 1 AU.
- ★ UVCS $\nabla T_{\rm p}$ implies heating rate **per particle** of $\sim$0.1 eV/s at 2 $R_\odot$, which is of the same order as the rate at the *coronal base!*

It's a very different environment from the base . . .

- ★ The plasma becomes collisionless.
- ★ "Laminar" open magnetic fields dominate over stochastic ensembles of closed loops:

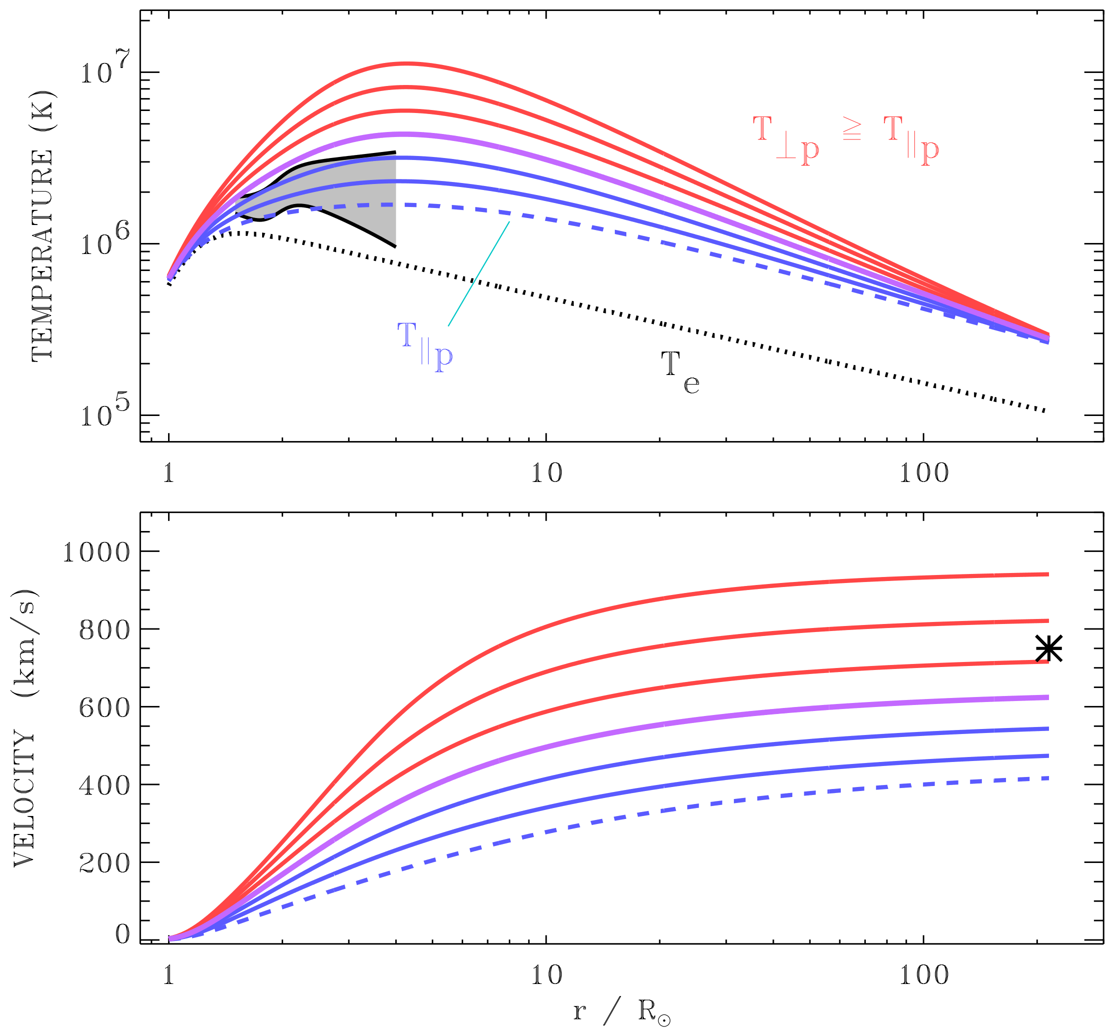


- ★ Energy for heating plasma must ultimately *propagate* up from the Sun; i.e., **waves, shocks, turbulent fluctuations.**
- ★ Dissipation of the fluctuation energy must be collisionless; i.e., **wave-particle resonances.**

Fast wind: Is extended heating *enough*?

Compute a series of empirically based "quasi-Parker" models:

- ⟹ Specify $\boldsymbol{T_e}$, $\boldsymbol{T_{p\parallel}}$, $\boldsymbol{T_{p\perp}}$ vs. radius $(\boldsymbol{u_p} = \boldsymbol{u_e})$
- ⟹ Superradial polar geometry: Banaszkiewicz et al. (1998)
- ⟹ NO collisions, wave pressure, heat flux, or viscosity

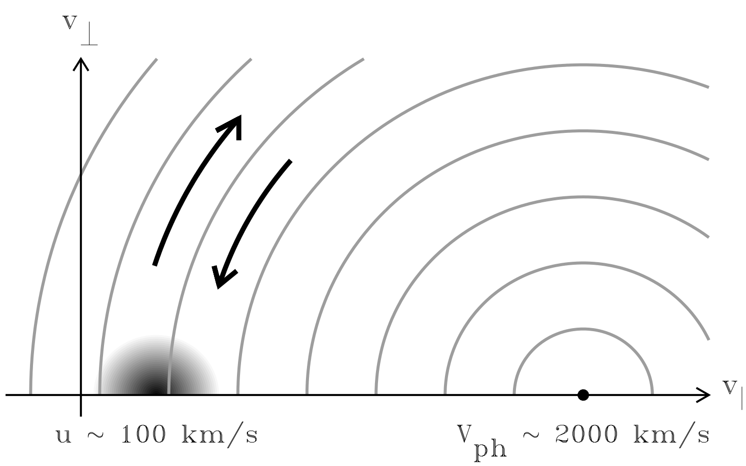


It is not yet clear if additional **momentum deposition** (from, e.g., wave pressure) is required (see also Tziotziou et al. 1998, A&A, 340, 203; for models based on *Yohkoh*/SXT temperatures).

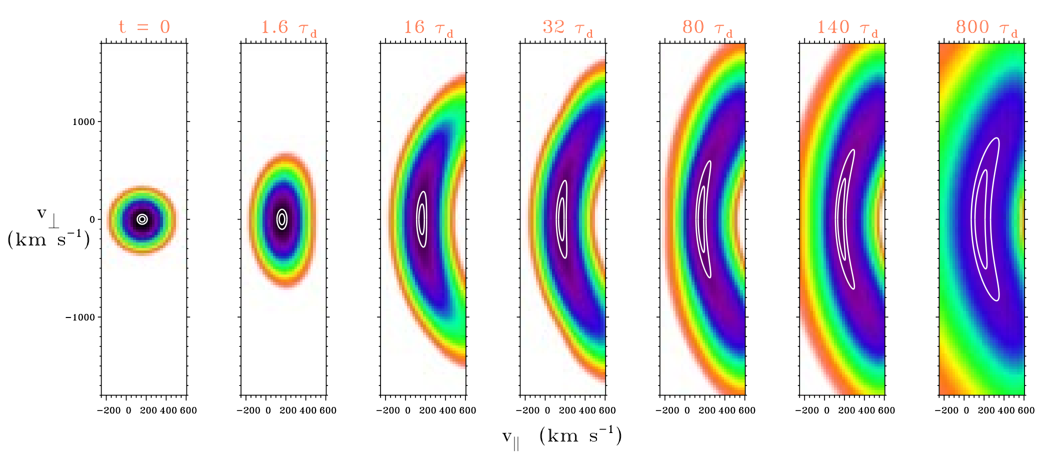
Better proton temperature measurements between 2 and 10 $R_\odot$ are needed!

Ion Cyclotron Resonance

- ⋆ **1970s–present:** Preferential ion heating/acceleration and anisotropies (detected both *in situ* and remotely) led theorists to investigate the damping of parallel-propagating ion cyclotron waves.
- ⋆ Dissipation of ion cyclotron waves produces **diffusion** in velocity space, along contours of ∼constant energy in the frame moving with the wave phase speed. $(V_A \gg v_{th})$



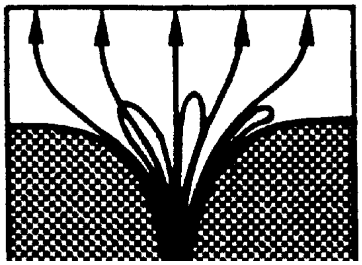
- ⋆ Quasi-linear diffusion model for O^{5+} ions in a homogeneous plasma:



- ⋆ Anisotropy grows naturally as long as there is an energy supply of resonant waves in the corona (e.g., Cranmer 2001, *JGR*, 106, 24,937).
- ⋆ Ions are accelerated *along* field both by: **(a)** forward curvature of velocity distribution, and **(b)** by magnetic mirroring of high–$v_\perp$ ions.

How are Ion Cyclotron Waves Generated?

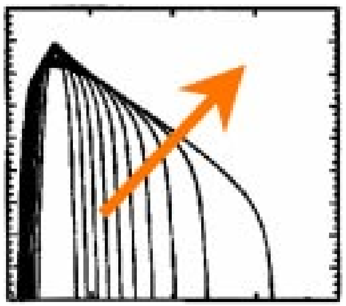
Alfvén waves with frequencies > 10 Hz have not yet been observed in the corona or wind, but ideas for their origin abound:



(1) Base generation by, e.g., "microflare" reconnection in the lanes that border convection cells (e.g., Axford & McKenzie 1997).

Problem: Low Z/A ions consume base-generated wave energy before it can be absorbed by, e.g., $\mathbf{O^{5+}}$, $\mathbf{He^{2+}}$, $\mathbf{p^{+}}$.

(2) Secondary generation: The Sun is suspected to emit low-frequency (< 0.01 Hz) Alfvén waves. This source of "free energy" may be converted into ion cyclotron waves *gradually* throughout the corona.



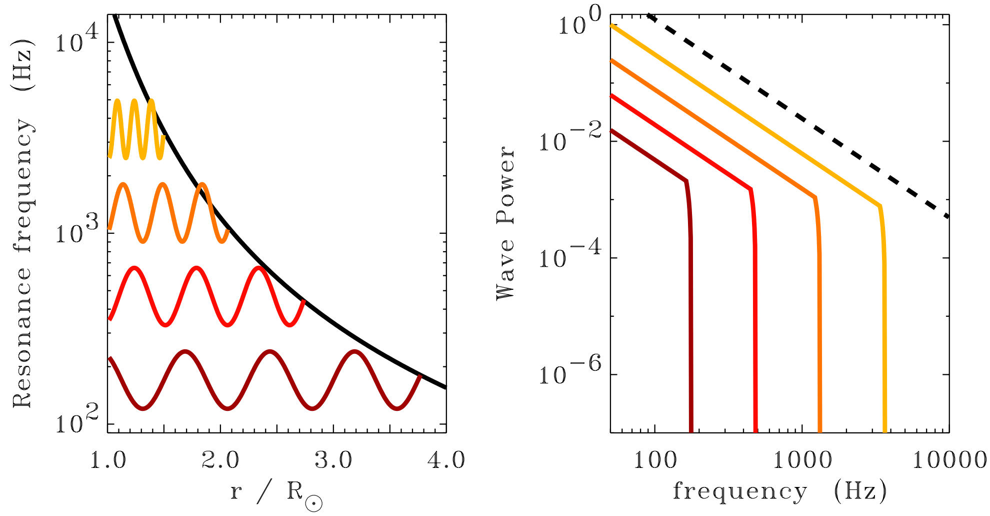
⇒ MHD turbulent cascade?

⇒ Instabilities seeded by non-Maxwellian distributions or large-scale velocity shears?

Problem: Turbulence produces mainly high-$k_\perp$ fluctuations (i.e., still low frequency). Ion cyclotron waves propagating parallel to the background field may comprise only a *small fraction* of the total fluctuation power!

Problems with Base Generation . . .

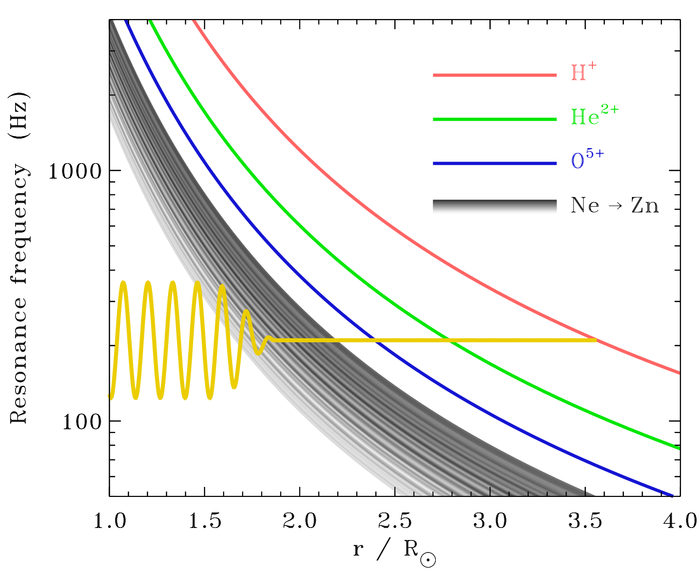
If high-frequency waves originate only at the base of the corona, extended heating "sweeps" across the spectrum:



However, *minor ions* can damp the waves as well:

$$\Omega_{\rm ion} = \frac{Z_{\rm ion}}{A_{\rm ion}}\,\Omega_{\rm p} \quad , \quad P \approx P_0\, e^{-\tau} \quad , \quad \tau \approx 10^5 \left(\frac{m_{\rm ion} n_{\rm ion}}{m_{\rm p} n_{\rm p}} \right)$$

Cranmer (2000) computed τ for 2523 species at 2 $R_\odot$:



If ion cyclotron resonance is indeed the process that energizes high charge-to-mass ratio ions, the wave power must be **gradually replenished** throughout the extended corona, and cannot come solely from the base.

Problems with Gradual Generation . . .

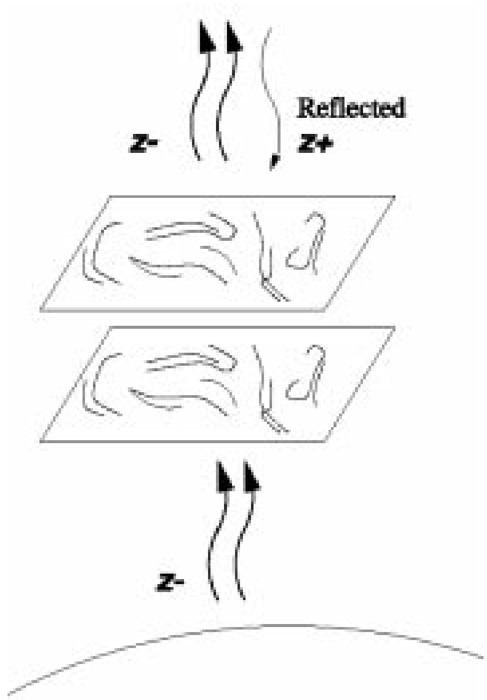
★ Most of the work on gyroresonance in the solar wind has been for waves propagating *along* the field **($k_{\parallel}$)**.

★ However, both simulations and analytic descriptions of MHD turbulence predict cascade from small to large *perpendicular* wavenumbers **($k_{\perp}$)**.

(Alfvénic fluctuations with large $k_{\perp}$ do not necessarily have large $\omega \to \Omega_{\mathrm{ion}}$)

★ Perpendicular ("2D") turbulence does dissipate on the smallest scales, but this may not heat and accelerate ions preferentially.

(Landau damping in a low–β plasma tends to heat **electrons** *preferentially...)*



★ *In situ* solar wind observations support this picture, but large-$k_{\parallel}$ fluctuations are **also** seen (e.g., Leamon et al. 1998, 2000).

Studies of (multiple harmonic) ion cyclotron resonance with highly *oblique* $(\mathbf{k} \cdot \mathbf{B} \approx 0)$ waves are underway . . . .

Conclusions

- ⋆ Departures from Maxwellian velocity distributions are crucial probes of *(still unknown)* heating and acceleration mechanisms in coronal holes.

- ⋆ We still don't know several key plasma parameters (e.g., $\boldsymbol{T}_{\mathrm{e}}$ and $\boldsymbol{T}_{\mathrm{p}}$) with sufficient accuracy!

  $\Rightarrow$ Future space-borne spectroscopy of the corona

  $\Rightarrow$ NASA's *Solar Probe* mission . . . ?

- ⋆ To make progress in theoretical modeling:

  Generation and nonlinear evolution of the solar wind **fluctuation spectrum** must be understood.

  Self-consistent **kinetic models** (corona $\rightarrow$ wind) of protons, electrons, and ions are needed.

- ⋆ Future models must predict the properties of **many minor ion species,** because these may be the only means of distinguishing between competing models that, e.g., predict the *same* bulk plasma heating rates!

- ⋆ The lines of communication must be kept open between:

  "solar physicists" (1 to 1.5 $R_\odot$),
  "coronagraphers" (1.2 to 20 $R_\odot$), and
  "space physicists" (60 to 10,000 $R_\odot$) **!**

- ⋆ *For more information:*

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

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