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How ultraviolet spectroscopy can constrain theories of MHD turbulence and kinetic wave dissipation in the solar wind

Steven R. Cranmer
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA

Background

- ⟶ Coronal heating “problems”
- ⟶ Observational constraints (remote and *in situ*)

Ion cyclotron resonance

- ⟶ How are the fluctuations generated?
- ⟶ Which wave modes are dominant?
- ⟶ What heating (damping) rates are required?

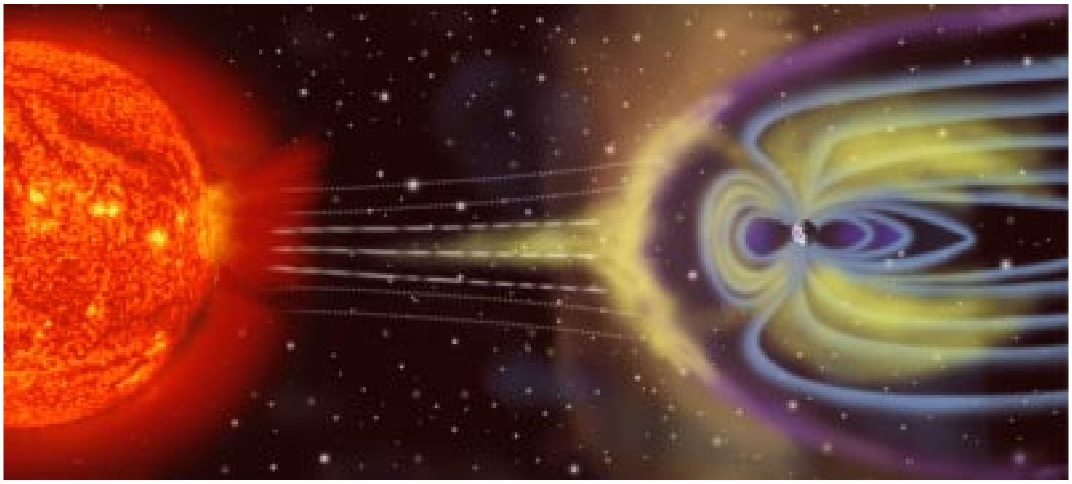
Why study the Sun?

- ⋆ Closest example of a star!
- ⋆ A “laboratory without walls” for many basic kinetic and MHD processes:

- ⋆ **gyroresonant wave damping**
- ⋆ **anisotropic turbulent cascade**
- ⋆ **shock acceleration**
- ⋆ **magnetic reconnection**

Solar corona and solar wind span **14** orders of magnitude in density (collisional $\longrightarrow$ collisionless , low $\beta \longrightarrow$ high β)

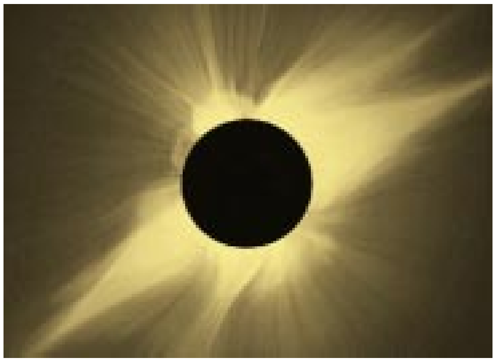
- ⋆ **Space weather** can affect satellites, power grids, and the safety of orbiting astronauts . . . .



The Sun’s Outer Atmosphere

The solar photosphere exhibits a $\sim$blackbody temperature of 5800 K.

The solar corona:

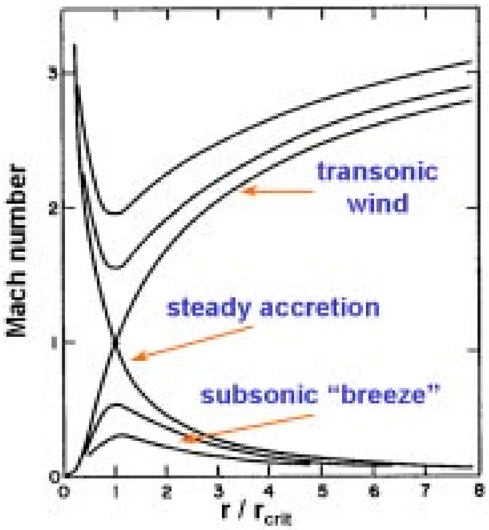


- 1870s: unknown emission lines; a new element called *“coronium?”*
- 1930s: Lines were identified as highly ionized ions: Ca^{12+}, Fe^{9+} to Fe^{13+}

$T >$ 1 million K

The solar wind:

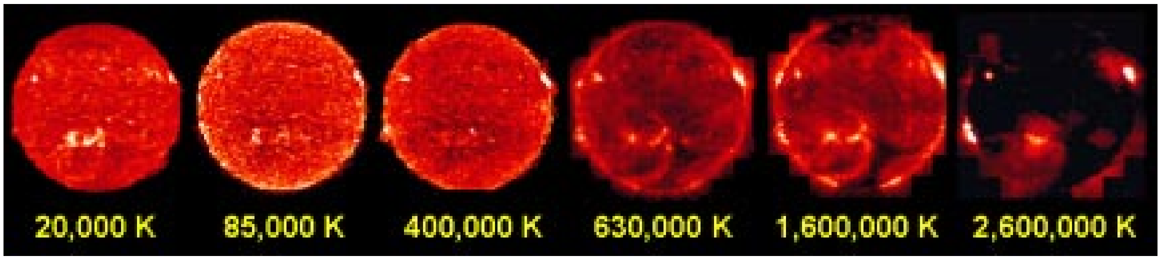
- 1860s–1950s: evidence for outflowing plasma in solar system builds (geomagnetic storms, comet tails)
- 1958: E. N. Parker proposed that the hot corona provides enough gas pressure to counteract gravity!
- 1962: *Mariner 2* provided direct confirmation of the supersonic solar wind.



We still have not uniquely identified the physical processes that heat the corona and accelerate the solar wind . . . .

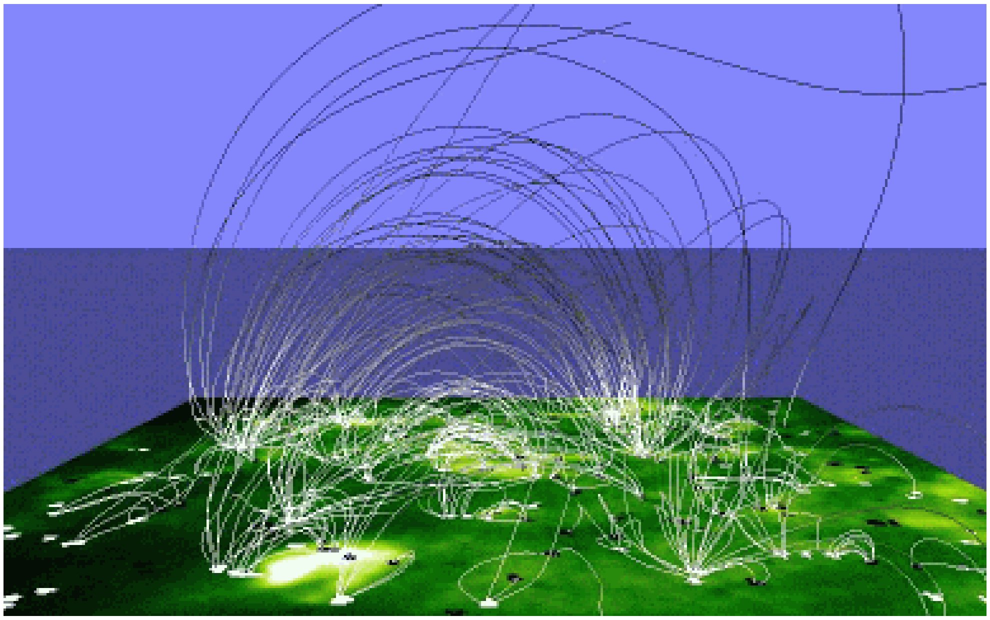
Heating the Coronal Base

- The sharp “transition region” ($10^4 \rightarrow 10^6$ K) is still not well understood.



- Most suggested mechanisms involve the storage and release of magnetic energy in **small-scale** twisted or braided flux tubes.

  (Magnetic flux continually emerges from the convective interior, replenishing itself every ∼40 hours.)



- **Dissipation** of the magnetic energy as heat probably occurs via Coulomb collisions (e.g., viscosity, resistivity, conductivity).

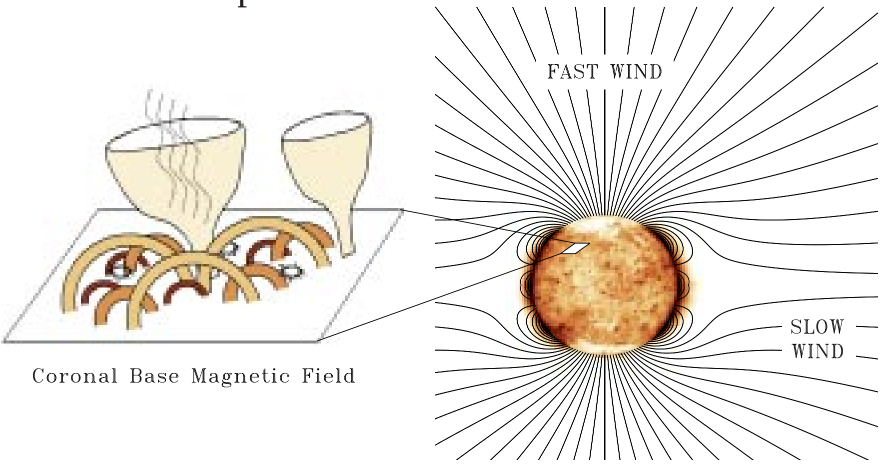
Heating the Extended Corona → Solar Wind

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.
- ⋆ **(Ultraviolet spectroscopy of extended corona)**

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

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



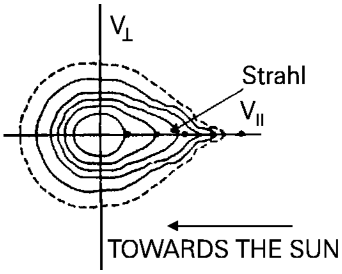
- ⋆ Energy for heating plasma must ultimately *propagate* up from the Sun; i.e., **waves, shocks, turbulent fluctuations.**
- ⋆ Dissipation of the fluctuation energy must be collisionless; i.e., **wave-particle resonances.**

In situ Particle Properties

- ⋆ *Mariner 2* confirmed the continuous nature of the solar wind in 1962, and found two relatively distinct components:

high-speed (500–800 km/s)	low density	∼laminar flow
low-speed (300–500 km/s)	high density	variable, filamentary

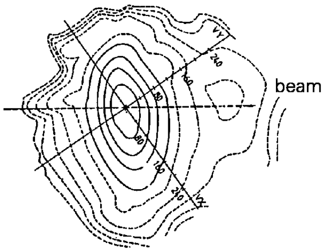
- ⋆ In the high-speed wind (that emerges from coronal holes),



Electrons: thermal “core” + beamed “halo”

- ⋆ suprathermals conserve $\mu = (T_\perp / B)$

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

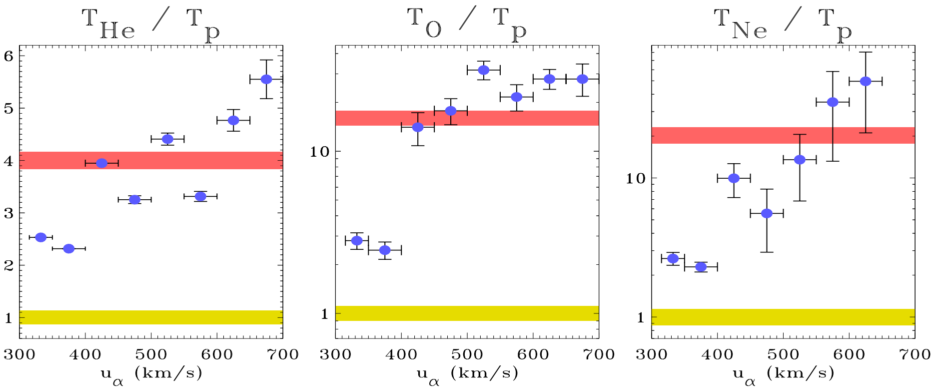


Protons: thermal core exhibits $T_\perp > T_\parallel$

- ⋆ μ grows ∼linearly with distance (0.3–1 AU)
- ⋆ beam flows ahead of core at $\Delta V \approx V_A$

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

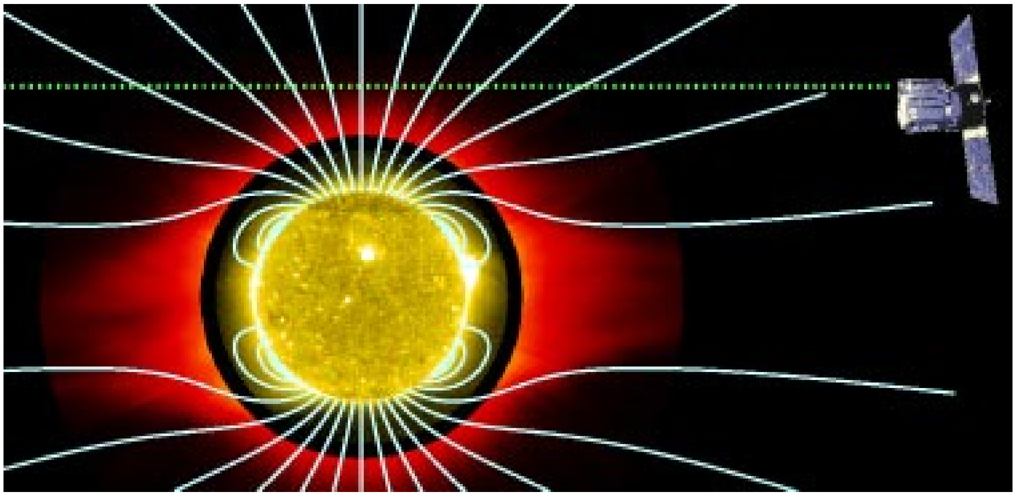
- ⋆ $(T_{\rm ion}/T_{\rm p}) \gtrsim (m_{\rm ion}/m_{\rm p})$



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

Ultraviolet Spectroscopy of the Corona

- **Motivation:** measure plasma properties of hot ($> 10^6$ K) protons, electrons, and ions as they **accelerate.** (Too near Sun for *in situ*.)
- The scattered photon emission is usually “optically thin:”



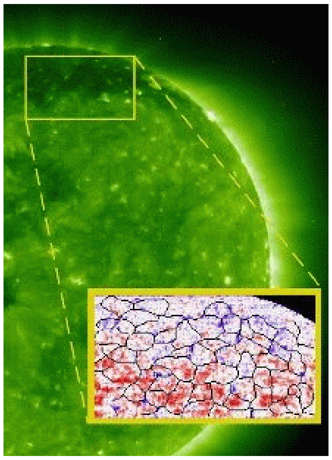
- **Off-limb Diagnostics:**

spectral line shape	. . .	velocity distribution along line-of-sight	$(T_\perp)$
scattered line intensities	. . .	velocity distribution in the sunward direction	$(T_\parallel, V_\parallel)$
(visible light polarization)	. . .	electron density	(n_e)

- Present-day instruments cannot detect departures from **bi-Maxwellian** distributions, but future instruments will have sufficient sensitivity to determine consistency or inconsistency with various non-bi-Maxwellian distributions.

Ultraviolet Spectroscopy: SOHO Results

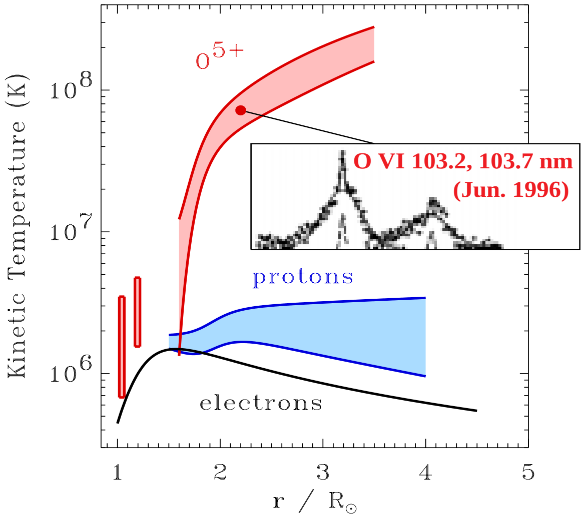
SUMER/SOHO:



- Blueshifted emission lines at the coronal base map out launching points of the high-speed wind (e.g., Hassler et al. 1999).
- T_{e} is not more than $\sim 10^6$ K in coronal holes. 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).

UVCS/SOHO:

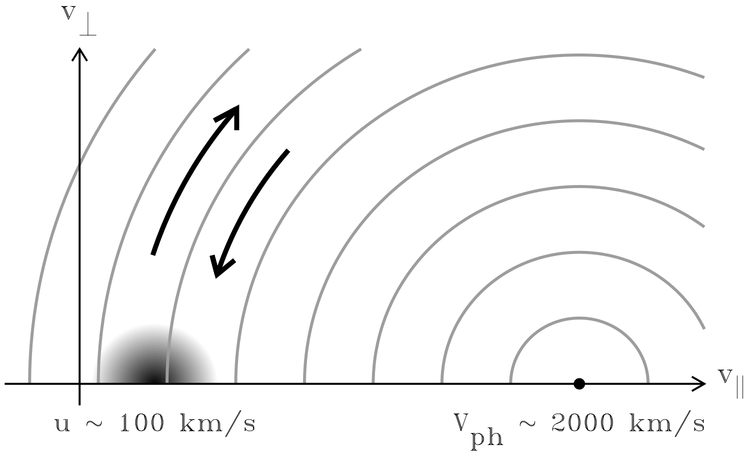
- Detailed analysis of line profiles and intensities allows us to deduce that H^0 and O^{5+} have **anisotropic** distributions between 1.5 and 4 $R_\odot$ in coronal holes (Kohl et al. 1997). For O^{5+}, $T_\perp / T_\parallel \approx$ 10–100.
- For O^{5+}, $T_\perp$ approaches **200 million K** at 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. 1999; Esser et al. 1999).



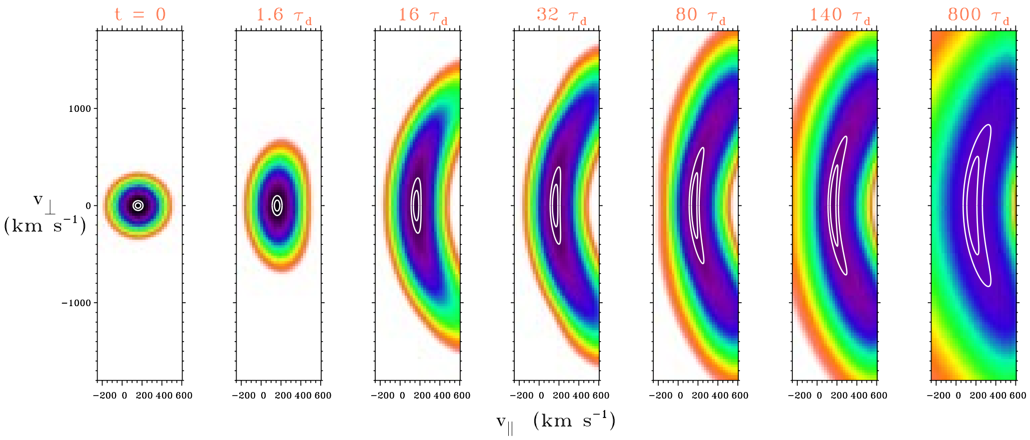
- Doppler dimmed line intensities are consistent with the **outflow speed** for O^{5+} being larger than the outflow speed for H^0 by as much as a factor of **two** (Li et al. 1998; Cranmer et al. 1999).

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:

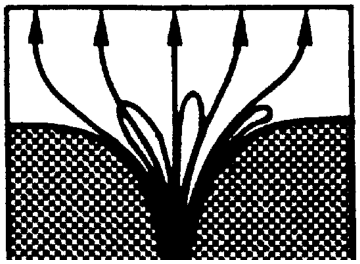


- Anisotropy grows naturally as long as there is an energy supply of resonant waves in the corona. **(Saturated by dispersion...)**
- Ions are accelerated *along* field both by: **(a)** forward curvature of velocity distribution, and **(b)** by magnetic mirroring of high–$v_\perp$ ions.

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).

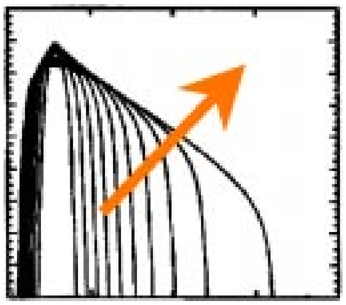


Problem: Low Z/A ions consume base-generated wave energy before it can be absorbed by, e.g., **O^{5+}, He^{2+}, p^{+}.**

(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?

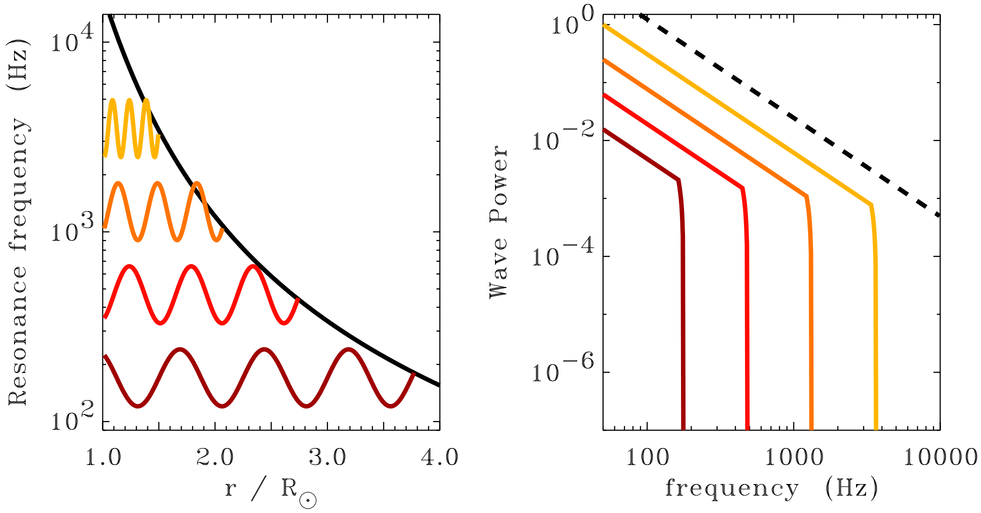
⇒ Instabilities seeded by non-Maxwellian distributions or large-scale velocity shears?



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 . . .

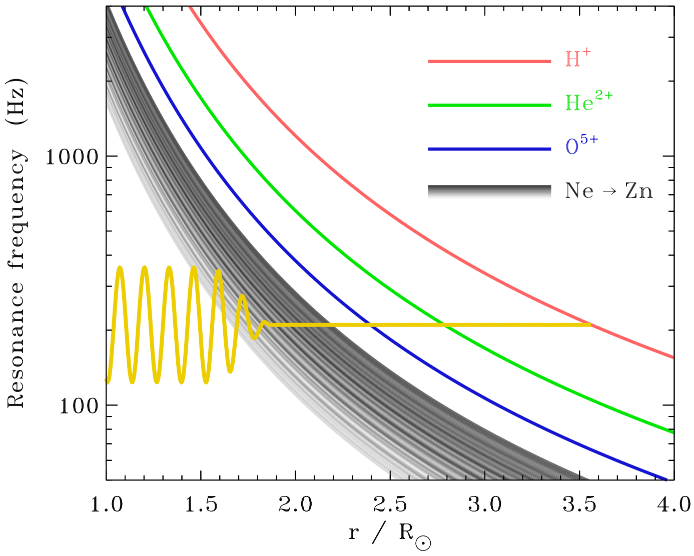
If high-frequency waves originate only at the base of the corona, extended heating “sweeps” across the spectrum:



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.

Gradual Generation of Ion Cyclotron Waves

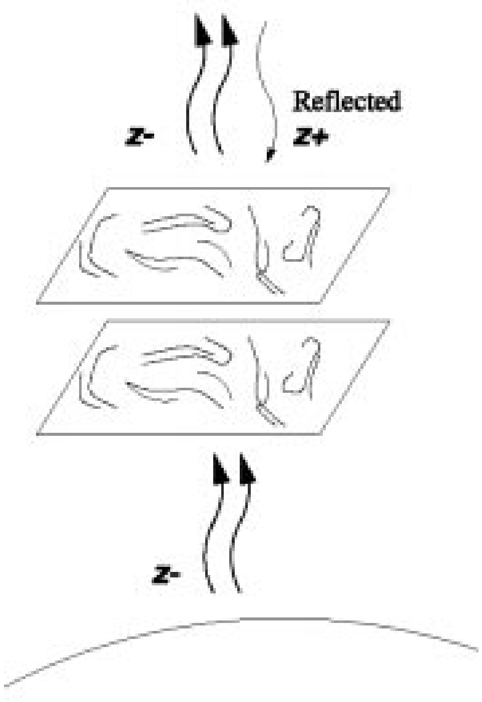
- Most of the work on gyroresonance in the solar wind has been for waves propagating *along* the field **($k_\parallel$)**.

- 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* $\omega \to \Omega_{\rm ion}$*)*

- Perpendicular ("2D") turbulence does dissipate on the smallest scales, but this probably does 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* $(\mathrm{k} \cdot \mathrm{B} \approx 0)$ waves are underway . . . .

Quantitative Heating Rates for Parallel Propagation (1)

It is worthwhile to ask:

How much heating can be “squeezed out” of a purely parallel-propagating spectrum of ion cyclotron waves?

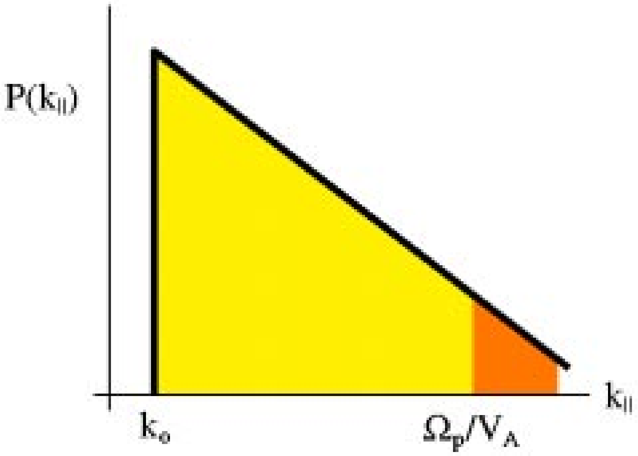
(i.e., maybe the empirically derived heating rates *themselves* give us constraints on the dominant range of obliqueness angles . . .)

Wave power constraints at 2 $R_\odot$:

$$\langle \delta B^2 \rangle = \int_0^\infty dk_\parallel \, P(k_\parallel) \qquad \langle \delta B^2 \rangle_{\rm res} = \int_{\Omega_p/V_A}^\infty dk_\parallel \, P(k_\parallel)$$

$$\frac{\langle \delta B^2 \rangle^{1/2}}{B_0} \approx 0.1$$

$$P(k_\parallel) = P_0 \left(\frac{k_\parallel}{k_0} \right)^{-\eta}$$



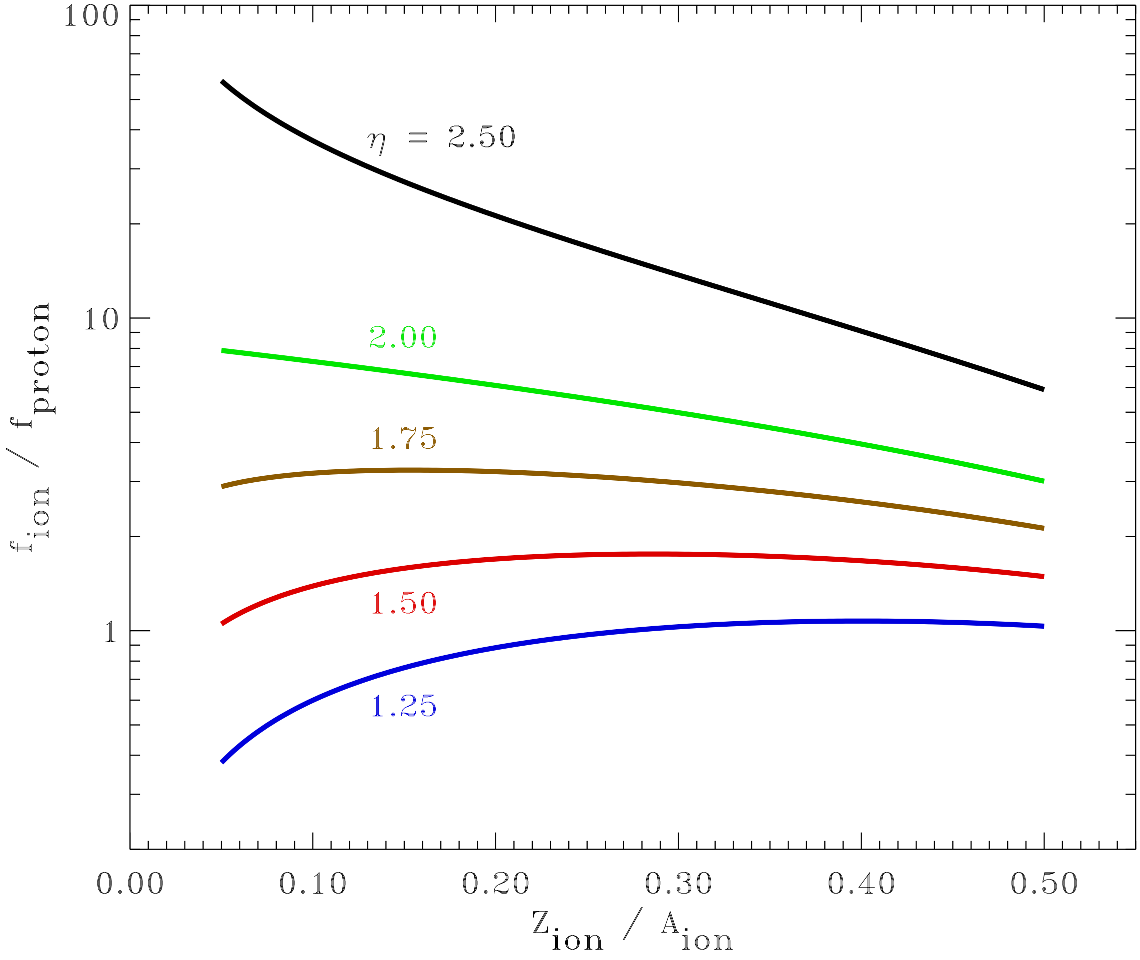
(This assumes that all Alfvén wave power at 2 $R_\odot$ is in “slab” waves...)

Quasi-linear heating rates:

$$\frac{Q_i}{m_i n_i} \approx \frac{\langle \delta B^2 \rangle_{\rm res}}{B_0^2} V_A^2 \, f(\eta, Z/A) \begin{cases} \Omega_p & \text{, if fast “cascade”} \\ k_{\rm res}^{-1} |\partial \Omega_p / \partial r| & \text{, if all sweeping} \end{cases}$$

Quantitative Heating Rates for Parallel Propagation (2)

Preferential ion heating arises in the dimensionless $f(\eta, Z/A)$ function:

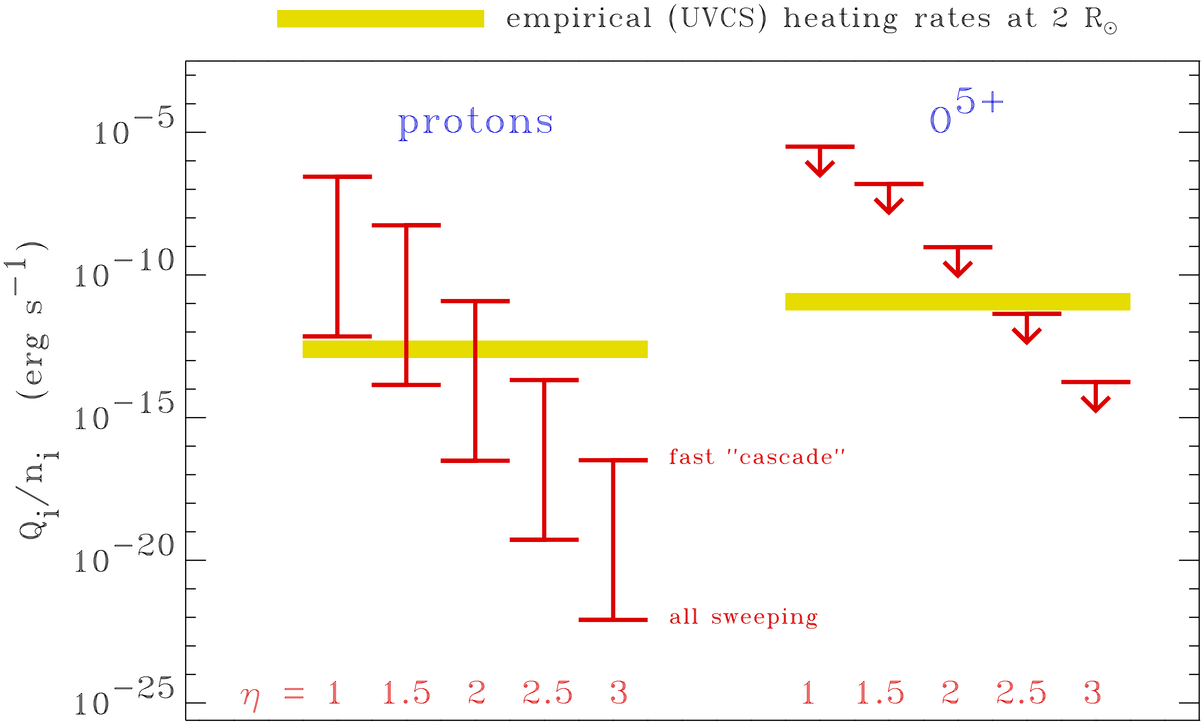


Ions receive more "bang for the buck" because:

- ★ Lower $\Omega_i \longrightarrow$ more power
- ★ Dispersion relation allows more ions to be resonant

Quantitative Heating Rates for Parallel Propagation (3)

Compare empirical heating rates with simple quasi-linear estimates:

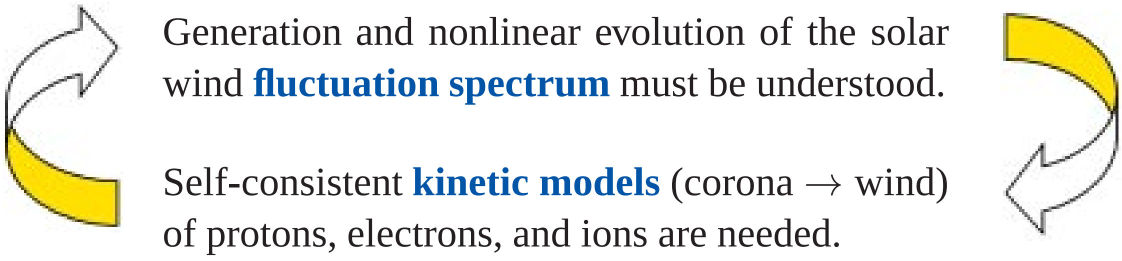


Conclusions:

- ★ **Protons** are probably **not** heated by parallel-propagating cyclotron waves!
- ★ As long as a (non-tiny) fraction of the wave power is in high-$k_{\|}$ modes, there **does** seem to be sufficient power to heat **minor ions.**

Conclusions

- Departures from Maxwellian velocity distributions are crucial probes of the *(still unknown)* heating and acceleration mechanisms.
  - ⇒ Future space-borne spectroscopy of the corona
  - ⇒ NASA’s *Solar Probe* mission . . . ?
- To make progress:



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

Self-consistent **kinetic models** (corona → 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* proton heating rates!
- The lines of communication must be kept open between plasma physicists and astrophysicists.

For more information:

http://cfa–www.harvard.edu/∼scranmer/

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FOR MORE INFORMATION, CONTACT: Steven R. Cranmer (scranmer@cfa.harvard.edu)
http://cfa–www.harvard.edu/∼scranmer/