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Heating of the Extended Solar Corona

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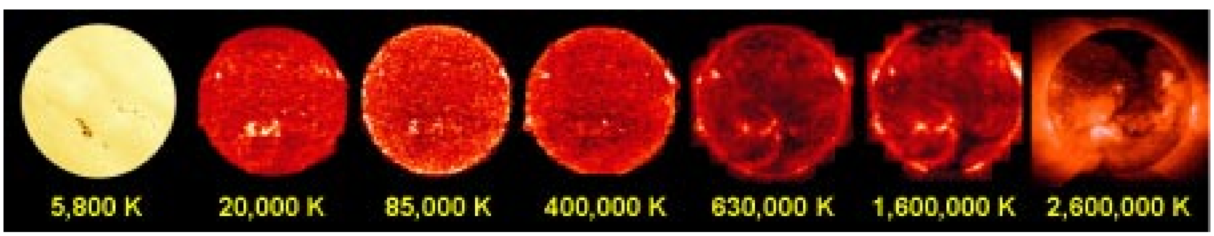
- **Background**
  - $\longrightarrow$ Coronal heating “problems”
  - $\longrightarrow$ Observational constraints (corona $\longrightarrow$ solar wind)
- **Complexity: current challenges**
  - $\longrightarrow$ Proposed heating & acceleration processes
  - $\longrightarrow$ Spatial scales from cm to $R_\odot$
- **Future prospects and “wish lists”**

The Solar Corona

- The outer solar atmosphere is a "laboratory without walls" for many basic kinetic and magnetohydrodynamic (MHD) processes:

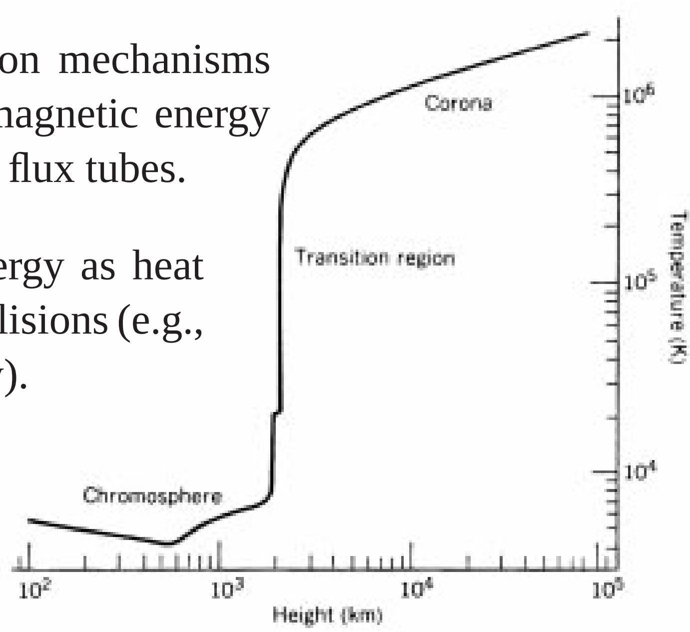
- **gyroresonant wave damping**
- **anisotropic turbulent cascade**
- **shock acceleration**
- **ambipolar diffusion**
- **magnetic reconnection**

- We still do not understand the physical processes responsible for heating the base of the corona ($10^4 \rightarrow 10^6$ K) . . .



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

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



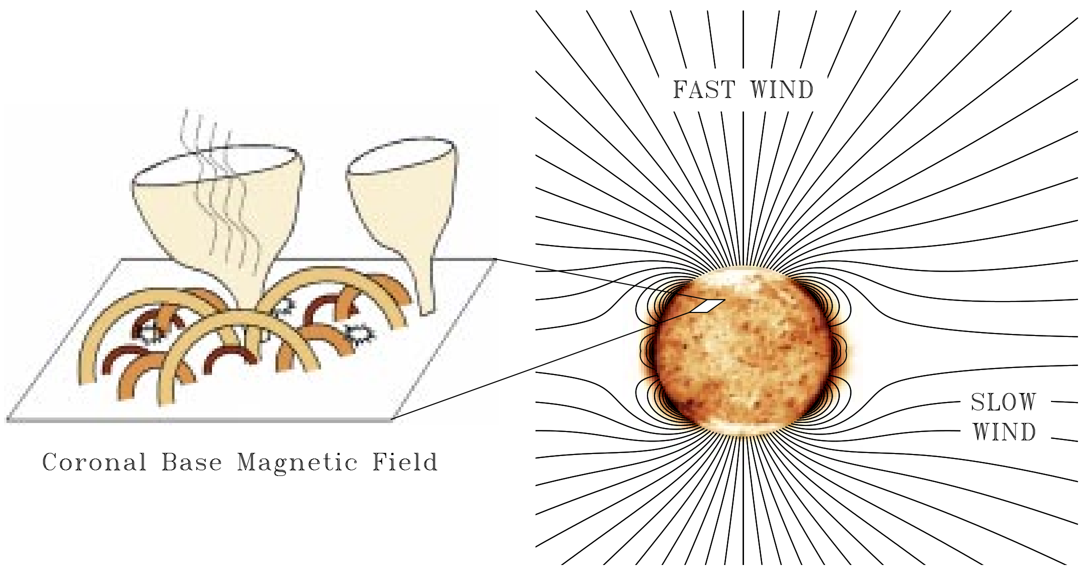
Heating the Extended Corona

Above 2 $R_\odot$, additional energy deposition is required in order to . . .

- ⋆ accelerate the high-speed ($v > V_{\rm esc}$) component of the solar wind;
- ⋆ produce the proton and electron temperatures measured in interplanetary space;
- ⋆ produce the strong preferential heating ($T_\perp \gg T_\parallel$) of heavy ions (in the wind's acceleration region) seen with UV spectroscopy.

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

- ⋆ Collisional $\longrightarrow$ collisionless



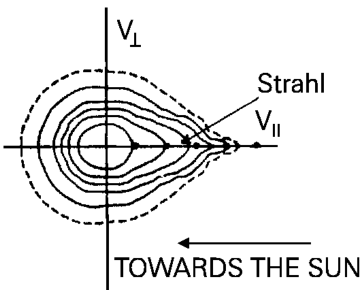
- ⋆ Energy for heating the plasma most likely *propagates* up from the Sun—i.e., **waves, shocks, turbulent fluctuations**—which probably dissipates via wave-particle resonances.

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

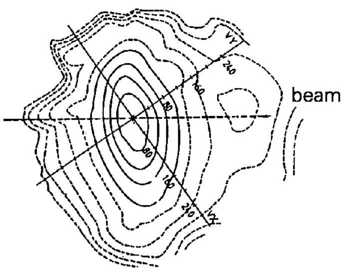
★ In the high-speed wind (that emerges from coronal holes),



Electrons: thermal "core" + beamed "halo"

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

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



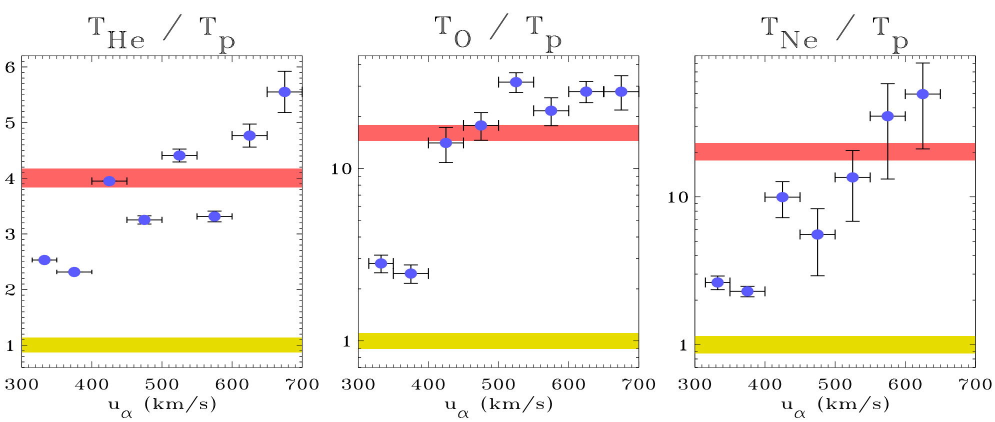
Protons: thermal core exhibits $\boldsymbol{T_\perp > T_\parallel}$

★ $\boldsymbol{\mu}$ 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 $\boldsymbol{(\Delta V \approx V_A)}$

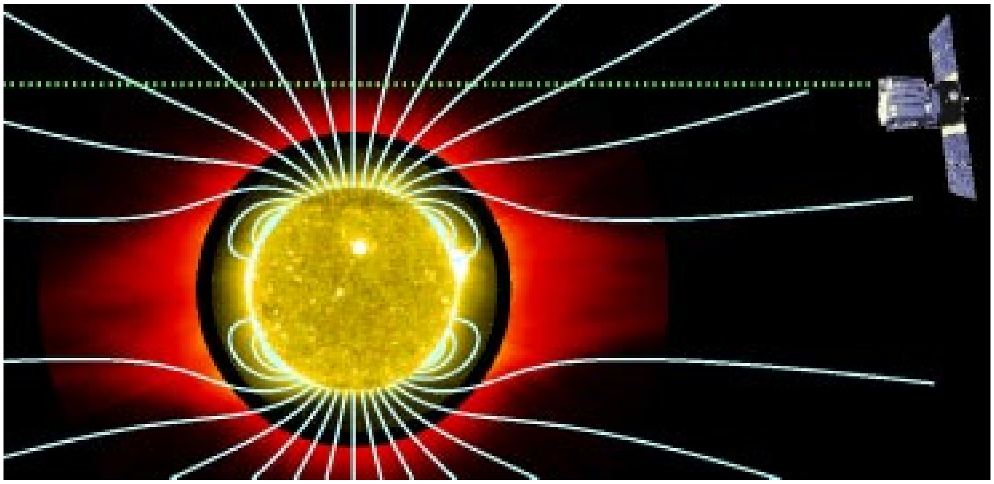
★ $\boldsymbol{(T_{\rm ion}/T_{\rm p}) \gtrsim (m_{\rm ion}/m_{\rm p})}$



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

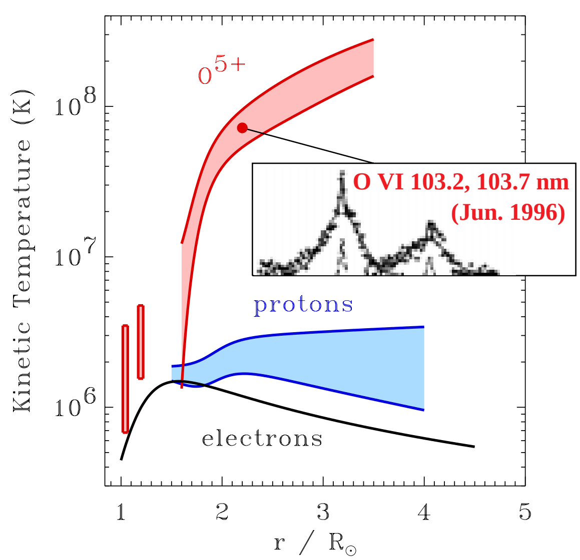
UVCS results: solar minimum (1996–1997)

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



★ H^0 and O^{5+} exhibit **anisotropic** velocity distributions between 1.5 and 4 $R_\odot$ in coronal holes. For O^{5+}, $T_\perp/T_\parallel \approx$ 10 to 100.

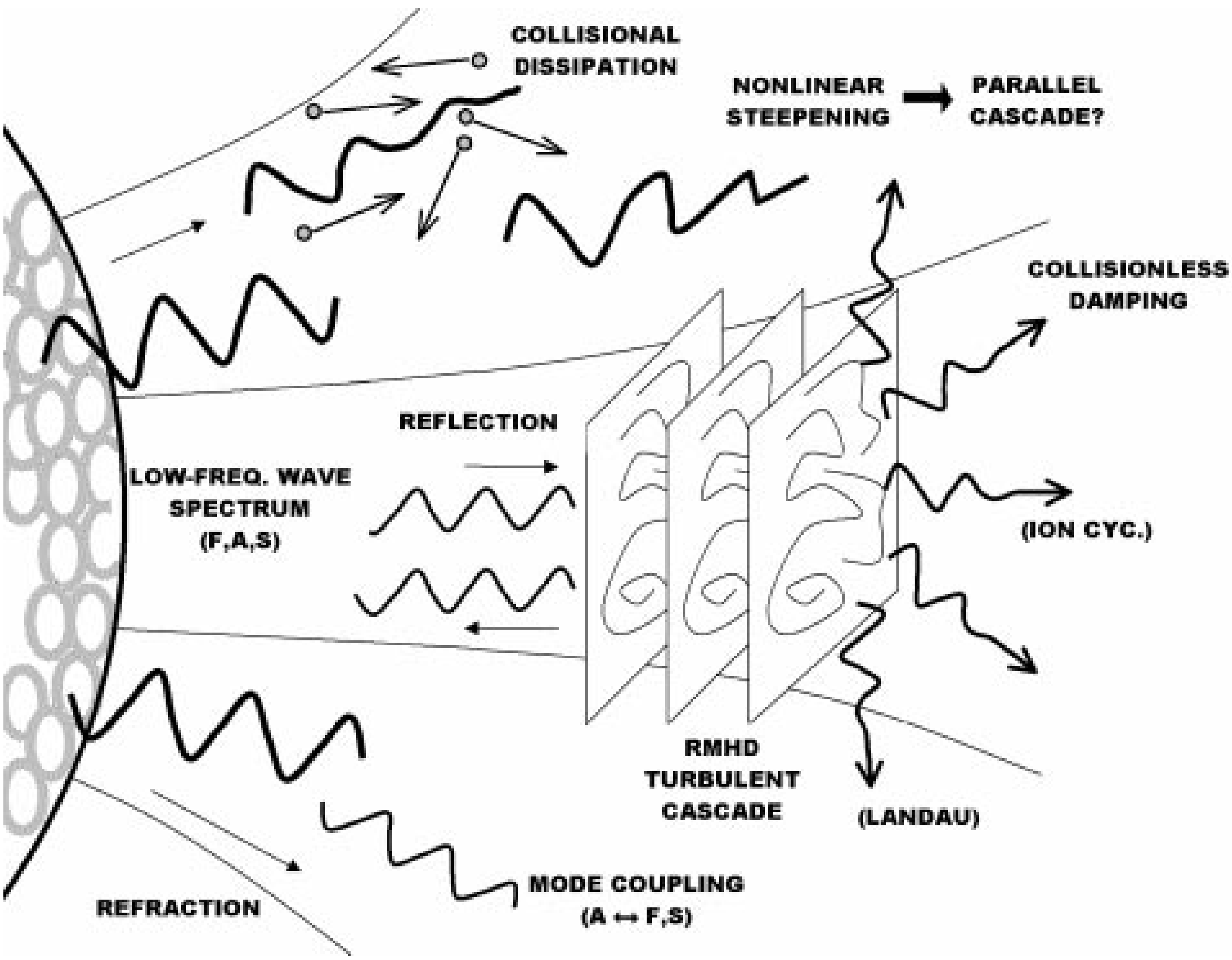
★ For O^{5+}, $T_\perp$ approaches **200 million K** at 3 $R_\odot$. The kinetic temperatures of O^{5+} and Mg^{9+} are much greater than mass-proportional when compared with hydrogen. **Outflow speeds** for O^{5+} are greater than those for the bulk proton-electron plasma by a factor of 2.



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

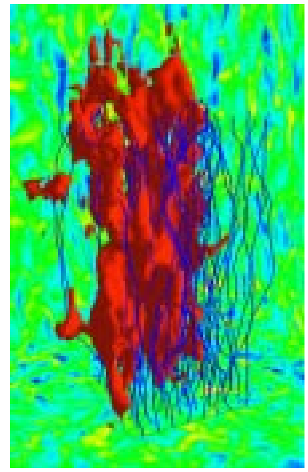
These observations have led to a resurgence of interest in theories of **ion cyclotron wave dissipation** in the extended solar corona.

Complexity: Current Challenges



Multiple scales: MHD turbulence

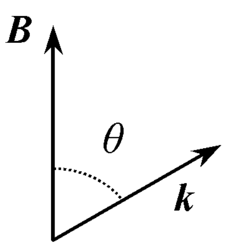
- ⋆ *In situ* δB, δv, $\delta \rho$ data (on time-scales from seconds to years) show evidence for turbulent cascade.

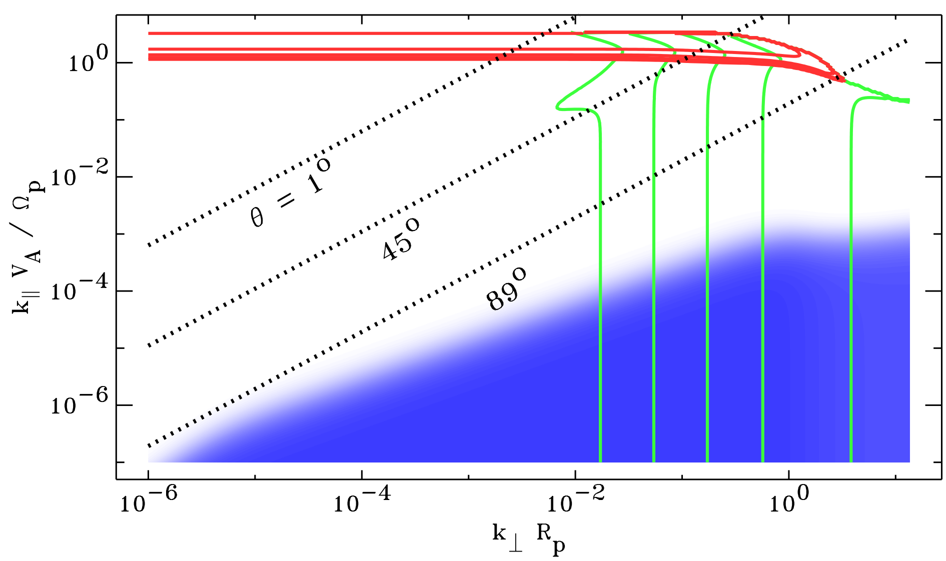


- ⋆ In the low-beta corona, MHD turbulence should proceed **anisotropically,** i.e., mainly from low to high $\boldsymbol{k}_\perp$ while leaving $\boldsymbol{k}_\parallel$ relatively unchanged.

  (In a strong background magnetic field, it is easier to mix field lines in directions perpendicular to **B** than it is to bend them.) (e.g., Stone et al. 1998) ⟹

- ⋆ When this anisotropic spectrum damps, how much heat goes into **electrons, protons,** and heavy ions?

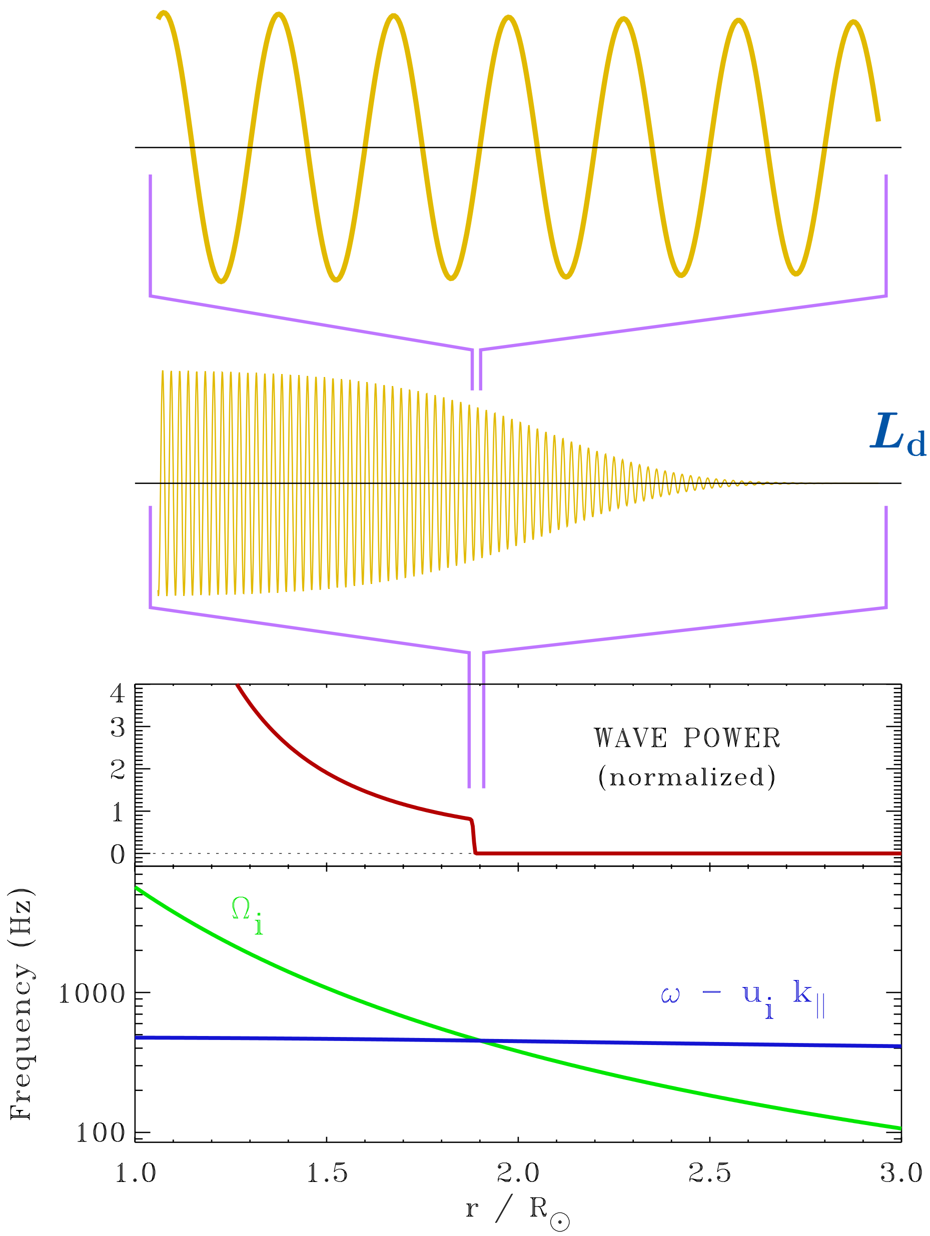




- ⋆ *In situ* solar wind observations support this picture, but large-$k_\parallel$ fluctuations are **also** seen (e.g., Leamon et al. 1998, 2000).

Multiple scales: Ion cyclotron damping

- ★ No matter how/where **high-$k_\parallel$** waves are generated, they damp rapidly once they become cyclotron resonant . . . even for "minor" ions!
- ★ **Below:** waves resonant with **O^{5+}** ions at 2 $R_\odot$ in the corona.



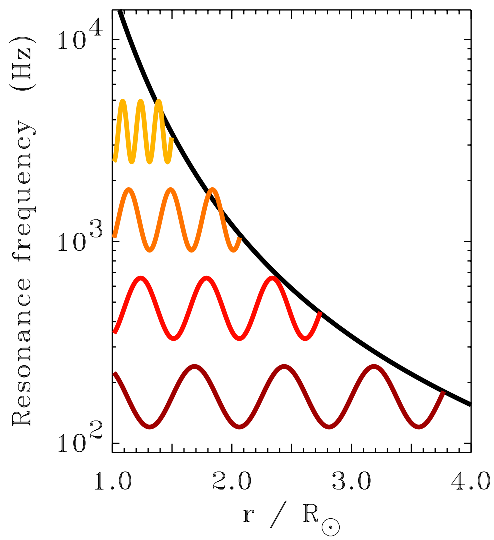
$$\lambda = 2\pi / k_\parallel \approx 10^{-6} R_\odot$$

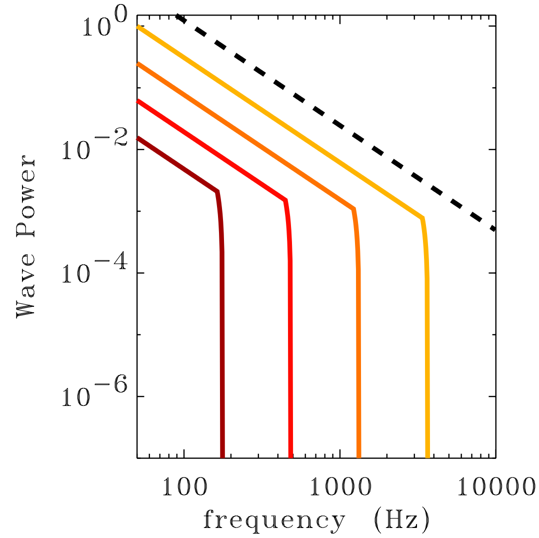
$$L_{\rm damp} \sim \frac{w_{\parallel \rm ion} k_\parallel}{|\partial \Omega_{\rm ion} / \partial r|} \approx 0.01 R_\odot$$

$$L_\Omega = \frac{\Omega_{\rm ion}}{|\partial \Omega_{\rm ion} / \partial r|} \approx 0.4 R_\odot$$

The impact of "minor" ions

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

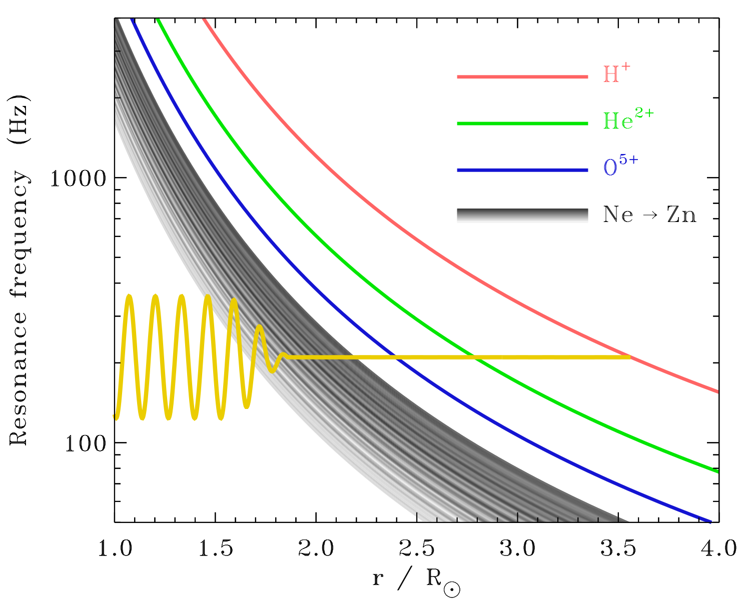




However, **heavy ions** can damp the waves as well:

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

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.

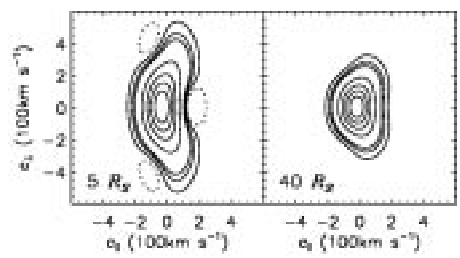
Kinetic vs. Multi-fluid models

- Because Coulomb collisions rapidly grow weaker in the extended corona, the particle velocity distribution functions (VDFs) become **non-Maxwellian** and their moments become **uncoupled.**

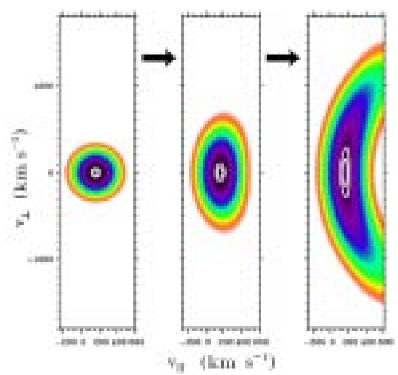
- **Multi-fluid** moment equations are easier to solve, but the shapes of the VDFs are rigidly maintained. **Kinetic** equations are more difficult to solve (and more difficult to include "phenomenological" heating), but are more self-consistent.

- State-of-the-art kinetic models should include . . . .

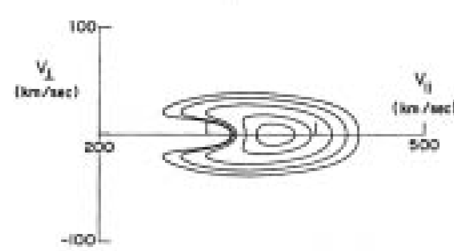
"Standard physics:" gravity, E-field, ∇P, magnetic mirroring (e.g., Li 1999).



Collisionless **wave-particle resonances,** e.g., ion cyclotron heating of O^{5+} ions (Cranmer 2001).



Low-frequency Alfvén **wave pressure** gradient force (e.g., Goodrich 1978).

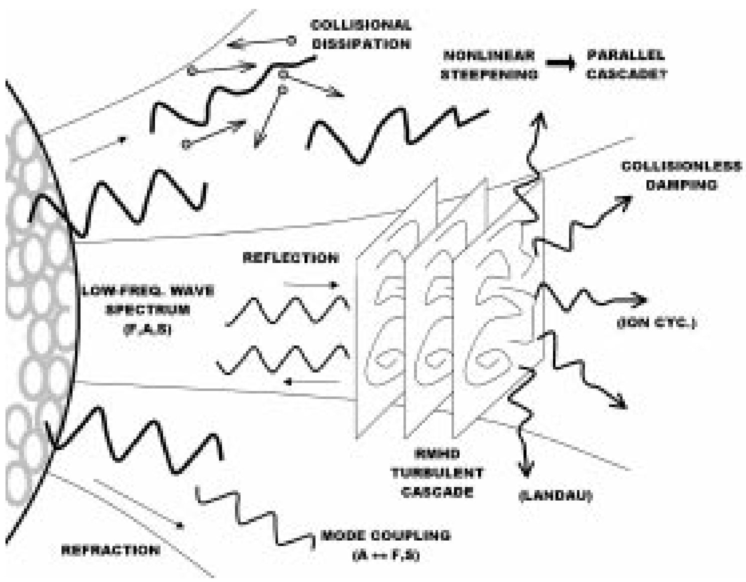


Other: suprathermal 'kappa' tails, electron beams and phase-space-holes, anisotropies limited by instabilities?

A “wish list” for solar wind models?

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.

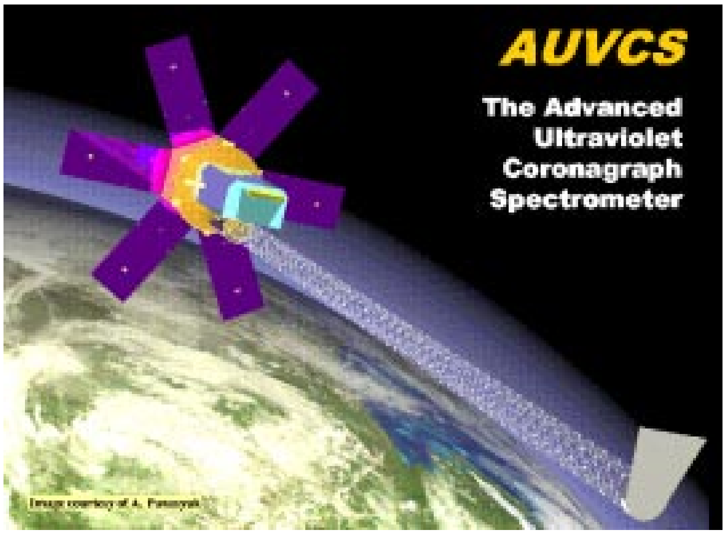


- ⋆ Because the multitude of proposed physical processes **interact with one another** on a wide range of scales, their impact can only be evaluated when they are all included together.

- ⋆ There is a need for scalable “phenomenological” terms that encapsulate the physics of nonlinear steepening, multi-mode coupling, refraction, etc., and allow them to be included in “linear” wave transport equations.

Conclusions

- ⋆ Our understanding of the dominant physics in the acceleration region of the solar wind is progressing rapidly **. . .** but so is the complexity!
- ⋆ We still don't know several key plasma parameters (e.g., $\boldsymbol{T}_{\mathrm{e}}$ and $\boldsymbol{T}_{\mathrm{p}}$) with sufficient accuracy!
  - ⇒ NASA's *Solar Probe* mission . . . ?
  - ⇒ Future space-borne spectroscopy of the extended corona



- ⋆ 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 between { solar, space, plasma } physicists must be kept open.
- ⋆ *See also:* **http://cfa–www.harvard.edu/∼scranmer/**