Non-Maxwellian Velocity Distributions in the Solar Corona

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- **Background & observations**
- **Modeled solar wind velocity distributions**
- **Ion cyclotron "diffusion"**
  - ⟶ **how efficient is this process?**
  - ⟶ **how does it affect UV emission line profiles?**

Solar Corona $\longrightarrow$ Solar Wind

⋆ The idea of a continuous outflow of charged particles from the Sun developed gradually in the first half of the 20th century . . . .



⋆ **1939:** Grotrian, Edlén determined that coronal plasma has $T \gtrsim 10^6$ K.

⋆ **1950–53:** In a hot corona, $\lesssim$ 50% of electrons have $v_r > V_{\rm esc}$
$\ll$ 1% of protons have $v_r > V_{\rm esc}$

Pikel'ner & van de Hulst modeled the resulting *electrostatic forces.*

⋆ **1957:** Chapman modeled electron heat conduction in a static corona, and found $T \propto r^{-2/7}$, but $\rho \propto r^{+2/7}$.

⋆ **1958:** Parker's **(Ap.J., 128, 664)** isothermal fluid solar wind:

$\Rightarrow$ high temperature allows a natural transition from a subsonic (quasi-static) atmosphere to a supersonic outflow.

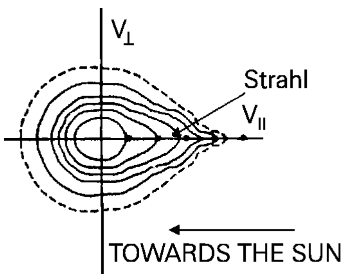
$\Rightarrow$ gas pressure is a collisionless phenomenon!

In situ Particle Properties

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

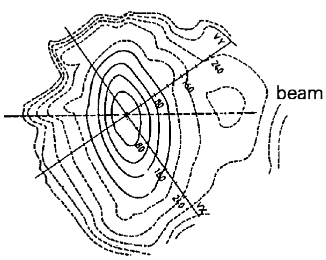
high-speed (500–800 km/s)	low density	∼laminar flow
low-speed (300–500 km/s)	high density	variable, filamentary

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



Electrons: thermal “core” + beamed “halo”

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

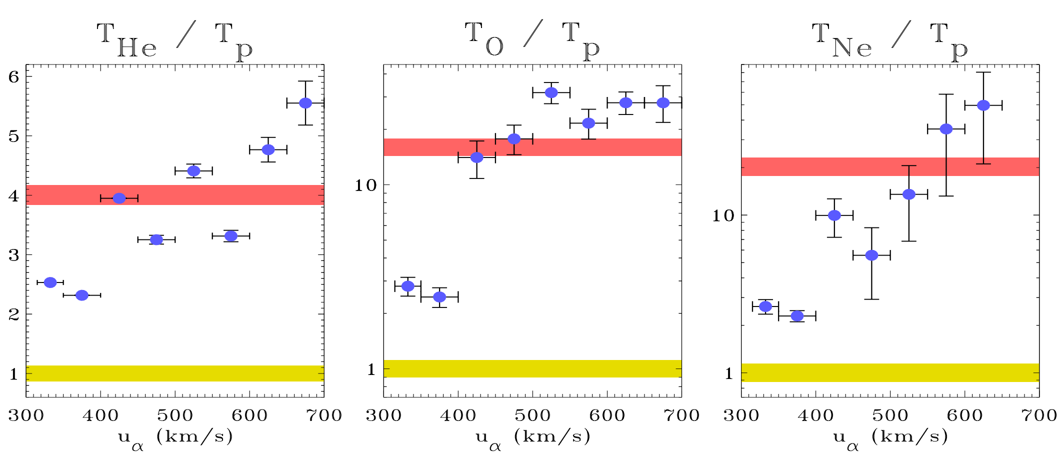


Protons: thermal core exhibits $T_\perp > T_\parallel$

- ⋆ 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 $(\Delta V \approx V_A)$

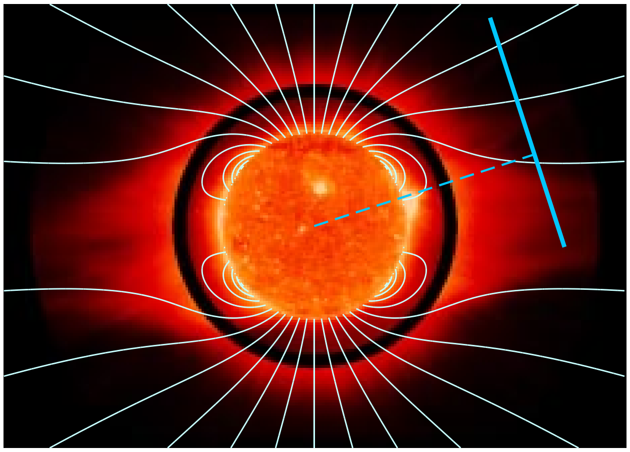
- ⋆ $(T_{\rm ion}/T_{\rm p}) \gtrsim (m_{\rm ion}/m_{\rm p})$



Ultraviolet Coronagraph Spectroscopy

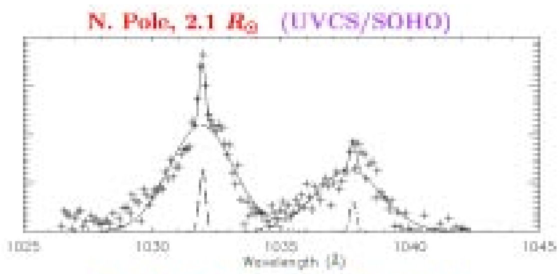
★ **Motivation:** measure plasma properties of hot (>10^6 K) protons, electrons, & ions as they accelerate.

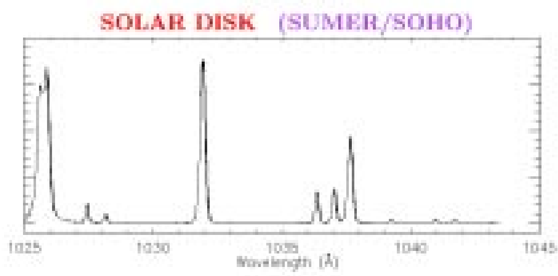
1979–1995: H I Lyα measured with rockets, Spartan 201
1996–present: dozens of lines measured with UVCS/SOHO



★ O VI 1032, 1037 lines very wide over polar coronal holes. For O^{5+}, $T_\perp$ approaches **200 million K** at 3 $R_\odot$ and $T_\perp/T_\parallel \approx$ 10–100.

★ Temperatures for O^{5+}, Mg^{9+} are $\gg$ mass-proportional, compared with H^0 (Kohl et al. 1997, 1998; Cranmer et al. 1999).





★ Outflow speeds of O^{5+} exceed **400 km/s** at 3 $R_\odot$, and are larger than those of H^0 by about a factor of two.

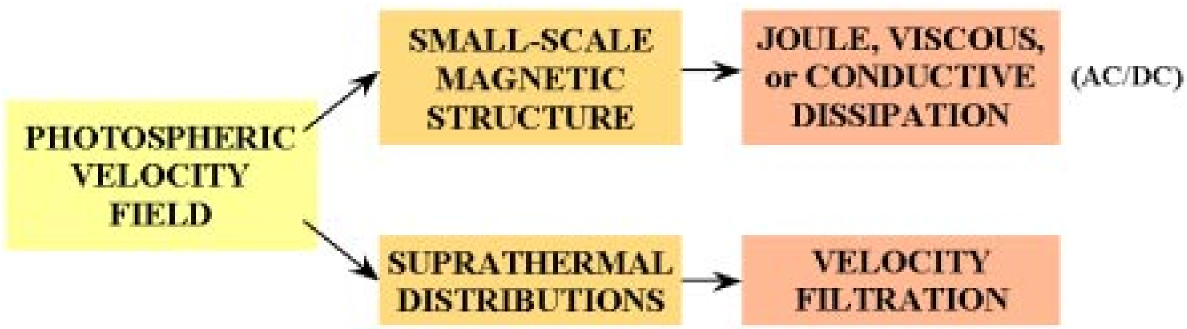
Coronal Heating Problems

⋆ Heat conduction *cannot* keep temperatures high in the extended (∼collisionless) corona! (e.g., Sturrock & Hartle 1966)

⋆ It makes sense to treat the base and the extended corona separately:

1. Transition Region ⟶ Lower Corona **(1–1.5 $R_\odot$)**

   ⋆ Coulomb collisions are strong; field topology is complicated.



2. Extended Corona ⟶ Heliosphere **($> 2\ R_\odot$)**

   ⋆ Coulomb collisions are weak; field expansion is ∼smooth.

   ⋆ The wind's mass flux is already determined, but the particles are accelerating and "differentiating."

   ⋆ Waves / shocks / jets / turbulence transport momentum and energy over long distances. How is it dissipated?

Solar Wind Models

★ Begin with the Boltzmann transport equation for ion species i:

$$\frac{Df_i}{Dt} \equiv \frac{\partial f_i}{\partial t} + \mathbf{v} \cdot \frac{\partial f_i}{\partial \mathbf{x}} + \underbrace{\mathbf{a}}_{-\mathbf{g} + \frac{q_i}{m_i}\left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right)} \cdot \frac{\partial f_i}{\partial \mathbf{v}} = \{\text{collisions}\}$$

★ **KINETIC** models solve for $f_i(\mathbf{x}, \mathbf{v})$ directly:

+ most complete and self-consistent method
− difficult to solve
− “heating” must be tied directly to physics

★ **FLUID** models assume a functional form for f_i and solve for its parameters (which are designed to be **moments** of the distribution):

$$\int d^3\mathbf{v}\ f_i(\mathbf{v}) \left\{ \begin{array}{c} 1 \\ v_\parallel \\ 2(v_\parallel - u_\parallel)^2 \\ v_\perp^2 \end{array} \right\} = \left\{ \begin{array}{c} n_i \\ n_i\, u_\parallel \\ n_i\, w_\parallel^2 \\ n_i\, w_\perp^2 \end{array} \right\}$$

+ moment equations are more straightforward to solve
+ heating rates can be included phenomenologically
− the shape of f_i is rigidly maintained

Maxwellian and Bi-Maxwellian Models

⋆ Parker-type models assume a drifting Maxwell-Boltzmann distribution:

$$f_i(\mathrm{v}) = \frac{n_i}{\pi^{3/2} w^3} \exp\left[- \left(\frac{\mathrm{v} - \mathrm{u}}{w} \right)^2 \right]$$

Typically, $\mathbf{u} \parallel \mathbf{B}$, $w = w_{\parallel} = w_{\perp} = \sqrt{\frac{2kT}{m_i}}$

The first and second moments of the Boltzmann equation become conservation equations for momentum and internal energy:

$$u \frac{\partial u}{\partial r} = -\frac{1}{m_i n_i} \frac{\partial}{\partial r}(n_i k T) - g$$

$$\frac{3}{2} n_i u k \frac{\partial T}{\partial r} = u k T \frac{\partial n}{\partial r} + Q$$

⋆ In strong magnetic fields, $w_{\parallel} \neq w_{\perp}$ (Chew, Goldberger, & Low 1956)

$$f_i(v_{\parallel}, v_{\perp}) = \frac{n_i}{\pi^{3/2} w_{\parallel} w_{\perp}^2} \exp\left[- \left(\frac{v_{\parallel} - u_{\parallel}}{w_{\parallel}} \right)^2 - \frac{v_{\perp}^2}{w_{\perp}^2} \right]$$

With no imposed heating or momentum deposition, the following "adiabatic invariants" are conserved:

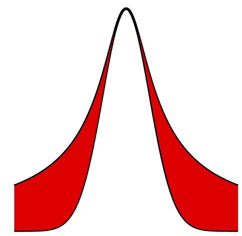
$$\frac{\partial}{\partial r} \left(\frac{w_{\perp}^2}{B} \right) = 0 \ , \quad \frac{\partial}{\partial r} \left(\frac{w_{\parallel}^2 B^2}{n_i^2} \right) = 0 \quad \Rightarrow \quad w_{\parallel} \gg w_{\perp} \text{ at 1 AU}$$

However, we observe $w_{\perp} \gtrsim w_{\parallel}$ in the solar wind!

Other Non-Maxwellian Velocity Distributions

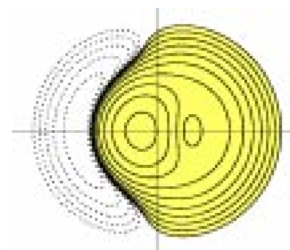
⋆ Suprathermal tails (Lorentzian, “κ”) become overpopulated as one moves up in a gravity well

(Vasyliunas 1968; Scudder & Olbert 1979; Scudder 1992a, 1992b; Treumann 1997; Maksimovic et al. 1997; Meyer-Vernet 1999)

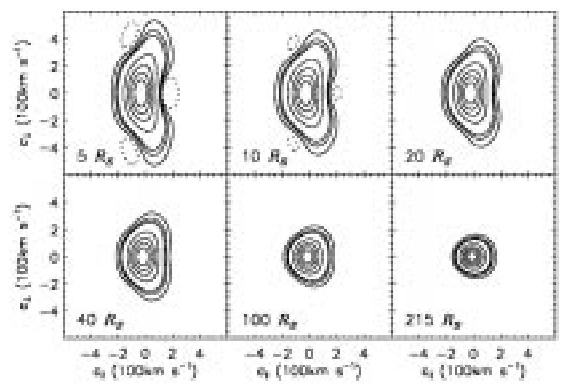


⋆ Polynomial expansions about Maxwellians model the heat flux transfer self-consistently

(Chapman & Cowling 1964; Schunk 1977; Demars & Schunk 1991; Olsen & Leer 1996)

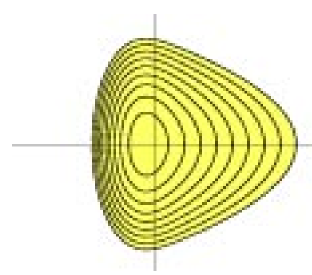


Li (1999) included perpendicular heating and parallel cooling to model the observed proton anisotropy:



⋆ Whealton & Woo (1971) derived an analytic distribution function for a constant Coulomb collision rate in a partially ionized plasma

(Leblanc & Hubert 1997, 1998, 1999)

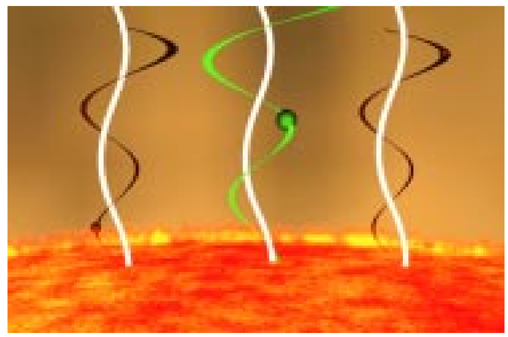


Ion Heating and Acceleration

- ⋆ The dominant physical processes in the corona should constrain how to best parameterize the velocity distributions.

- ⋆ Of the many proposed mechanisms, only the damping of **ion cyclotron resonant waves** seems able to provide:

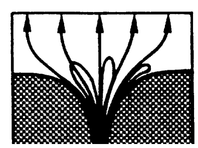
$$\left\{ \begin{array}{rcl} T_\perp & > & T_\parallel \\ (T_{\rm ion}/T_p) & > & (m_{\rm ion}/m_p) \\ u_{\rm ion} & > & u_p \end{array} \right\}$$



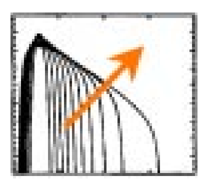
- ⋆ High-frequency (10–10,000 Hz) parallel-propagating Alfvén waves damp when $(\omega - V_{\rm ion} k_\parallel) = \Omega_{\rm ion}$. Kinetic energy is transferred easily from wave motions to particle motions.

How are these *unobserved* waves generated?

- ⋆ **Microflare reconnection** in the supergranular network?



- ⋆ **MHD turbulent cascade** of low-frequency Alfvén wave power to higher frequencies?

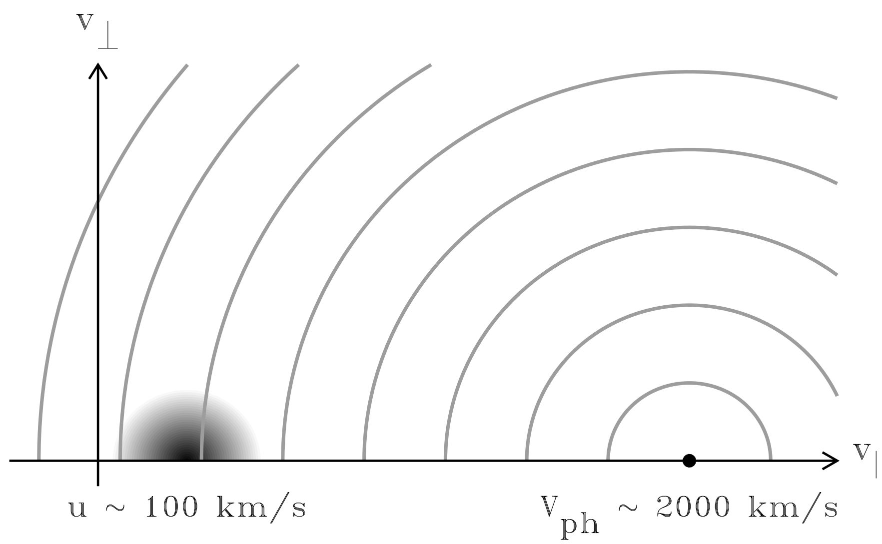


- ⋆ **Plasma instabilities** of non-Maxwellian velocity distributions (? $\longrightarrow$ particle $\longrightarrow$ wave $\longrightarrow$ particle)

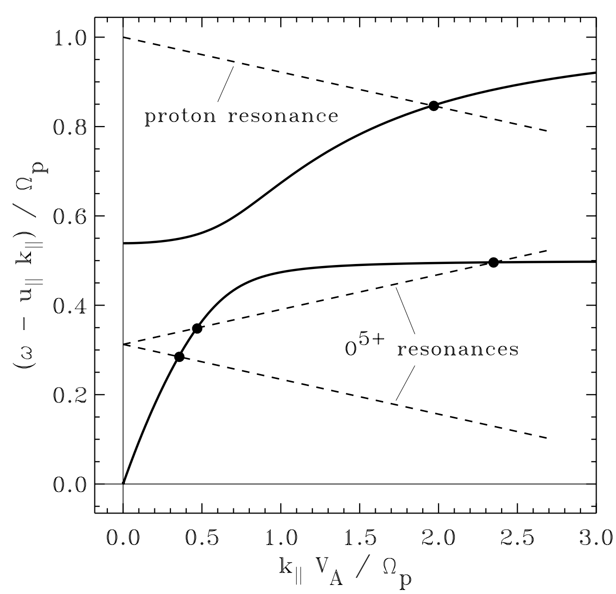
Ion Cyclotron Diffusion

★ Dissipation of ion cyclotron waves distorts velocity distributions away from Maxwellian shapes.

★ On a kinetic level, it produces a **diffusion** in velocity space ∼along contours of constant kinetic energy in the frame moving with the wave phase speed:



★ Diffusion only occurs at parallel speeds where simultaneous solutions exist to the dispersion and resonance conditions. Only half of the **proton** distribution can be resonant!



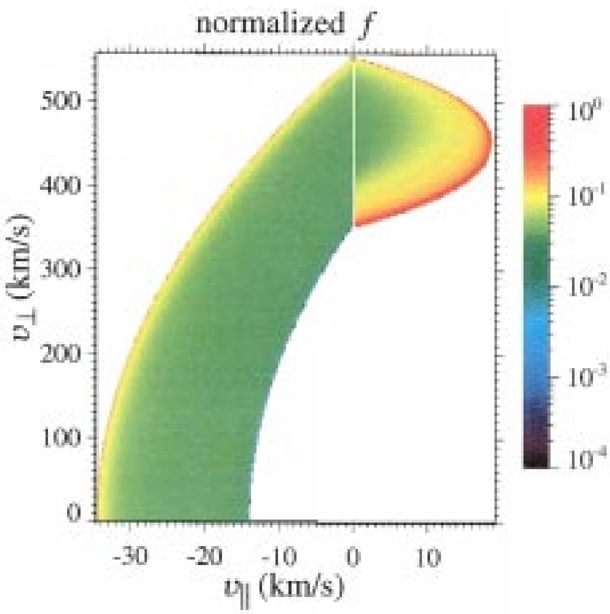
“Instant” Diffusion Models for Protons

★ Two recent papers have presented proton distributions that result from ion cyclotron diffusion—in the limit of abundant wave power (i.e., **rapid** diffusion compared to all other solar wind time scales):

★ Isenberg, Lee, & Hollweg (2000)

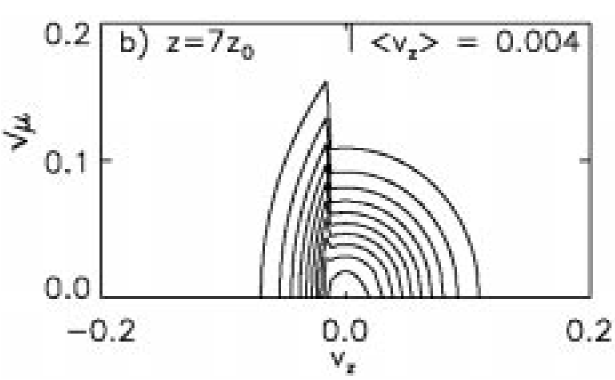
⇒ assumes evenly-filled “shells” for $v_\parallel < u_\parallel$

⇒ follows particle trajectories numerically for $v_\parallel > u_\parallel$



★ Galinsky & Shevchenko (2000)

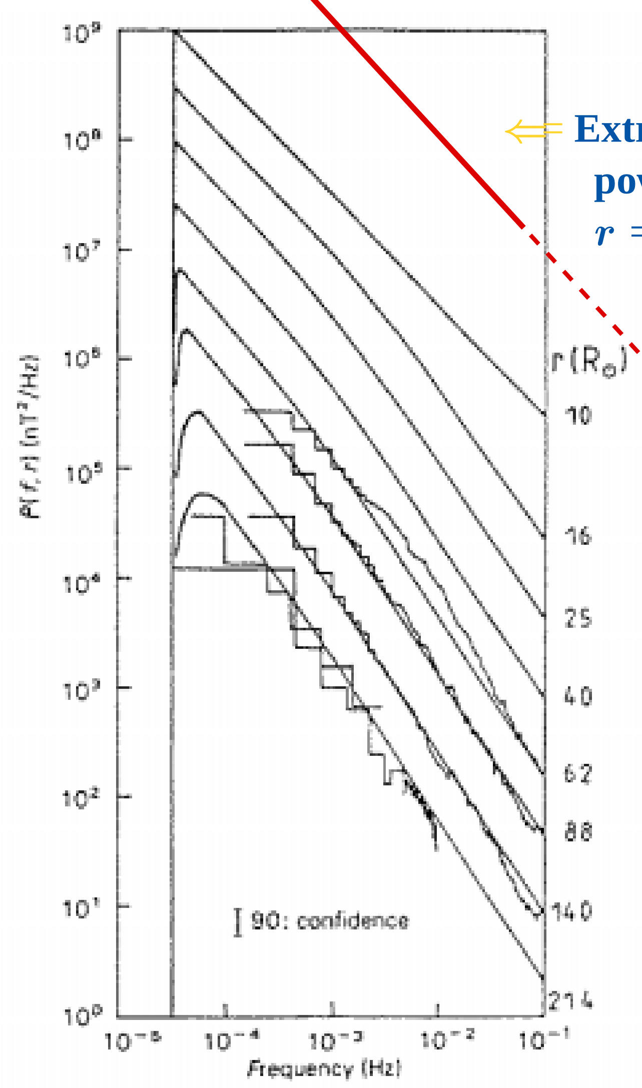
⇒ applies “time scale separation” to treat the diffusion and solar wind evolution together; solves for the distribution and the wave spectrum ∼analytically



How Instant is the Resonant Diffusion?

★ One can define a **“doubling time,”** i.e., the time it takes for resonant diffusion to double $w_\perp$ starting with a Maxwellian distribution:

$$\tau_d = \frac{3}{2\pi}\left(\frac{m_i c}{q_i}\right)^2 \frac{V_A}{P_B(k_{\parallel \mathrm{res}})}\left(\frac{w_{\perp\,\mathrm{init}}}{V_A}\right)^2$$



⇐ **Extrapolation of *in situ* power spectra down to $r = 3\,R_\odot$**

$\tau_d \approx 10^{-3}$ sec

O VI modeled heating at $r = 3\,R_\odot$

⇓

$\tau_d \approx 100$ sec

(see, e.g., Tu 1987; Tu & Marsch 1995)

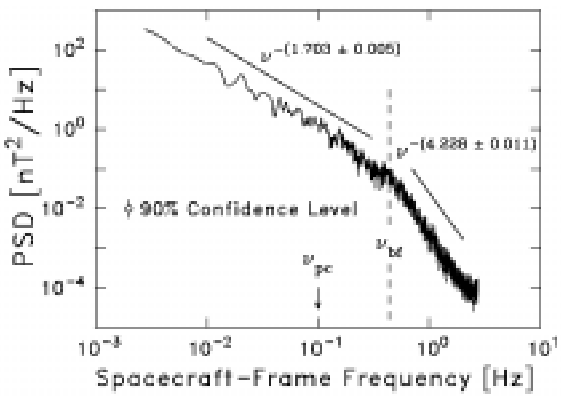
Resonant $k_{\|}$ Wave Power

There are several reasons to believe that the ion cyclotron fluctuation power in the corona is **weaker** than the simple WKB extrapolation:

1. Turbulence may not be fully developed.

- $\Rightarrow$ inward waves not yet excited?
- $\Rightarrow$ outward wave amplitudes are still $\sim$linear

2. Even if the turbulence is fully developed, the spectral slopes around the ion cyclotron frequency are expected to be steeper than f^{-1} (cascade combats strong damping!)



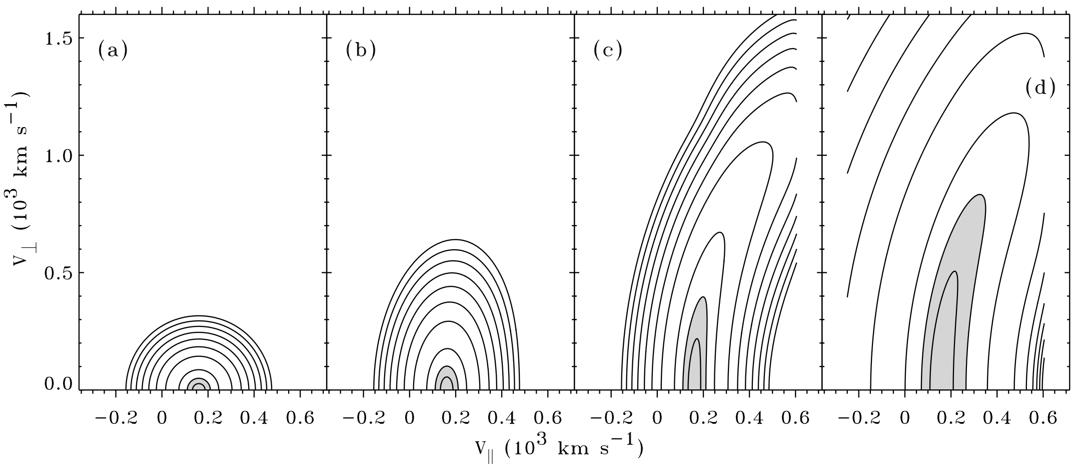
3. The above WKB extrapolation assumed all the power was in **parallel-propagating** waves. In reality, there should be a continuous distribution of wavevector inclination angles.

- $\Rightarrow$ Matthaeus et al. (1999) & Leamon et al. (2000) claim that coronal turbulence is dominated by **large-$k_{\perp}$, low-freq.** waves.

A Diffusion Model for O^{5+} Ions

- ⋆ For ease of comparison with bi-Maxwellian moment models, assume a **homogeneous plasma:** everything scales with τ_d.

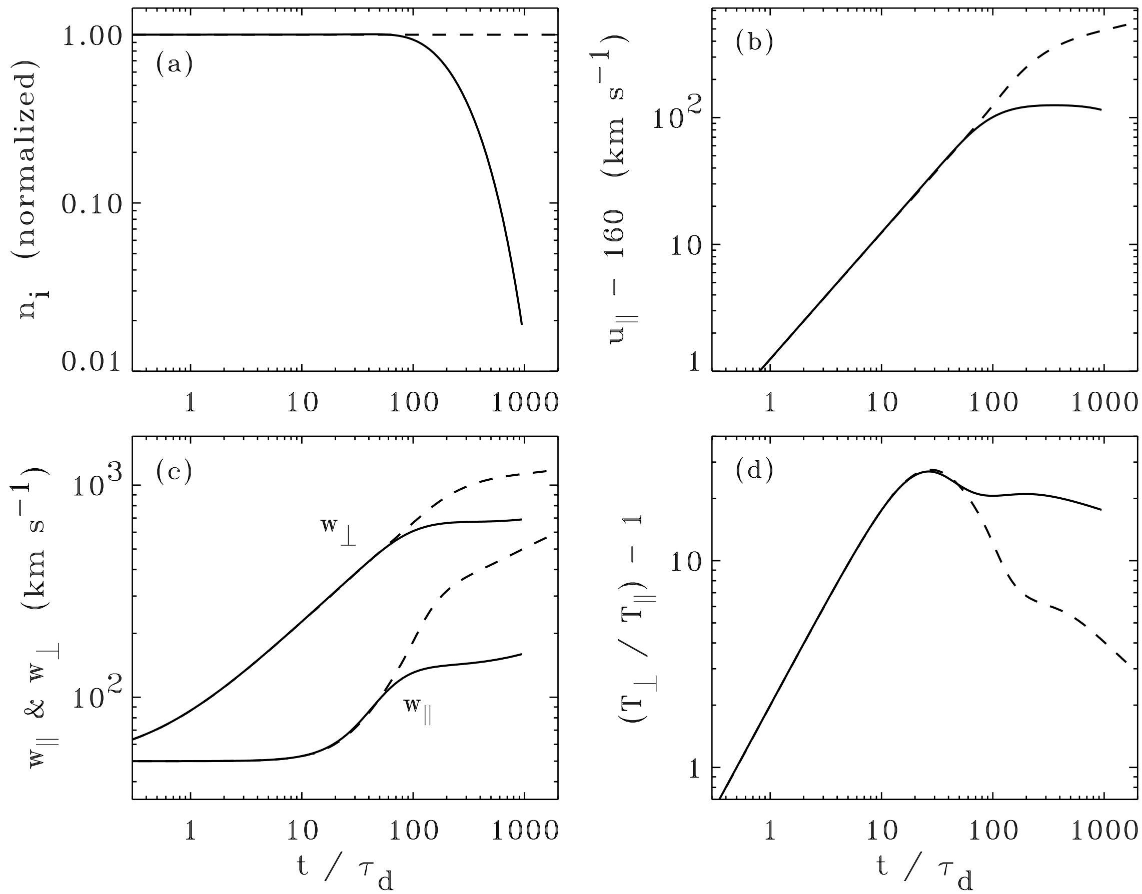
- ⋆ O^{5+} ions are resonant for $v_\| < 610\ \mathrm{km\ s^{-1}}$. Use this as upper boundary:



$t/\tau_d =$ **0** **1.5** **32** **800**

- ⋆ The distribution never diffuses completely:
  - ⇒ Diffusion is the result of a random walk process
  - ⇒ "Scatterings" in both directions on shells are required
  - ⇒ Near the resonance/non-resonance boundary in $v_\|$, this does not occur!

O^{5+} Moments: Diffusion vs. Bi-Maxwellian



Models also computed for:

- **He^{+}** $(Z/A = 0.25)$
- O^{5+} $(Z/A = 0.31)$
- **Mg^{9+}** $(Z/A = 0.37)$

⋆ For higher Z/A, shells are more tightly curved, and the boundary between resonance and non-resonance *decreases* in $v_{\|}$. **“Saturation” occurs sooner!**

Physically Inspired Analytic Distributions?

True circular shells:

$$\boldsymbol{f_i(r, \theta)} \;\propto\; \exp\left[-\left(\frac{\boldsymbol{r - r_0}}{\Delta \boldsymbol{r}}\right)^2 - \left(\frac{\boldsymbol{\theta}}{\Delta \boldsymbol{\theta}}\right)^2\right]$$

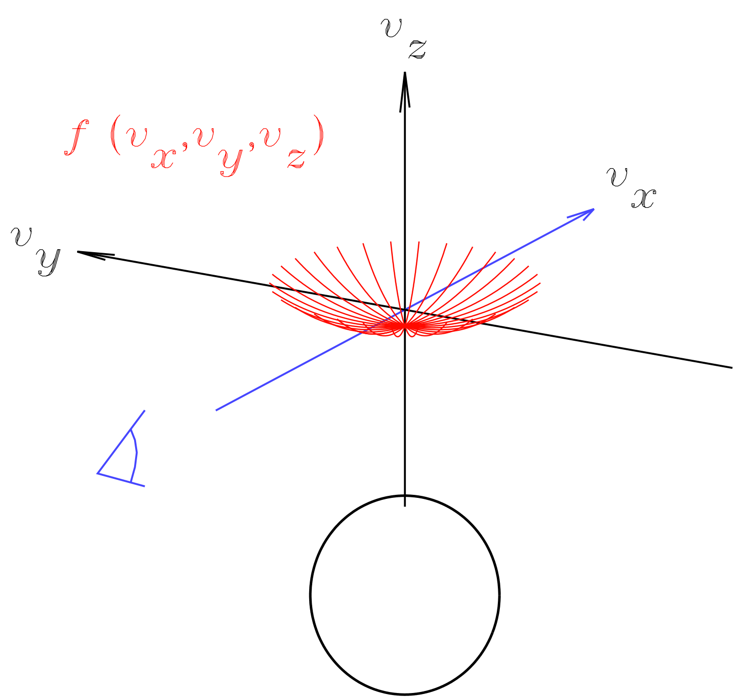
Rotated ellipses: (only one extra, easily-defined moment)

$$\boldsymbol{f_i(v_{||}, v_{\perp})} \;\propto\; \exp\left[-\left(\frac{\boldsymbol{v_{||} - u_{||}}}{\boldsymbol{w_{||}}}\right)^2 - \left(\frac{\boldsymbol{v_{\perp}}}{\boldsymbol{w_{\perp}}}\right)^2 + \boldsymbol{\epsilon}\left(\frac{\boldsymbol{v_{||} - u_{||}}}{\boldsymbol{w_{||}}}\right)\left(\frac{\boldsymbol{v_{\perp}}}{\boldsymbol{w_{\perp}}}\right)\right]$$

Emission Line Formation

★ **Line-of-sight integral of local emissivities:**

$$I_\lambda = \int dx \, (j_{\rm coll} + j_{\rm res})$$

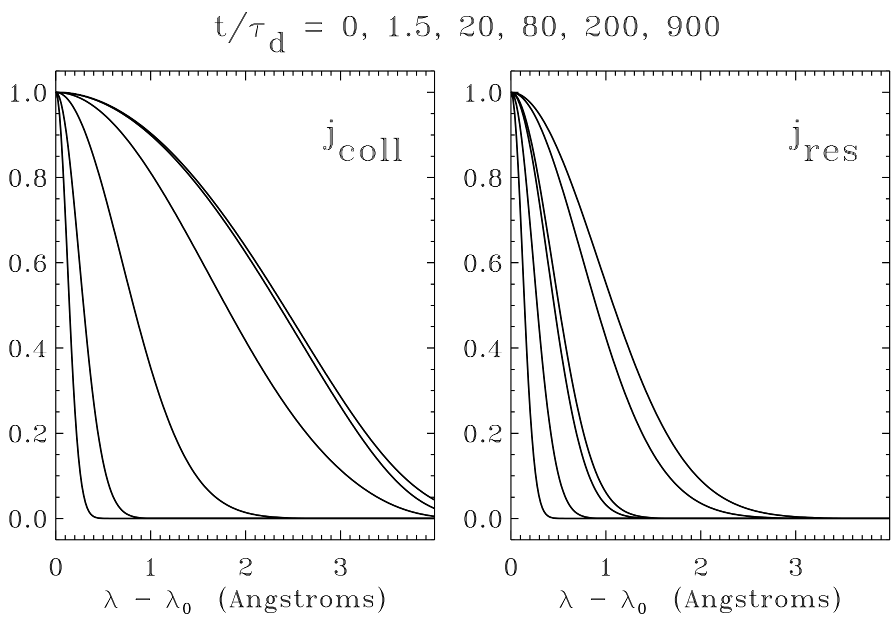


$$j_{\rm coll} \propto n_e \, n_i \, q_{jk}(T_e) \int dv_y \, dv_z \, f\left(\frac{c}{\lambda_0}(\lambda - \lambda_0)\,,\ v_y\,,\ v_z\right)$$

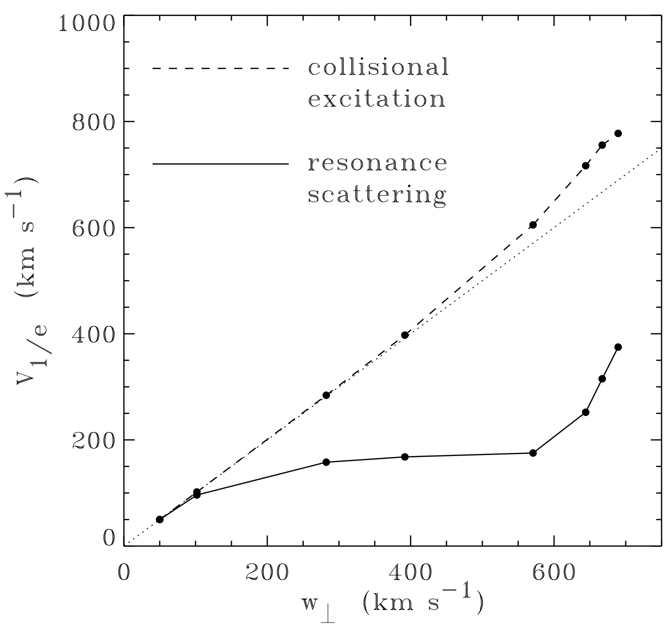
$$j_{\rm res} \propto n_i \, B_{jk} \int d\lambda' \int d\Omega' \, I_{\rm disk} \int dv_y \, f\left(\frac{c}{\lambda_0}(\lambda - \lambda_0)\,,\ v_y\,,\ \frac{c}{\lambda_0}(\lambda' - \lambda_0)\right)$$

Numerical O VI Line Profiles

★ For various times in the diffusion calculation, the full velocity distribution $f_i(v_x, v_y, v_z)$ was output and used to compute O VI λ1032 emissivity profiles (assuming delta-function disk profiles):

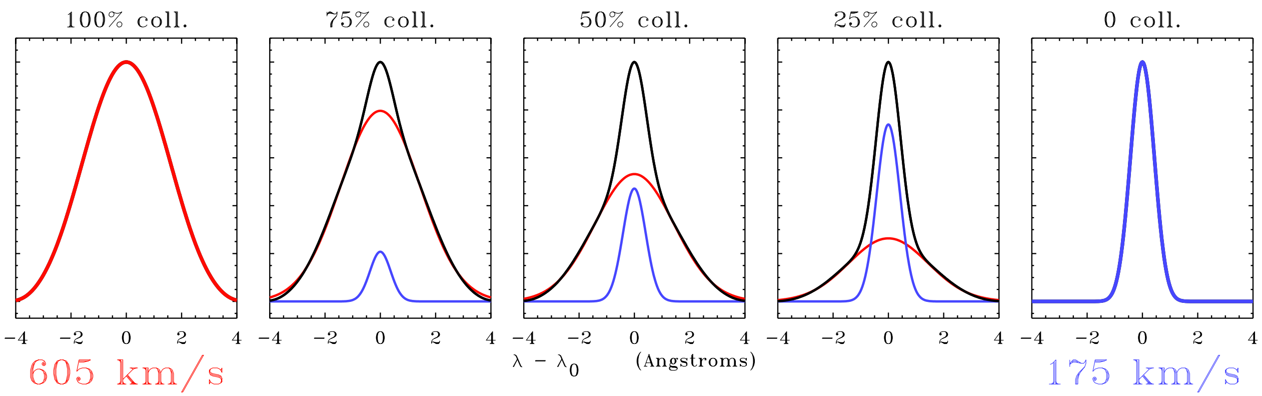


★ Gaussian fits compared with **perpendicular most-probable speeds:**

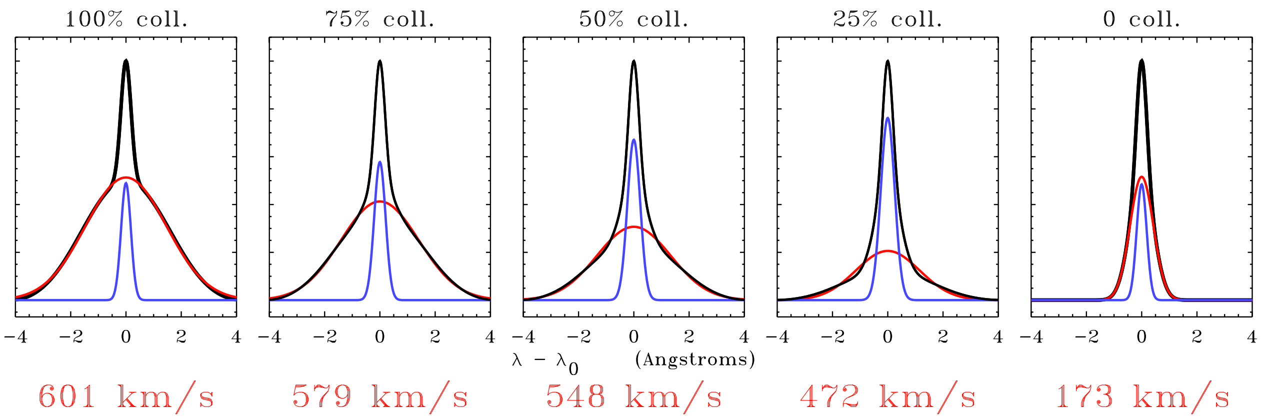


Multiple "Broad Components" ?

★ For $t/\tau_d \approx 80$, vary the relative collisional and resonant peak intensities:



★ Also include a **75 km/s wide** "narrow component" and fit with 2 Gaussians:



Conclusions and Ongoing Questions

- ⋆ If cyclotron resonance diffuses ions into shell distributions, then resonance scattering profiles must be narrower than expected from their perpendicular most-probable speeds. **This may NOT strongly affect broad component widths from 2-Gaussian fits.**

- ⋆ Self-consistent models of coronal holes will have distributions different from those presented here, because they will include, e.g.,

  { gravity, electric field, mirror force, $\Omega(r)$ **}**

- ⋆ Do ion cyclotron waves heat and accelerate the **primary** solar wind constituents (i.e., protons, electrons, alphas), or do low-frequency nonlinear fluctuations dominate?

Turbulent Cascade:

- ⇒ Does real MHD turbulence produce **high** $k_{\|}$ fluctuations?
- ⇒ Is the turbulence sufficiently "wave-like" to be able to use linear damping rates?

(Next-generation coronagraph spectroscopy would provide constraints to help answer these questions)