Towards a Universal Physics-based "Coronal Heating Function"

for electrons, protons, and heavy ions in the solar wInd

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Abstract

The Sun is often highlighted as a benchmark for the study of other stars, and as a stepping stone to the study of galaxies and cosmic distances. Not to be outdone, the solar wind is rapidly becoming a key baseline for the understanding of basic plasma phenomena such as **MHD turbulence, kinetic wave-particle interactions, and nonlinear wave-mode coupling.**

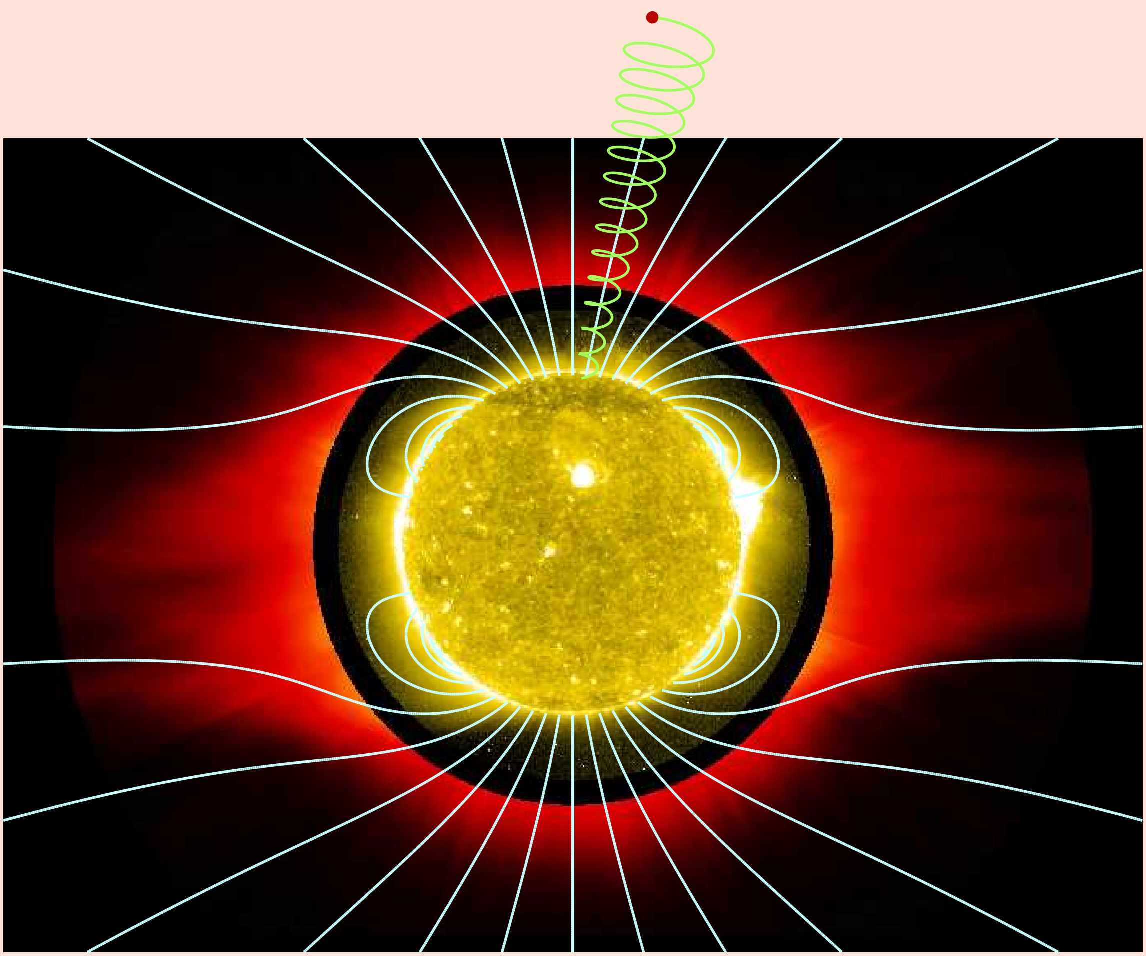
In keeping with the IHY focus on these kinds of universal processes, we present a distillation of recent modeling efforts to understand how Alfvén waves are generated, reflected, cascaded, and damped throughout the solar wind. A physical understanding of solar wind turbulence is crucial to the modeling of energetic particle transport in the heliosphere and the interaction with interstellar neutrals.

The [ultimate] goal of this work is to derive a useful "recipe" for solar wind modelers that, given the background zero-order plasma properties, yields the wave amplitudes, the turbulent cascade rates, and the kinetic partitioning of the resultant heating into electrons, protons, and heavy ions (differentiating between parallel and perpendicular heating as well). We also discuss preliminary ideas concerning how the collisionless particle heating is modified if the turbulent cascade ends with the production of small-scale reconnection current sheets.

This work is supported by the National Aeronautics and Space Administration under grants NAG5-11913, NNG04GE77G, and NNG04GE84G to the Smithsonian Astrophysical Observatory, by Agenzia Spaziale Italiana, and by the Swiss contribution to the ESA PRODEX program. SOHO is a project of international cooperation between ESA and NASA.

1. Introduction

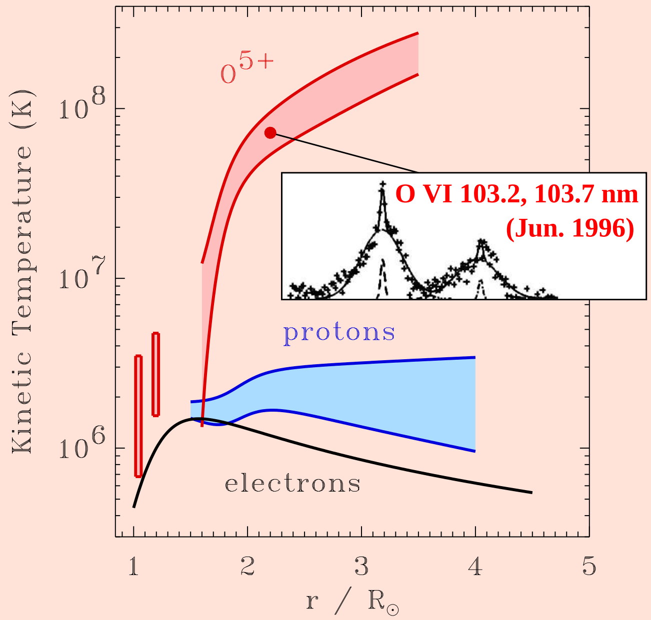
- The solar wind is a complex and highly structured plasma governed by sources of energy and momentum that have been unknown for almost a half century.
- At solar minimum, high-speed wind ($u > 600$ km s^{-1}) emerges from polar coronal holes to fill the majority of the heliosphere.
- The work presented here explores a wide class of proposed mechanisms for heating and accelerating the fast wind: generation, reflection, and collisionless turbulent dissipation of Alfvén waves (for more details, see Cranmer & van Ballegooijen 2003, 2005).



Inner image: **EIT/SOHO,** Outer image: **UVCS/SOHO** (both from August 1996), Magnetic field line model: Banaszkiewicz et al. (1998)

Alfvén Waves in the Extended Corona

★ UVCS/SOHO spectroscopy has revealed evidence for preferential heavy ion acceleration (as much as twice the proton wind speed), **>100 million K** ion temperatures, and strong departures from isotropic Maxwellian distributions (**$T_\perp / T_\parallel \gtrsim$ 3–10**); Kohl et al. (1997, 1998, 1999).



★ In the extended corona, energy must propagate up from the Sun and ultimately dissipate collisionlessly to heat the particles as observed:

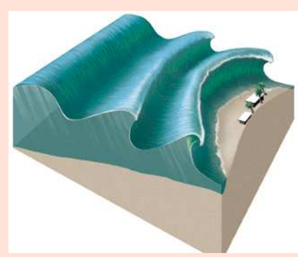
$$\left\{ \begin{array}{c} T_{\rm ion} \gg T_{\rm p} > T_{\rm e} \\ (T_{\rm ion}/T_p) > (m_{\rm ion}/m_p) \\ T_\perp \gg T_\parallel \\ u_{\rm ion} > u_p \end{array} \right\}$$

★ **Ion cyclotron waves** (10^2–10^4 Hz) have been suggested as a natural energy source that can be tapped to preferentially heat and accelerate ions (see reviews by Hollweg & Isenberg 2002; Cranmer 2002a).

★ MHD waves with frequencies $>$ 10 Hz have not yet been observed in the corona or wind, but there is ample evidence for **lower-frequency Alfvén waves** ($<$ 0.01 Hz) which may be converted into ion cyclotron waves gradually in the corona.

★ Other possibly important effects of Alfvén waves:

collisional damping (∼negligible)



wave-pressure acceleration

Solar Wind: an interdisciplinary physics testbed

⋆ A firm understanding of the physical processes responsible for the solar wind is important not only for practical reasons (e.g., space weather), but also key to **establishing a baseline of knowledge** that is directly relevant to other astrophysical systems.

⋆ Crooker (2004) summarized **IHY efforts** to study processes common to an array of solar-related phenomena—but we contend that the solar wind cuts across still *more* topical areas (see multi-color additions ⇓):

⋆ **S:** The origins of collisionless ion heating, suprathermal tails, and SEP seed populations may be interrelated in various kinds of **Fermi acceleration** (Smith & Miller 1995; Isenberg 2001, 2005).

⋆ **S:** *In situ* measurements yield a range of periodicities: hours (g-modes?) to 1–2 years (tachocline?); may probe properties of the **solar dynamo** (Thomson et al. 2001; Mursula & Vilppola 2004).

⋆ **E:** **Polar plumes** and **jets** exist on a wide range of spatial/temporal scales. LASCO "blobs" are not just in streamers, but everywhere in the extended corona (e.g., Tappin et al. 1999).

Table 1. Processes Common to Various Solar Phenomena.

E: established
S: speculative

PROCESSES \ PHENOMENA	CMEs & flares	solar wind	solar cycle	granulation	cosmic ray modulation	irradiance
reconnection	E	E	S	S	E	
particle acceleration	E	S				
shocks & waves	E	E			E	
dynamo		S	E	E		E
turbulence/ convection	S	E	E	E		E
multi-scale structures	E	E	S		E	
energy storage & release	E	E				
radiative transfer		E				E

Image credit: T. Forbes & S. Gibson

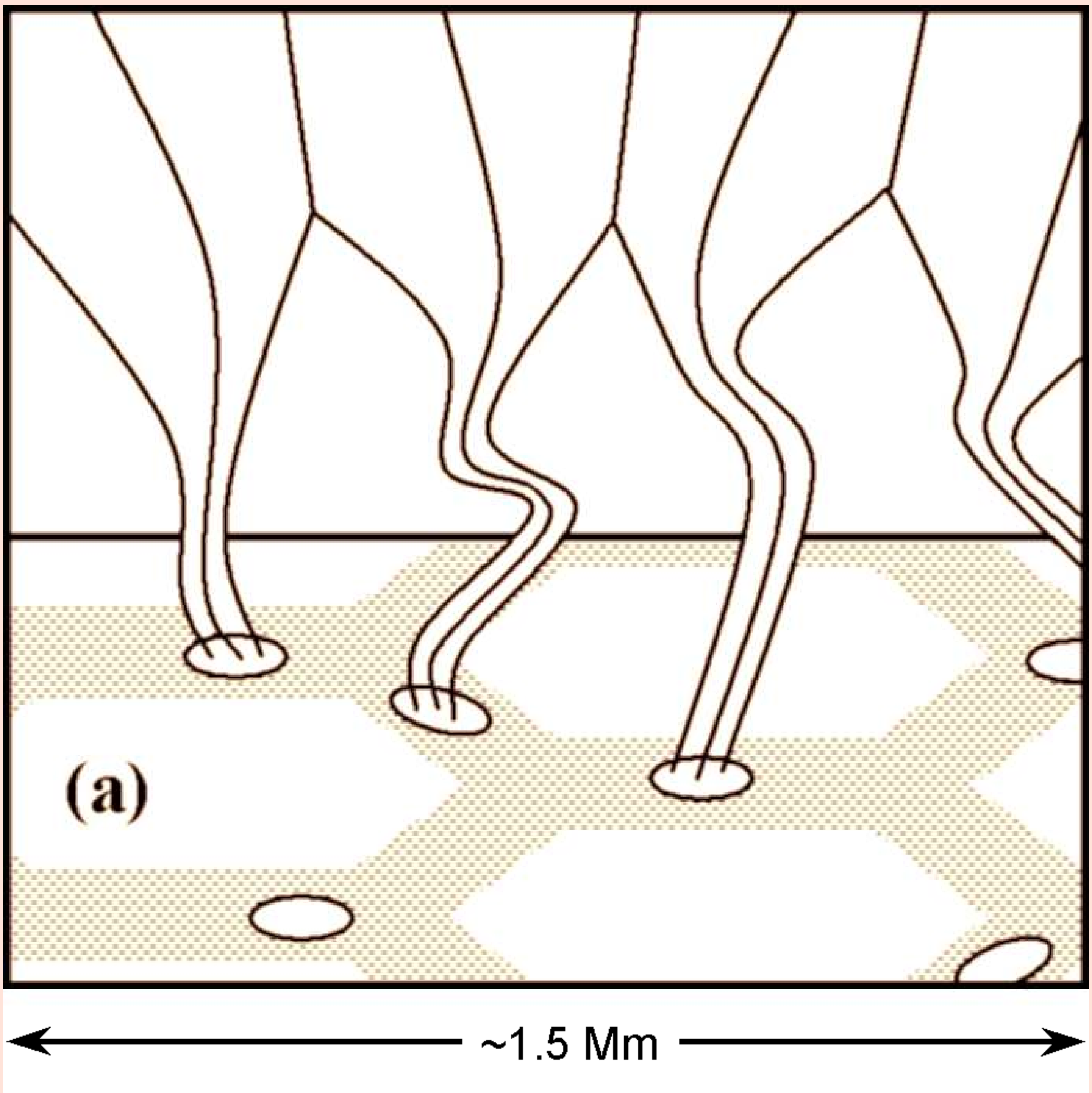
⋆ **E:** Mechanical energy is, in effect, "stored" in the form of **waves** then "released" gradually as the fluctuations damp & heat the plasma.

⋆ **E:** Although there is still not universal agreement about what sets the solar wind **mass loss rate,** a leading contender remains Hammer's (1982) idea of radiative energy balance: radiative losses directly influence the pressure balance in the T.R., which sets $\dot{M}$.

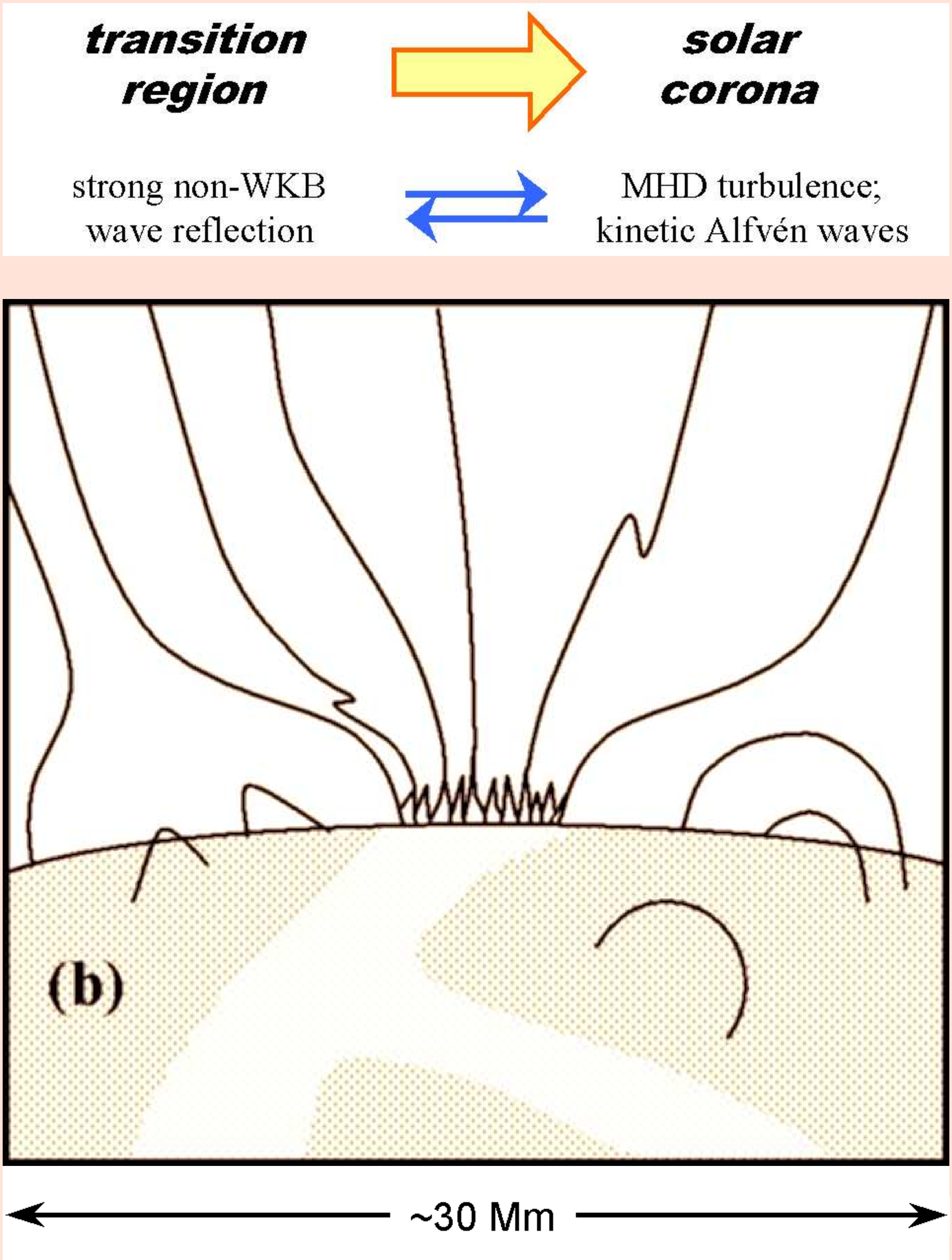
An Interconnected System (1)

photosphere → ***chromosphere***

G-band bright point motions ⇄ kink-mode waves (thin → thick tubes)



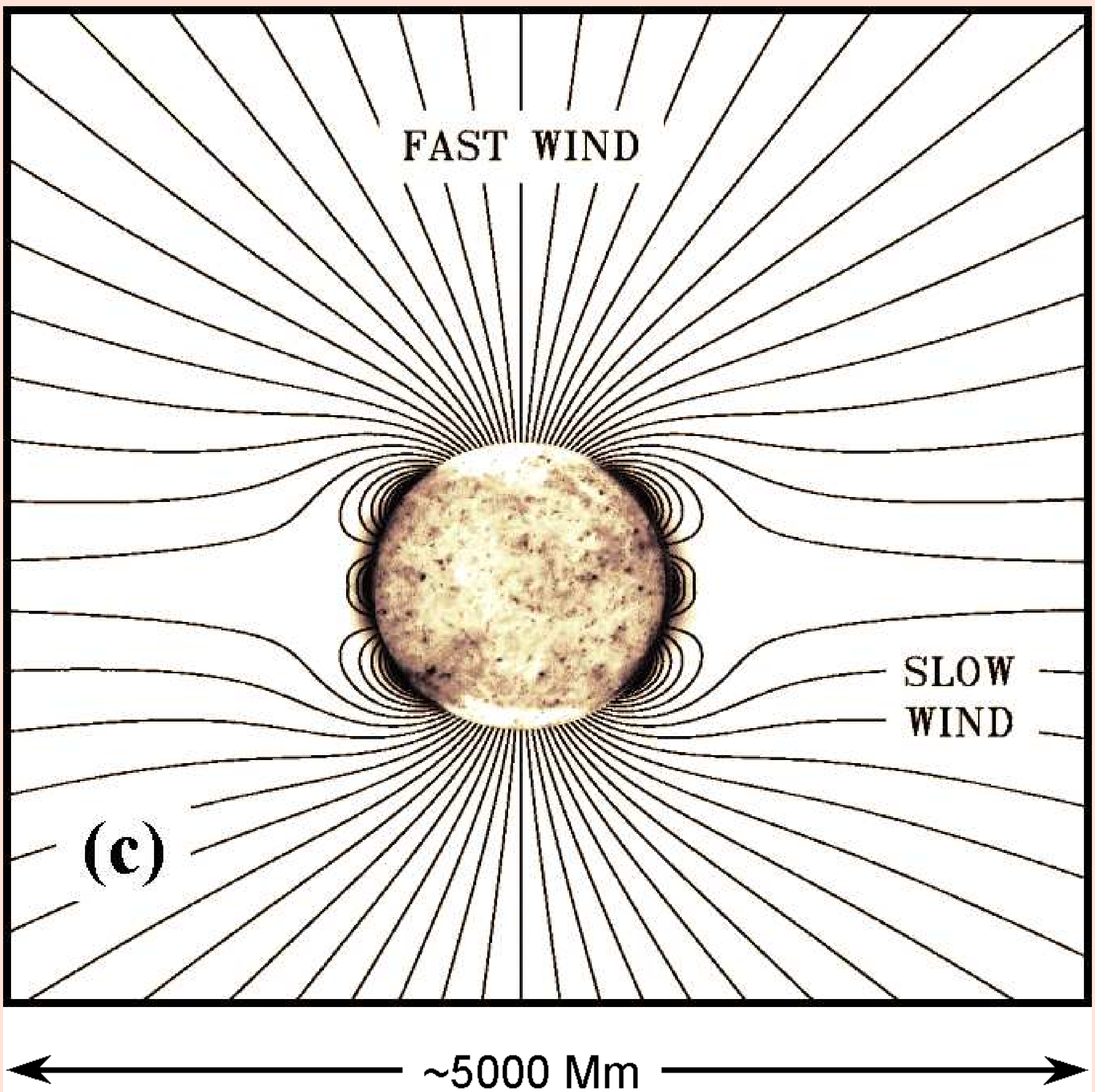
An Interconnected System (2)



An Interconnected System (3)

accelerating solar wind → ***heliosphere***

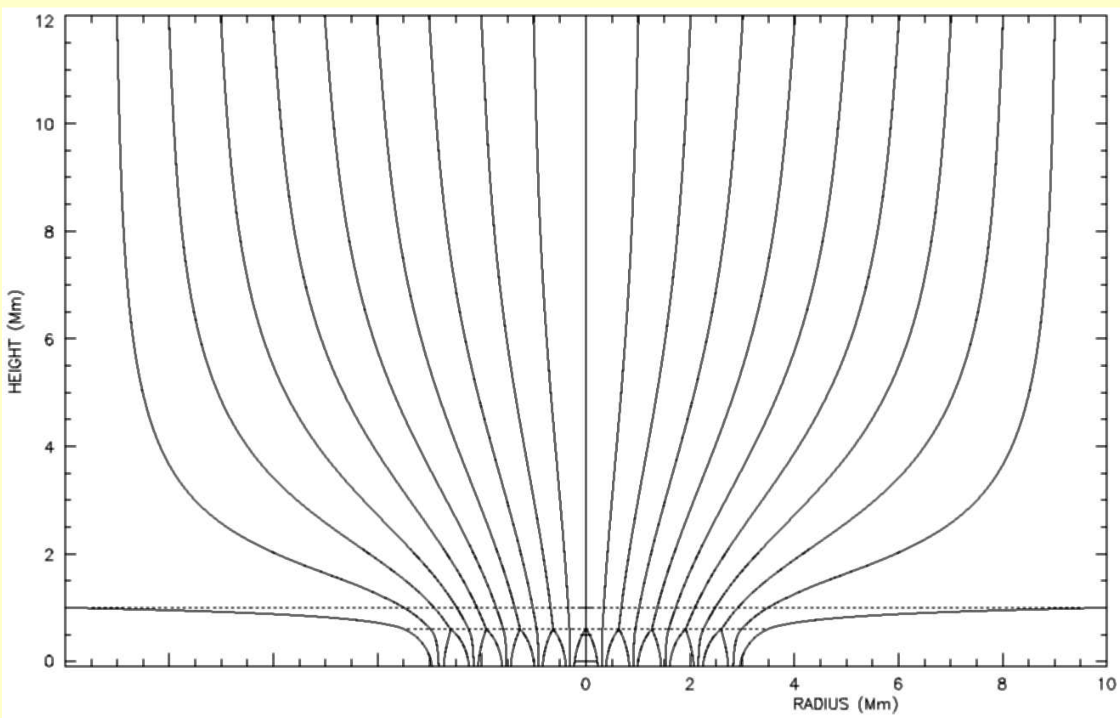
low-beta plasma ($\delta B/B_0 << 1$) ⇄ high-beta plasma (saturation; instabilities)



2. *Steady-State "Background"*

Fragmented Flux Tube Model

- ⋆ The open magnetic field from the photosphere to a height of 12 Mm is modeled assuming magnetostatic equilibrium, cylindrical symmetry, and total pressure balance between the flux tubes and field-free surroundings. For details, see Cranmer & van Ballegooijen (2005).
- ⋆ Gas pressures were taken from the latest generation of semi-empirical PANDORA **Model C** and **MCO** atmospheres (E. Avrett, personal communication; see also Fontenla et al. 1993, 2002).



- ⋆ **z = 0–600 km:** "Isolated" bright-point flux tubes, with cross sections and plasma properties computed in thin-tube limit ($R \propto p_{\rm ext}^{-1/4}$).
- ⋆ **z = 600–1000 km:** "Merged" flux tube (supergranular network) bounded by field-free cell-centers (with overlying canopy).
- ⋆ **z = 1000–12,000 km:** "Fully merged" field with outer boundary representing the effect of neighboring network elements.

Open Coronal Funnels and Fast Solar Wind

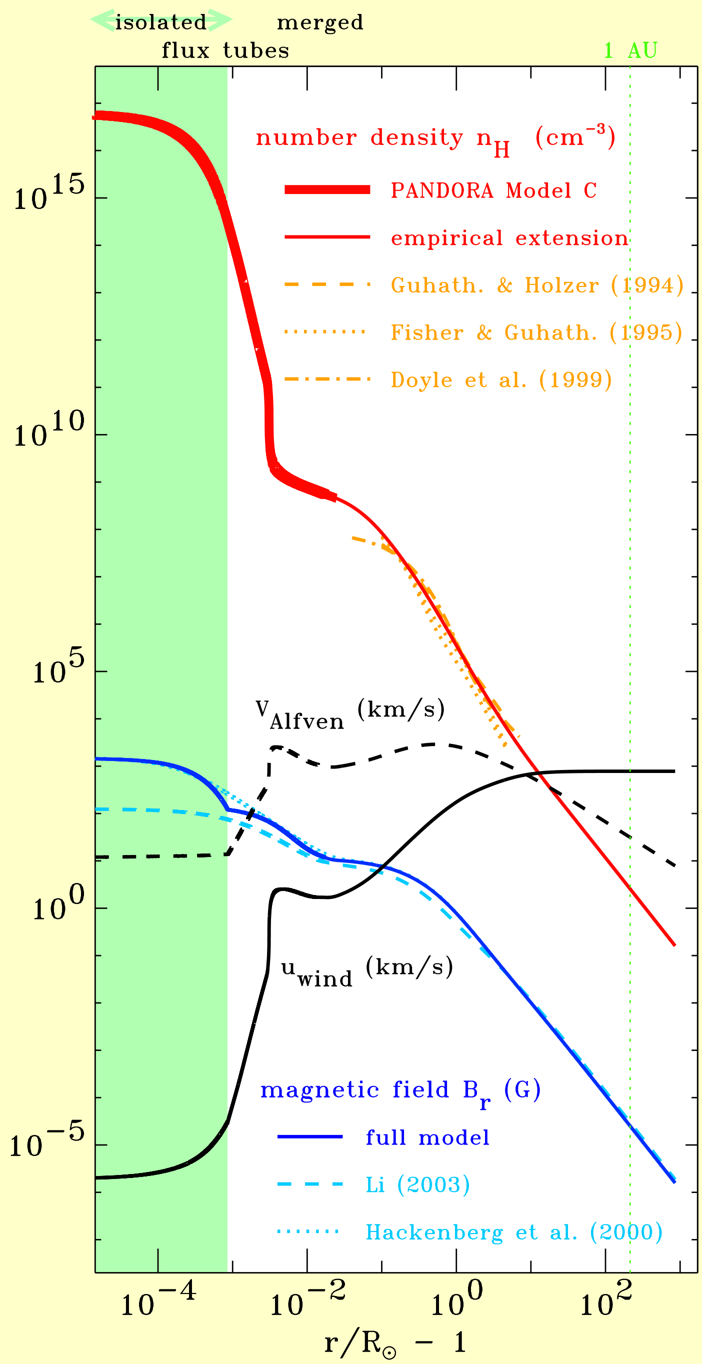
- ⋆ The magnetostatic/PANDORA model (z = 0–0.017 $R_\odot$) was extended into the corona and interplanetary space using latest empirical data.
- ⋆ The goal is to model the properties of "average" flux tubes that emerge from polar coronal holes at solar minimum . . .
- ⋆ **Density:** A multiple power law fits the coronal observations (orange) & *Ulysses* data:

$$\frac{n_e}{1.3 \times 10^5\ \mathrm{cm}^{-3}} = \frac{1}{r^2} + \frac{25}{r^4} + \frac{300}{r^8} + \frac{1500}{r^{16}} + \frac{5796}{r^{33.9}}$$

- ⋆ **Magnetic field:** The total flux Φ in the magnetostatic model was chosen to match the extended-corona model of Banaszkiewicz et al. (1998). Other "funnel" models (cyan) are similar.
- ⋆ **Wind speed:** Mass flux conservation was applied, with $(nu)_{1\,\mathrm{AU}} = 2 \times 10^8\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

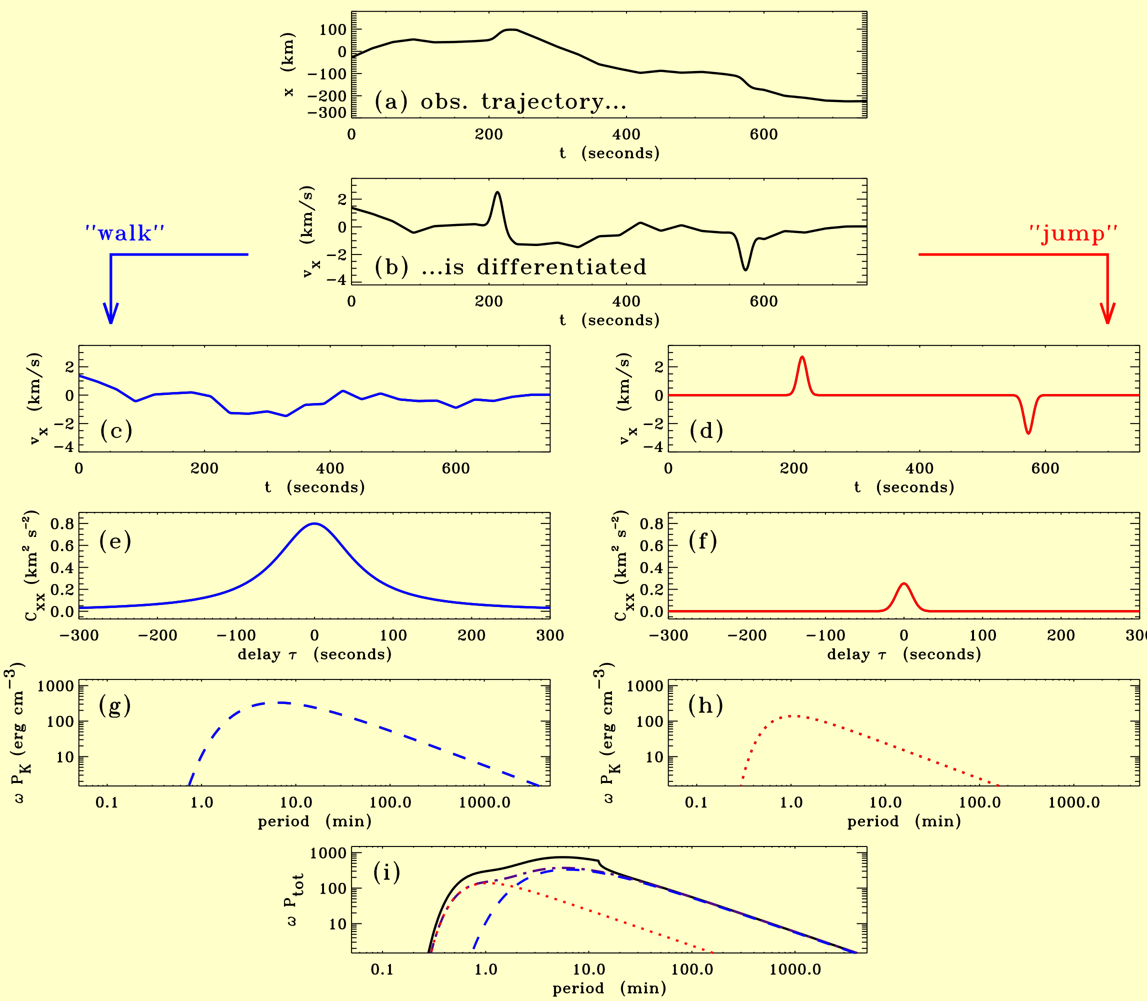
max(u) = 782 km/s

max(V_A) = 2890 km/s



3. Lower Boundary Condition

- ⋆ The photospheric spectrum of transverse fluctuations is specified from observations of G-band **magnetic bright point (MBP)** motions.
- ⋆ There are 2 observable phases of motion: **(1) random walk** of isolated flux tubes (van Ballegooijen et al. 1998; Nisenson et al. 2003); **(2) rapid jumps** when MBPs merge, fragment, or reconnect with surrounding field (e.g., Berger & Title 1996; Berger et al. 1998).
- ⋆ Empirical autocorrelation functions $C_{xx}(\tau) \sim < v_x(t) v_x(t+\tau) >$ for each phase are Fourier transformed to obtain the kinetic energy power spectrum $P_x(\omega)$ [no preferred direction, so $P_x = P_y$].



- ⋆ There is only one free parameter: the **jump velocity amplitude σ_j** (realistically ranges between 0 and ∼6 km/s).

4. *Wave Transport Equations*

- ⋆ **Below the "merging height"** (600 km), we examine incompressible Lagrangian perturbations of the central axis of a ∼vertical flux tube.

- ⋆ Spruit (1981) showed that the MHD equations can be expressed as a single **thin-tube wave equation** for the velocity $v_\perp$ of **kink modes:**

$$\frac{\partial^2 v_\perp}{\partial t^2} = \frac{g\,\Delta\rho}{\rho_{\rm tot}}\frac{\partial v_\perp}{\partial r} + V_{\rm ph}^2\frac{\partial^2 v_\perp}{\partial r^2}$$

- ⋆ where $\rho_{\rm tot}$ is the sum of the on-axis density ρ and the "external" (field-free) density ρ_e, $\Delta\rho$ is their difference, and $V_{\rm ph} = B_0/\sqrt{4\pi\rho_{\rm tot}}$. Near the merging height we modify $\rho_{\rm tot}$ and $\Delta\rho$ so that isolated nature of the flux tubes "switches off" gradually.

- ⋆ **Above the "merging height"** we examine incompressible Eulerian perturbations along the axis of the superradially expanding flux tube with nonzero wind speed (e.g., Heinemann & Olbert 1980; An et al. 1990; Barkhudarov 1991; Velli 1993).

- ⋆ The [non]linear wave transport equations in this region are:

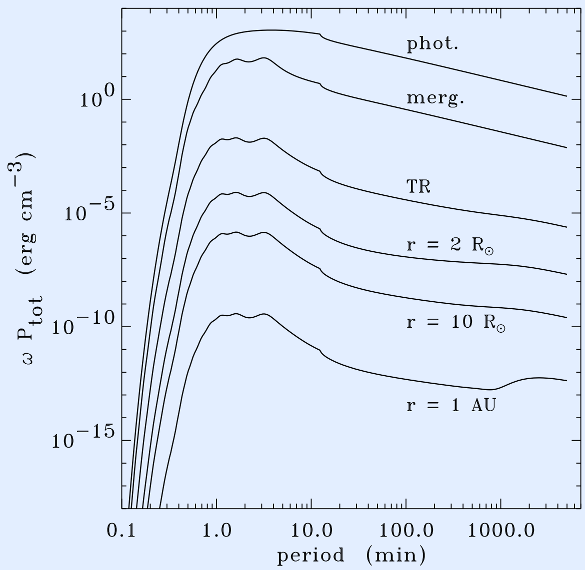
$$\frac{\partial Z_\pm}{\partial t} + (u \mp V_A)\frac{\partial Z_\pm}{\partial r} = (u \pm V_A)\left(\frac{Z_\pm}{4H_D} + \frac{Z_\mp}{2H_A}\right) - \frac{Z_\pm |Z_\mp|}{2L_\perp}$$

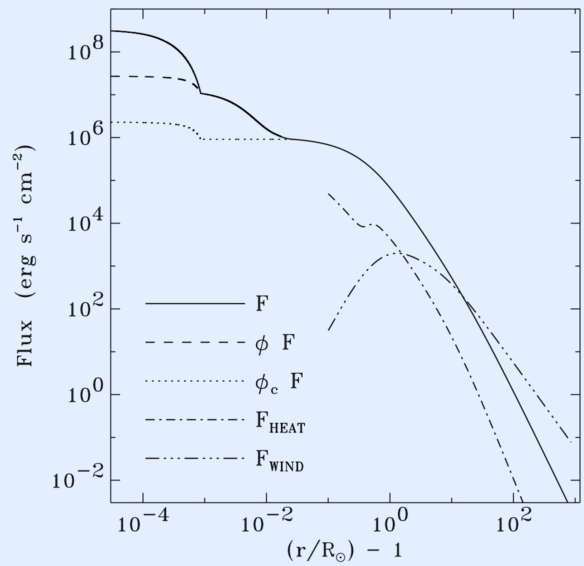
- ⋆ where $Z_\pm \equiv v_\perp \pm B_\perp/\sqrt{4\pi\rho}$ are Elsasser variables that track **outward** (Z_-) and **inward** (Z_+) Alfvén waves, and H_D and H_A are signed scale heights for density and Alfvén speed. $L_\perp$ is the transverse correlation length of turbulence (Zhou & Matthaeus 1990; Dmitruk et al. 2001).

- ⋆ We assume monochromatic waves ($Z_\pm \propto e^{i\omega t}$) and solve the equations using Barkhudarov's (1991) critical-point constraints and 4th-order Runge Kutta integration in radius. We integrate *downward* to the merging height, then use the values of $v_\perp$ and $B_\perp$ there as upper boundary conditions to solve the Spruit (1981) thin-tube equations.

5. Summary of Results

- The wave transport equations were solved for 300 "monochromatic" frequencies (periods of **3 sec → 3 days**), then renormalized using the photospheric total power spectrum:



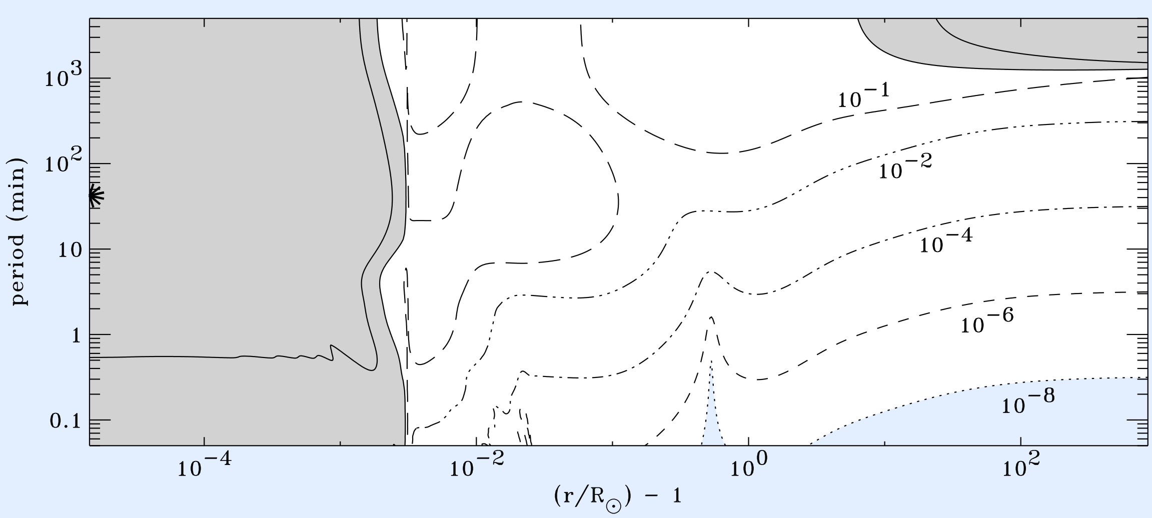


$$P_{\rm total}(\omega, r) = P_{\rm K} + P_{\rm B} \; = \; P_+ + P_-$$

$$\text{Flux:} \quad F = \int d\omega \; [u(P_{\rm K} + 2P_{\rm B}) + V_A(P_- - P_+)]$$

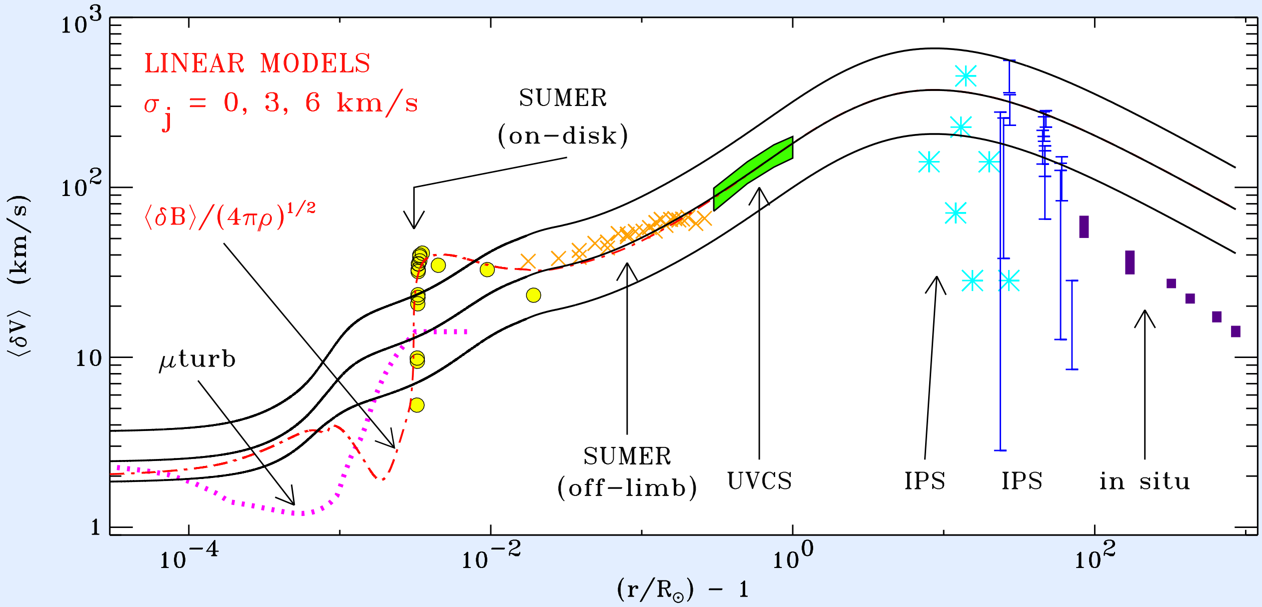
ϕ = granular MBP filling factor, $\phi_{\rm C}$ = supergranular canopy filling factor

- There is **strong reflection** below the transition region ($z \approx 0.003\, R_\odot$). Below we plot contours of an effective "reflection coefficient" (P_+/P_-); gray denoting ratios ≥ 0.5

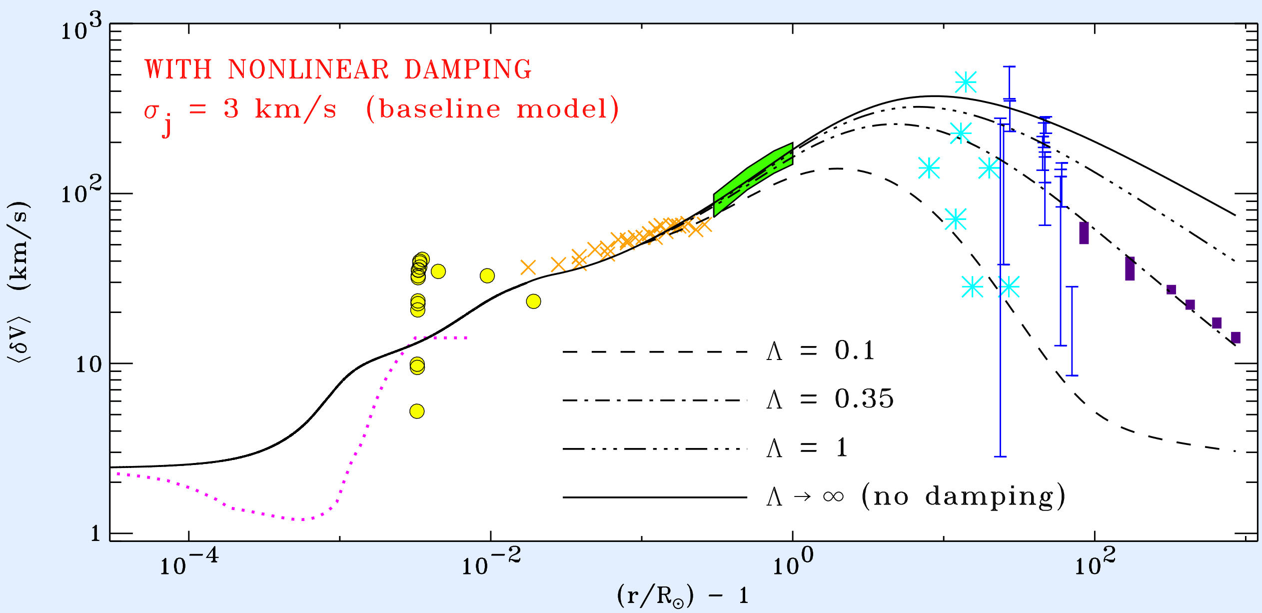


Frequency-integrated Velocity Amplitudes

⋆ The frequency-integrated **transverse velocity amplitude** $\langle \delta V \rangle$ is plotted below for 3 values of the photospheric "jump" amplitude σ_j



⋆ When including the effects of nonlinear damping, we scale $L_\perp$ with $B_0^{-1/2}$. $L_\perp$ is normalized by defining the ratio $\Lambda = L_\perp(z_{\rm merge})/R_{\rm network}$, where $R_{\rm network}$ = 3 Mm is the transverse radius of the network at $z_{\rm merge}$.



References

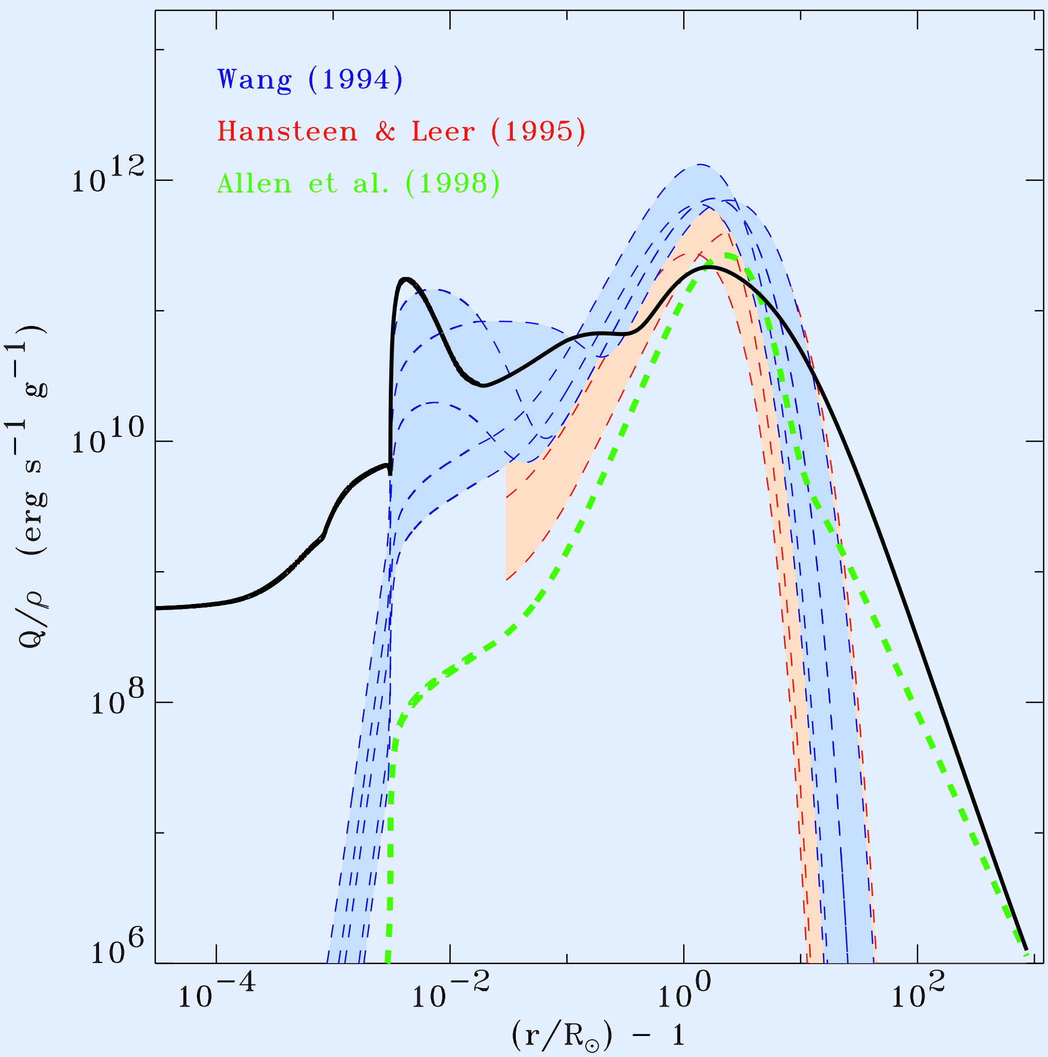
⋆ μturb: PANDORA code; E. Avrett, personal communication (Fontenla et al. 1993, 2002)
⋆ SUMER (on-disk): Chae et al. 1998
⋆ SUMER (off-limb): Banerjee et al. 1998
⋆ UVCS: Esser et al. 1999
⋆ IPS (stars): Armstrong & Woo 1981
⋆ IPS (bars): Canals et al. 2002
⋆ in situ: Bavassano et al. 2000

Turbulent Coronal Heating

- ⋆ Energy lost in the turbulent cascade is assumed to go into **heating,** and we use the phenomenological rate derived by Hossain et al. (1995), Matthaeus et al. (1999), and others:

$$Q = \rho \frac{\langle Z_- \rangle^2 \langle Z_+ \rangle + \langle Z_+ \rangle^2 \langle Z_- \rangle}{4L_\perp}$$

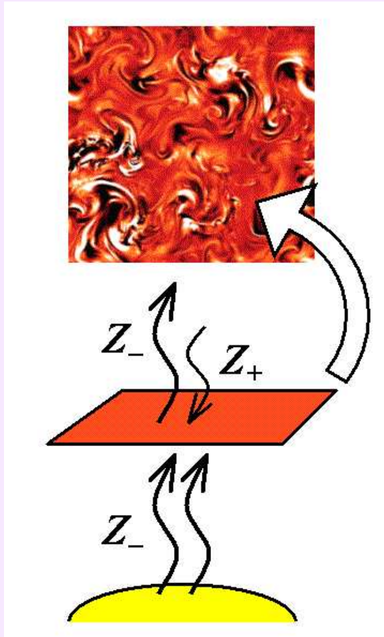
- ⋆ In the extended corona, the $\Lambda = 0.35$ case (which agrees best with *in situ* damping) also agrees best with **empirical heating functions:**



- ⋆ Below $z \approx 0.1\,R_\odot$, Q is shown for illustrative purposes only; no damping was applied below 0.1 because turbulence should not have time to develop on such small scales (Dmitruk & Matthaeus 2003).

6. Anisotropic Turbulence

- ⋆ Hydrodynamic turbulence is describable by an **isotropic** transfer of wave energy from large to small eddies in wavevector (**k**) space.



- ⋆ In a strong background magnetic field, it is easier to mix field lines perpendicular to **B** than it is to bend them (e.g., Higdon 1984; Shebalin et al. 1983; Oughton et al. 2004).
- ⋆ MHD cascade proceeds **anisotropically,** i.e., mainly from low to high $\boldsymbol{k}_\perp$ while leaving $\boldsymbol{k}_\parallel$ relatively unchanged.
- ⋆ In a low-beta ("nearly incompressible") plasma, MHD Alfvén waves cascade into **kinetic Alfvén waves** having small transverse scales but still **low frequencies!**
- ⋆ Goldreich & Sridhar (1995, 1997) proposed that the anisotropy in strong Alfvénic turbulence is limited by a **critical balance** condition:

$$\boldsymbol{k}_\perp \boldsymbol{v}_\perp \sim \boldsymbol{k}_\parallel \boldsymbol{V}_{\mathbf{A}}$$

LHS: eddy turnover rate
RHS: Alfvén wave freq.

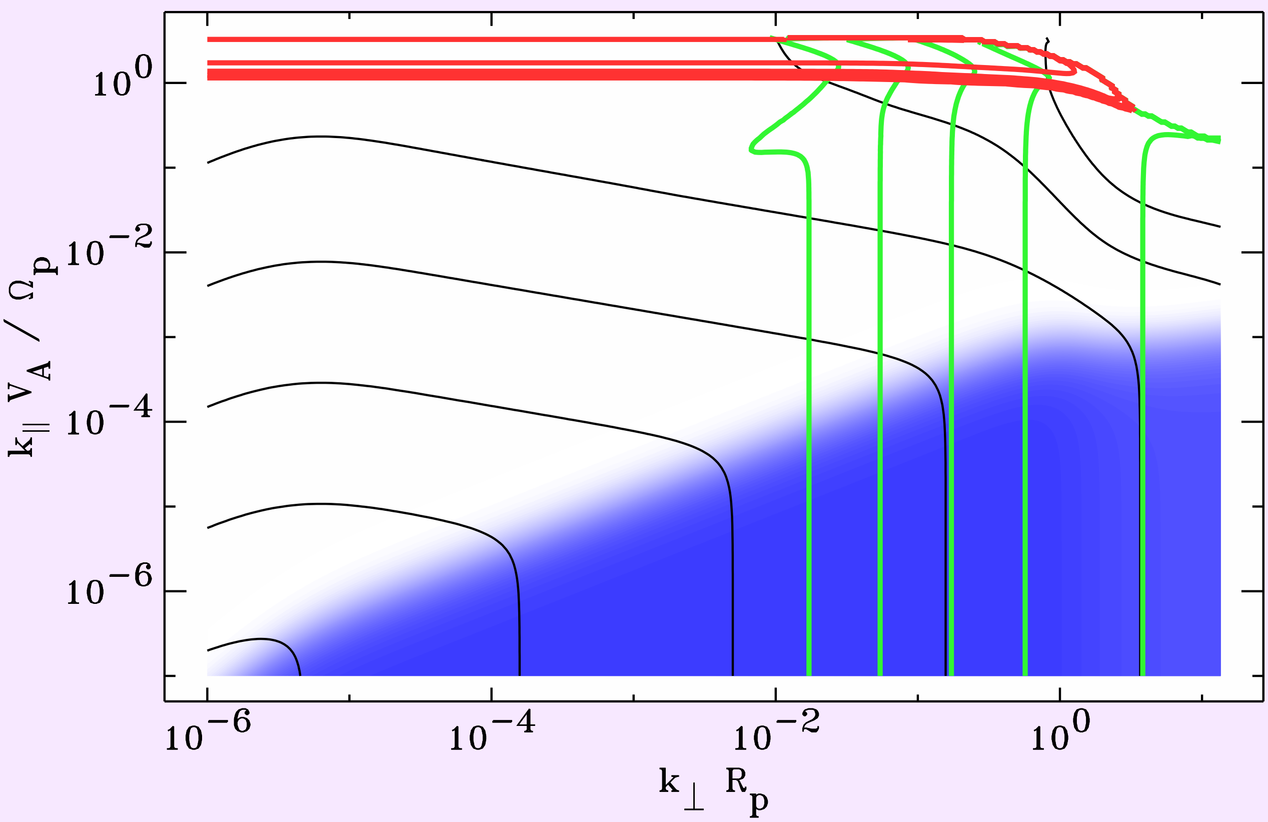
- ⋆ When $\boldsymbol{k}_\perp$ increases to this level, a wave packet travels only about one wavelength before nonlinear processes transfer its energy to smaller scales. Turbulence decays for $\boldsymbol{k}_\parallel$ values above the critical balance "cone" ($\boldsymbol{k}_\parallel \propto \boldsymbol{k}_\perp^{2/3}$).
- ⋆ The above anisotropy proceeds alongside the different kind of **asymmetry** along the field (discussed above) between waves propagating outward ($\boldsymbol{Z}_-$) and inward ($\boldsymbol{Z}_+$).

Preferential Electron Heating?

★ Cranmer & van Ballegooijen (2003) modeled anisotropic cascade with phenomenological advection and diffusion in **k**-space (at 2 $R_\odot$)

$\Longrightarrow$ Dominant cascade to high-$k_\perp$ produces waves damped by the **Landau resonance** and **parallel electron heating.**

$\Longrightarrow$ Residual "leakage" to high-$k_\parallel$ produces waves damped by the **ion cyclotron resonance** and **perpendicular proton/ion heating.**



★ **Black contours:** wave power (1 contour per 10^5 in energy density)

★ **Blue region:** modes most strongly excited by the anisotropic cascade

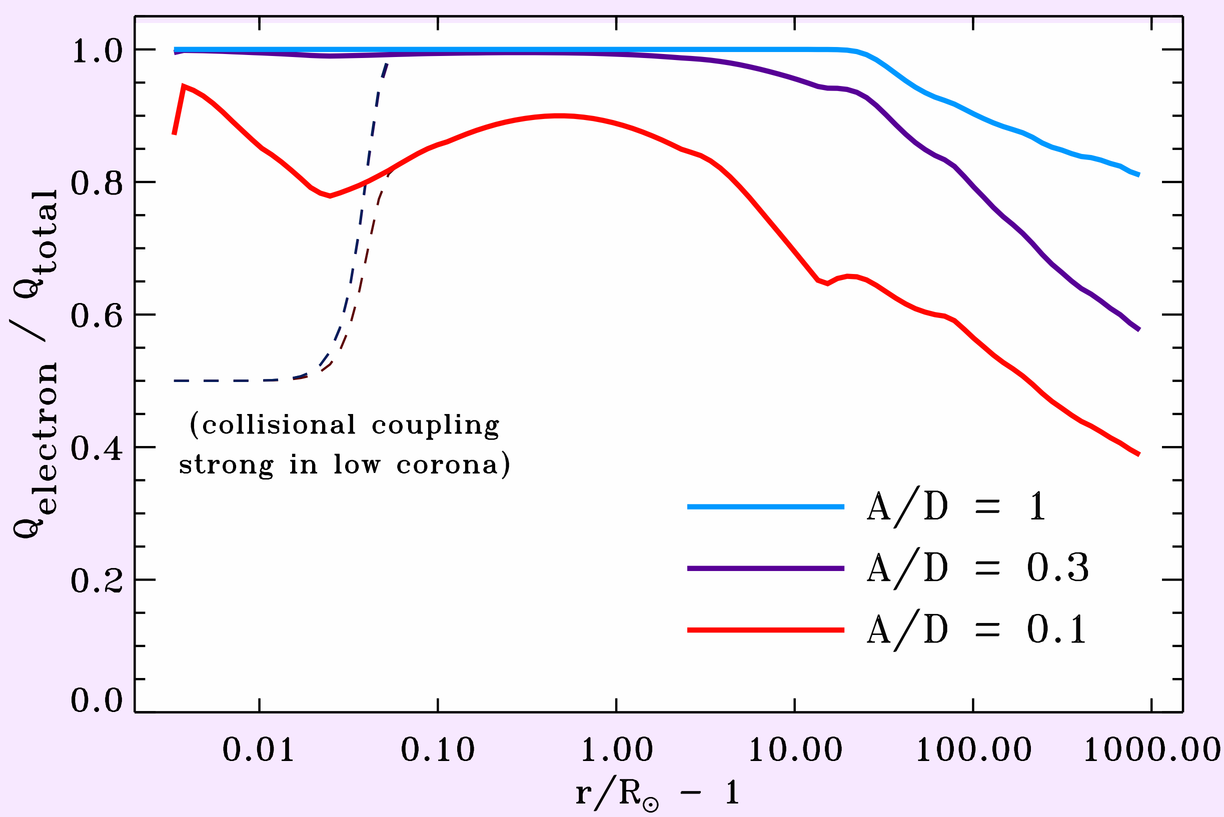
★ **Red contours:** strong proton heating ($\omega \to \Omega_p$)

★ **Green contours:** strong electron heating (KAW regime)

(see also Shukla et al. 1999; Gary & Borovsky 2004)

How is Heating Partitioned in the Solar Wind?

- ⋆ The relative amount of **electron** vs. **proton/ion** heating depends on how much wave energy cascades to high-$k_{\parallel}$, and thus on the ratio of the strengths of wavenumber advection to wavenumber diffusion (A/D).
- ⋆ Applying the quasilinear theory used by, e.g., Quataert (1998), Marsch & Tu (2001), and Cranmer & van Ballegooijen (2003), we can compute the collisionless fraction of Q_e versus $Q_{\text{total}} \equiv (Q_e + Q_p)$ as a function of distance from the photosphere:



(background plasma model of Cranmer & van Ballegooijen 2005)

- ⋆ At the coronal base, van Ballegooijen (1986) modeled turbulence as footpoint-driven **random walks,** with key result $A/D \approx 1$. Ultimately, simulations or laboratory experiments should help determine A/D in actual MHD turbulence . . .
- ⋆ If, though, $A/D \approx 1$, there is **insufficient power** at ion cyclotron frequencies to heat protons and heavy ions in the extended corona!

7. How are ions heated?

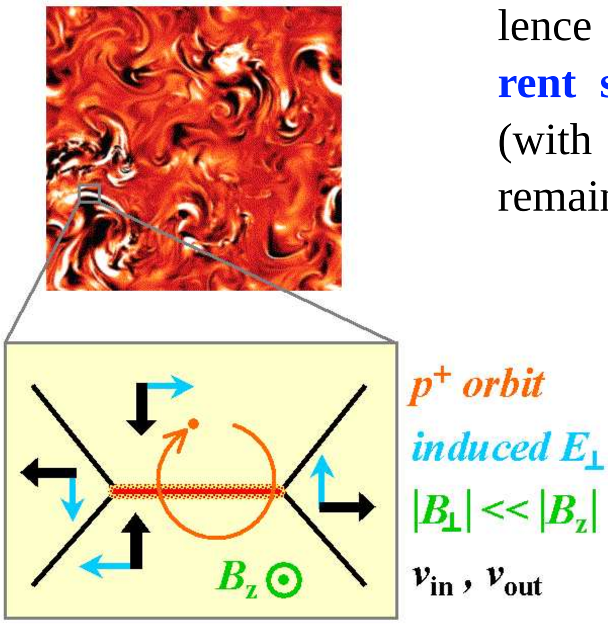
Variations on the theme of "ion cyclotron resonance:"

- ⋆ Additional unanticipated **frequency cascades** due to, e.g., ions of successively higher Z/A going into and out of resonance? (Gomberoff et al. 2004) . . . or other kinds of freq. cascade? (Medvedev 2000)
- ⋆ Diffusive Fermi-like **random walks** in velocity space when inward/outward waves coexist? (heavy ions: Isenberg 2001; protons: Gary & Saito 2003)
- ⋆ Impulsive plasma **micro-instabilities** that locally generate high-frequency waves? (e.g., Markovskii & Hollweg 2004)
- ⋆ **Nonlinear/nonadiabatic** wave-particle damping effects for kinetic Alfvén waves? (Voitenko & Goossens 2004)
- ⋆ Coherent Larmor "spinup" in dissipation-scale **current sheets?** (Dmitruk et al. 2004)

Other ideas:

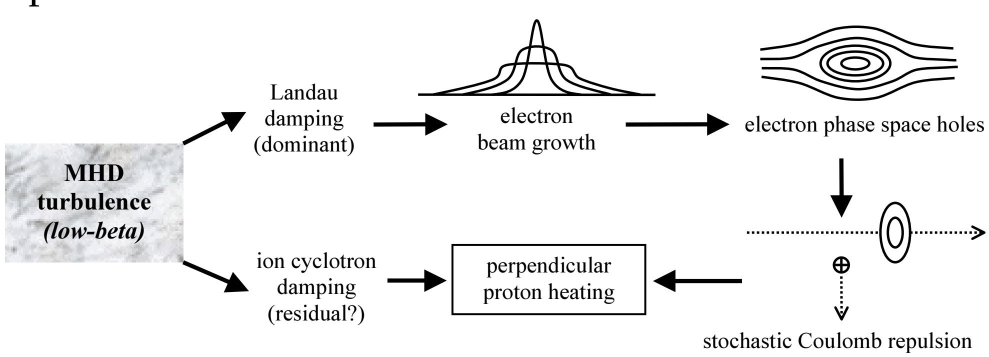
- ⋆ KAW damping leads to electron beams and Debye-scale **electron phase-space holes** which heat ions perpendicularly? (Ergun et al. 1999; Cranmer & van Ballegooijen 2003)
- ⋆ Collisionless **velocity filtration** of suprathermal ion tails? (Pierrard et al. 2004)
- ⋆ Unanticipated breakdown of the 'coronal conductive thermostat' for heavy ions with *low* Spitzer-Härm conductivities? (Owocki 2004; Lie-Svendsen & Esser 2005)

Two possibilities . . .



- On the smallest scales, MHD turbulence evolves to a state of **tiny current sheets** undergoing reconnection (with the large-scale "guide field" B_z remaining ∼unchanged).
  - Dmitruk et al. (2004) test-particle simulations showed how protons get coherently "spun up" ⊥ to guide field.
- If nothing stops spinup from continuing until Larmor radius ≈ current sheet length, $T_{\perp p}$ could exceed 10^9 K!

- KAW Landau damping can lead to **non-Maxwellian tails** in electron ($v_{||}$) distributions (e.g., Tanaka et al. 1989).
- Electron beams may be unstable to Langmuir turbulence, which exhibits periodic E-potential wells that can **trap** electrons; adjacent wells can merge to form saturated "electron phase space holes" (Bernstein et al. 1957; Omura et al. 2001).
- Cranmer & van Ballegooijen (2003) showed how EPSHs could heat protons via Coulomb-like "collisions:"



Conclusions

Current work:

- ⋆ We have produced a comprehensive model of the global properties of **Alfvénic turbulence** in the solar atmosphere and the fast solar wind, including a first cut at how collisionless damping heats protons vs. electrons.
- ⋆ The relatively small degree of **reflection** in the extended corona ($|Z_+|/|Z_-| \approx 10^{-4}$) seems sufficient to drive the cascade and provide the required open-corona heating.
- ⋆ This work is incomplete because it ignores **longitudinal / acoustic** waves, but in the low-β solar atmosphere, the **transverse / kink / Alfvénic** fluctuations should be dominant. The methodology outlined here takes account of their behavior over a large range of spatial orders of magnitude.

Future work:

- ⋆ We still don't understand fully how protons and heavy ions are heated and accelerated in the corona!
- ⋆ Upcoming missions (*SDO*, *STEREO*, *Solar-B*) will help build a more complete picture, but we really need **next-generation UVCS and LASCO** instruments to more fully diagnose the collisionless aspects of coronal heating:
  - ⟹ properties of more ions (vs. charge & mass)
  - ⟹ accurate $T_e(r)$ above $\sim$1.5 $R_\odot$
  - ⟹ departures from bi-Maxwellian velocity distributions

(see, e.g., Fineschi et al. 1998; Cranmer 2001, 2002b; Gardner et al. 2003)

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