

*SOHO-15: Coronal Heating, 6–9 September 2004,
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Coronal Heating “versus” Solar Wind Acceleration

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- ☀ **Background and brief history**
 - ☀ **Fast wind: coronal heating**
 - Basal heating vs. extended heating
 - MHD turbulence as a heat source
 - ☀ **Fast wind: wave–particle acceleration:**
 - Alfvén waves: results from a non–WKB reflection model
 - What about fast-mode magnetosonic waves?
 - ☀ **Slow wind: how similar/different from fast wind?**
 - ☀ **Conclusions and future missions**
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Exploring the Solar Wind (pre-SOHO)

- ★ 1958: Eugene Parker proposed that the hot corona provides enough **gas pressure** to counteract gravity.
- ★ 1962: *Mariner 2* provided first direct confirmation of the continuous, supersonic solar wind . . . in two relatively distinct modes:

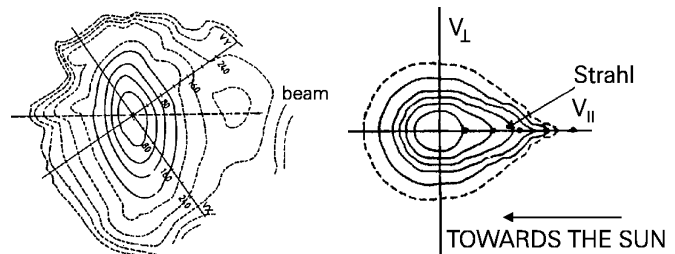
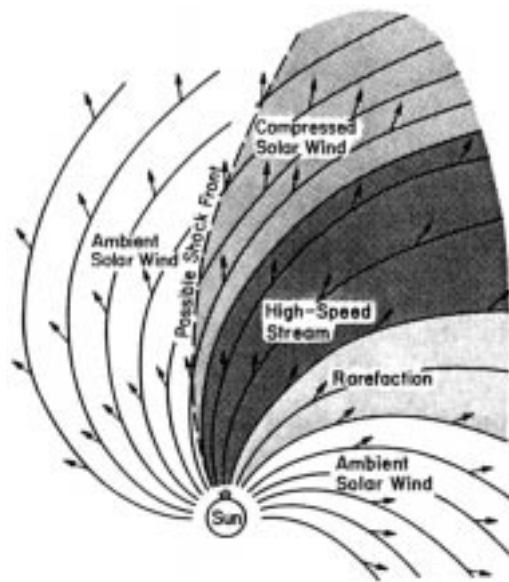
high-speed (500–800 km/s)	low density	~laminar flow
low-speed (300–500 km/s)	high density	variable, filamentary

- ★ Uncertainties about which type is “ambient” persisted because measurements were limited to the ecliptic plane . . .

- ★ **Ulysses** left the ecliptic; provided 3D view of wind’s **source regions**.

- ★ By ~1990, it was clear that the fast wind needed something besides gas pressure to accelerate so fast!

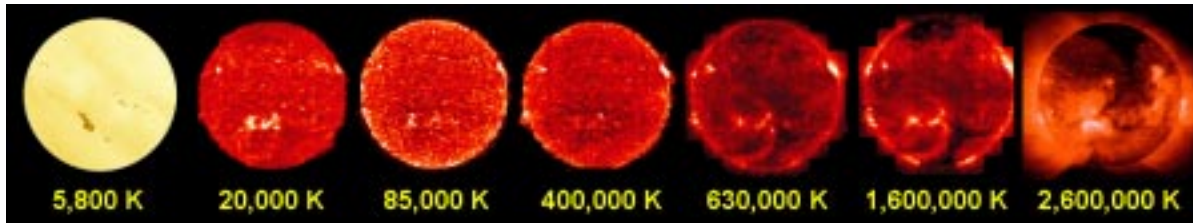
- ★ **Helios** explored the inner solar wind (0.3–1 AU); saw strong **departures from Maxwellian** velocity distributions:



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

Heating the Extended Corona

Most of this meeting is devoted to studying the heat deposited at the “base” of the corona, e.g.,



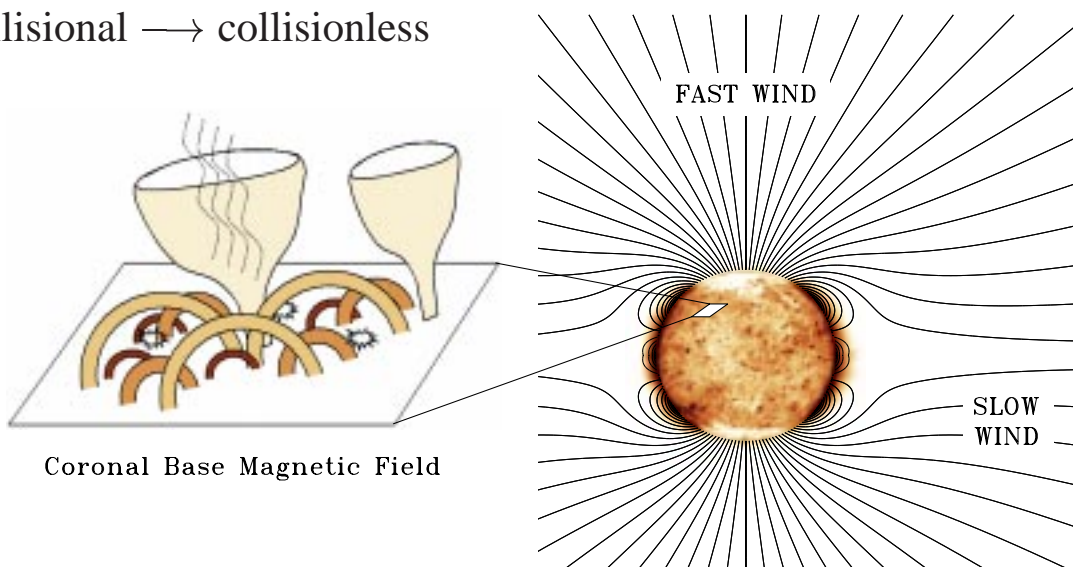
Above $2 R_{\odot}$, additional energy deposition is required in order to . . .

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



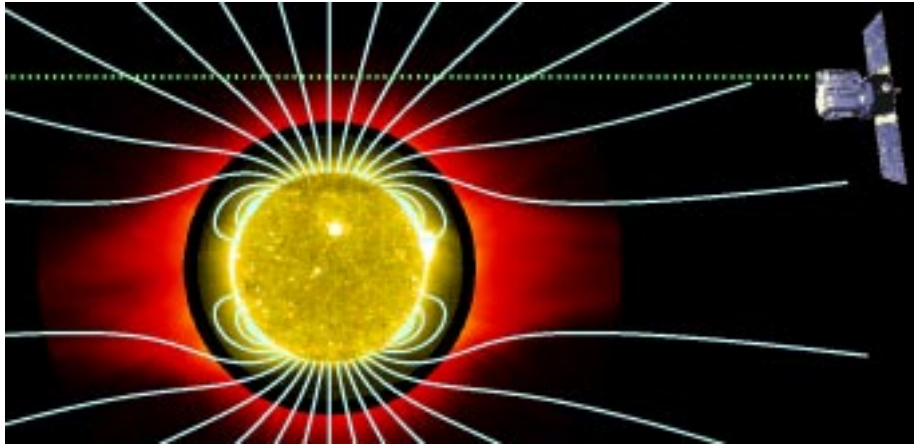
It’s a very different environment from the base . . .

- ★ Collisional \rightarrow collisionless

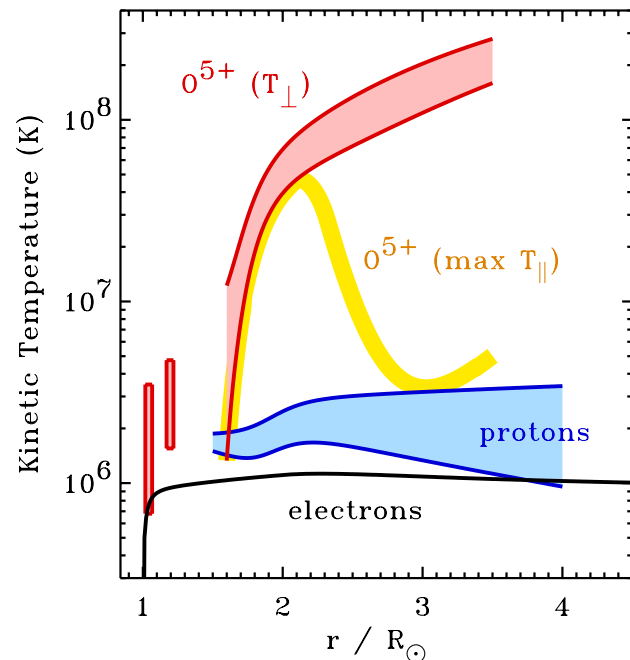


UVCS results: solar minimum (1996–1997)

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



- ★ O^{5+} exhibits an anisotropic velocity distribution above $\sim 2 R_{\odot}$ in coronal holes: $(T_{\perp}/T_{\parallel} \approx 10 \text{ to } 100)$
- ★ 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 as much as a factor of 2.



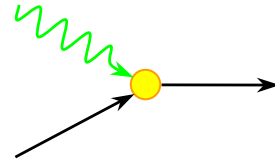
$$\left\{ \begin{array}{l} T_{\text{ion}} \gg T_p > T_e \\ (T_{\text{ion}}/T_p) > (m_{\text{ion}}/m_p) \\ T_{\perp} \gg T_{\parallel} \\ u_{\text{ion}} > u_p \end{array} \right.$$

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

Wave Generation & Damping

- ★ Much effort has gone into “working backwards” from the UVCS and SUMER data—i.e., identifying the ultimate **kinetic wave damping mechanisms**.

- ★ Quasi-linear wave-particle resonances:



Landau damping

$$\omega - u_{\parallel} k_{\parallel} = 0$$

$$T_e > T_p \quad (\text{low-}\beta)$$

$$T_{\parallel} > T_{\perp}$$

Ion cyclotron damping

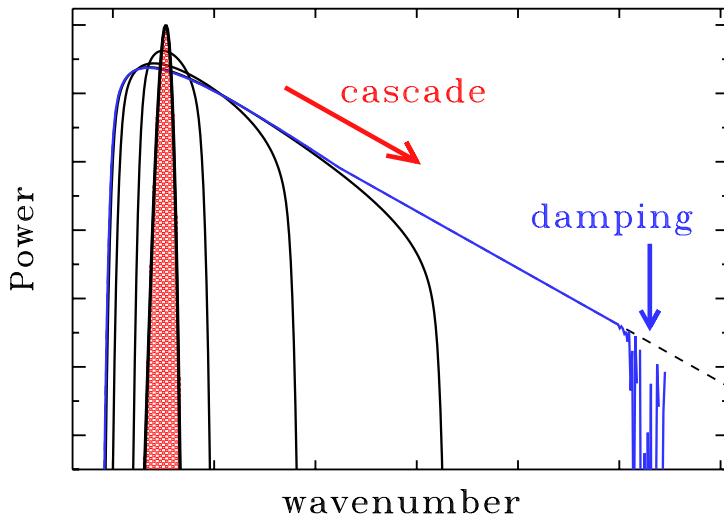
$$\omega - u_{\parallel} k_{\parallel} = \pm n \Omega_{\text{ion}}$$

$$T_{\text{ion}} \gg T_p > T_e$$

$$T_{\perp} > T_{\parallel}$$

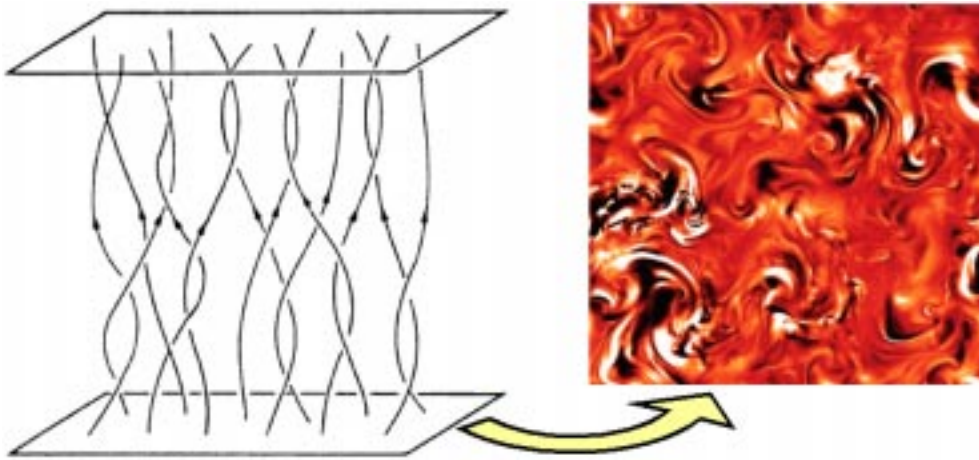
- ★ But how are these tiny-wavelength fluctuations generated?
- ★ Many suspect a **turbulent cascade** from the dominant large-scale (granular / supergranular) waves emitted in the low atmosphere:

$$\mathcal{E}_{\text{out}} = \frac{\rho v_{\text{eddy}}^3}{\ell_{\text{eddy}}} \rightsquigarrow \rightsquigarrow \rightsquigarrow Q_{\text{heat}} \approx \mathcal{E}_{\text{out}}$$



Anisotropic MHD Turbulence

- ★ The Kolmogorov heating rate ($\rho v^3/\ell$) has been used in many coronal and solar wind models (1986–present).
- ★ However, in the low- β corona (i.e., mag. pressure \gg gas pressure), it is easier to **mix** field lines in directions perp. to \mathbf{B} than it is to **bend** them parallel to \mathbf{B} .



k_{\parallel} : Alfvén waves travel up and down; they damp weakly and **reflect** because $\nabla V_A \neq 0$.



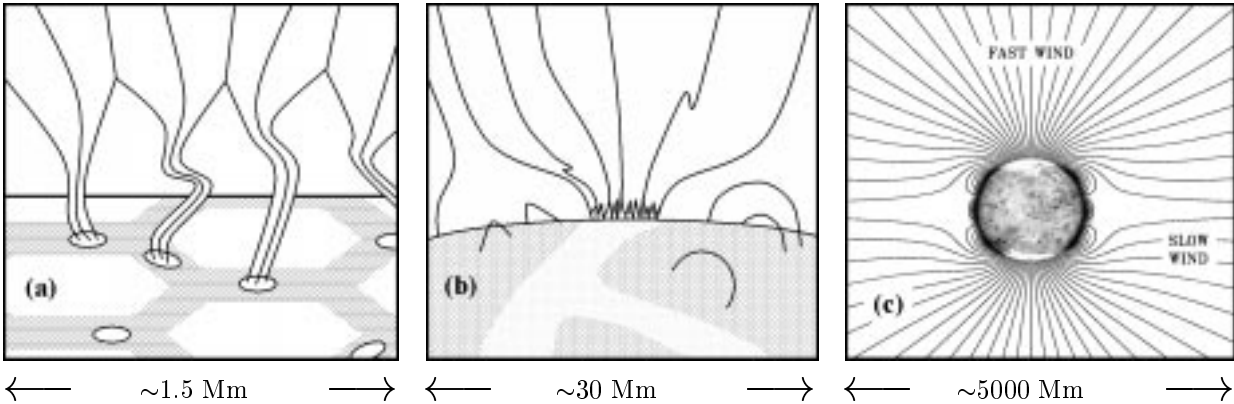
k_{\perp} : cascade proceeds rapidly . . . but not to high-freq.?

- ★ Because the turbulence is far from isotropic, the energy injection rate (and thus the **heating rate**) is modified:

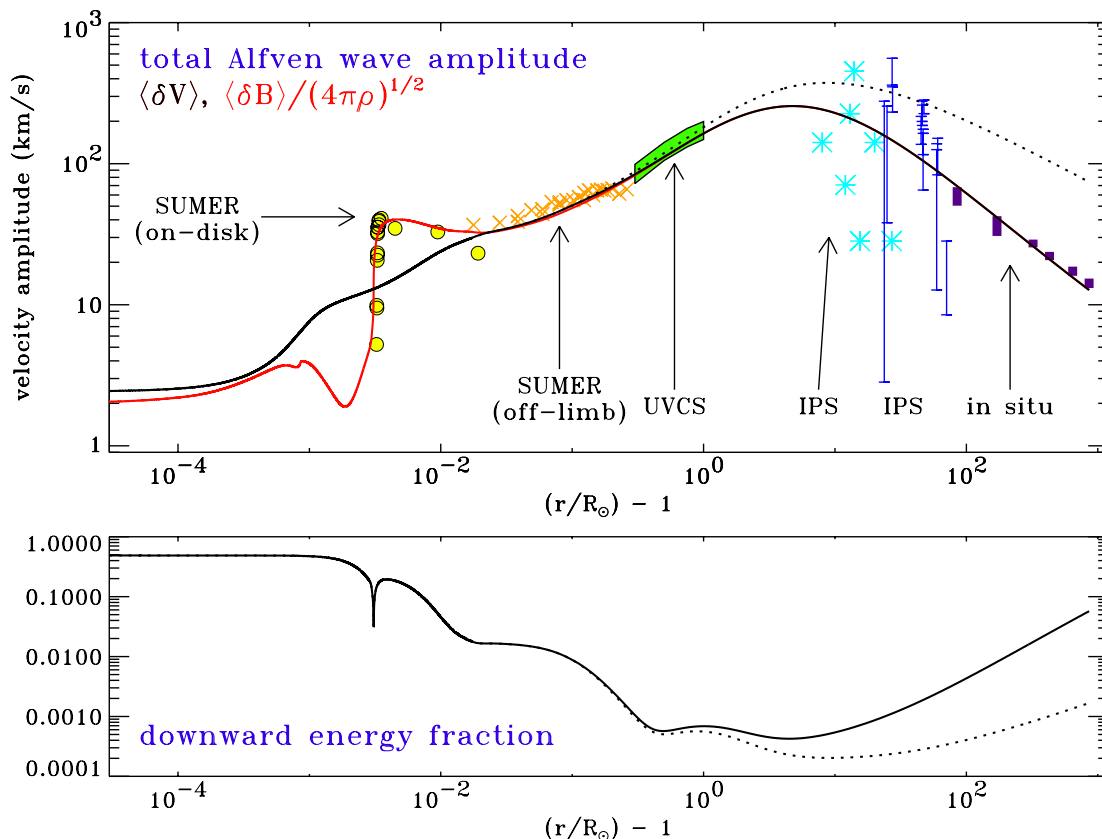
$$\mathcal{E}_{\text{out}} = \frac{\rho v_{\text{eddy}}^3}{\ell_{\text{eddy}}} \quad \longrightarrow \quad \frac{\rho (v_{\perp \text{ up}}^2 v_{\perp \text{ down}} + v_{\perp \text{ up}} v_{\perp \text{ down}}^2)}{2 \ell_{\perp \text{ eddy}}}$$

Alfvén wave reflection in coronal holes

- ★ Cranmer & van Ballegooijen (2004) built a model of the global properties of Alfvén waves in an open coronal-hole flux tube. Note successive **merging** of flux tubes on granular & supergranular scales:

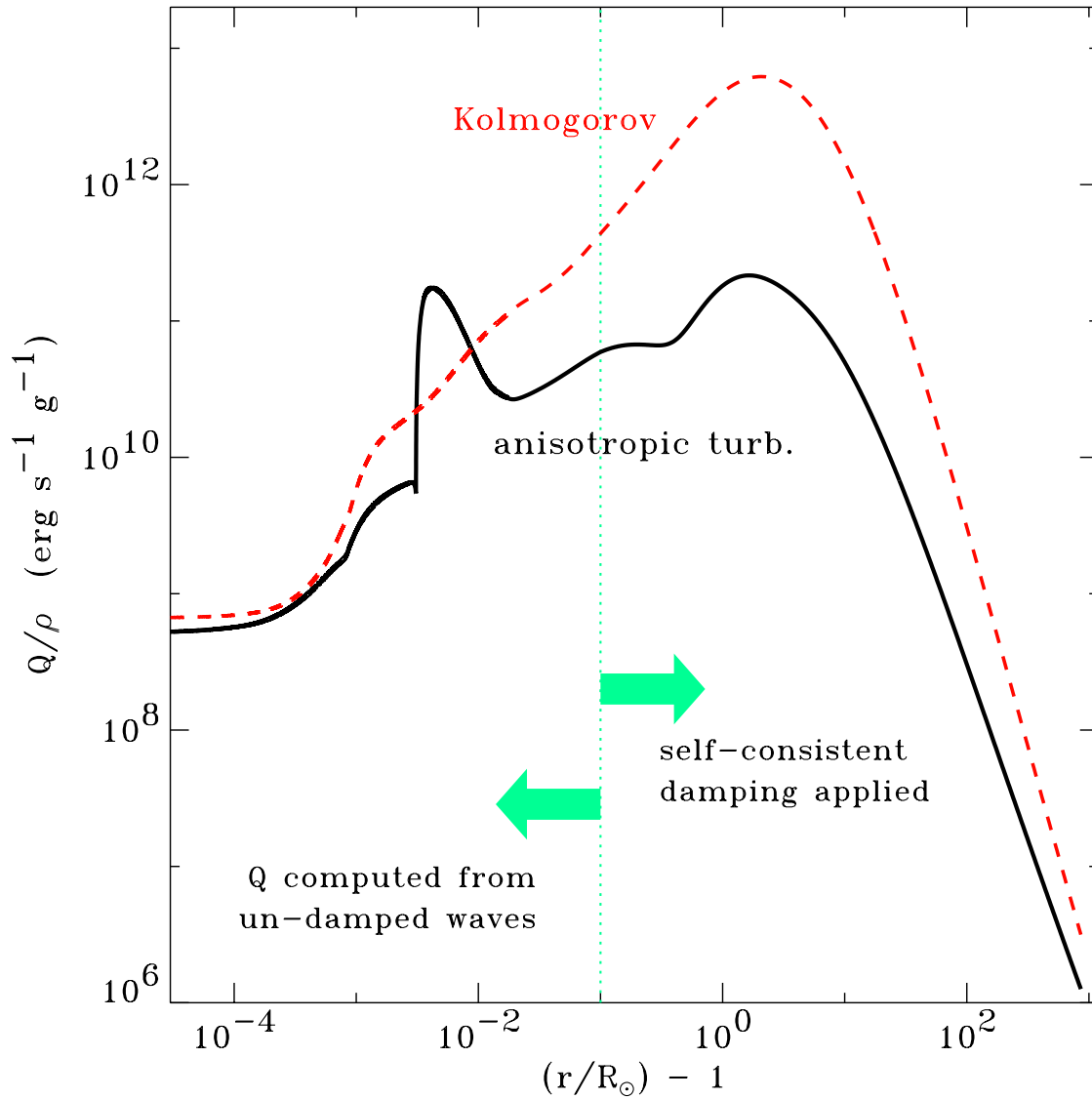


- ★ Non-WKB wave reflection was modeled for individual frequencies comprising an empirical power spectrum. $\ell_{\perp \text{eddy}} \propto B_0^{-1/2}$ normalized to produce correct damping at 1 AU.



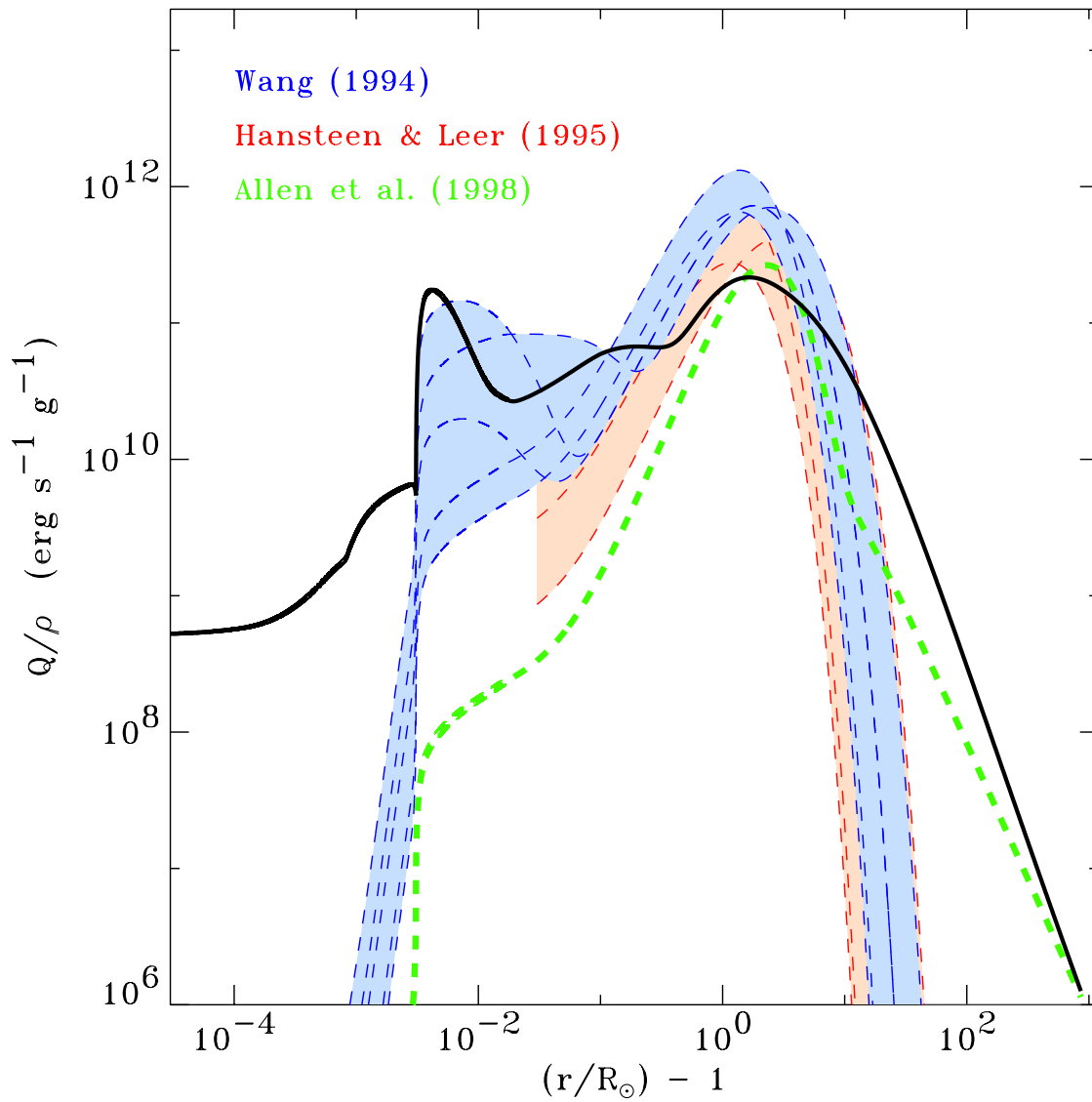
Turbulent Heating Rate (1)

- ★ The isotropic Kolmogorov formula **overestimates** the heating in regions where $v_{\perp\text{up}} \neq v_{\perp\text{down}}$. . . by as much as a factor of 30.



Turbulent Heating Rate (2)

- ★ Dmitruk et al. (2002) predicted that this anisotropic heating rate may account for much of the expected (i.e., empirically constrained) coronal heating in open magnetic regions . . .

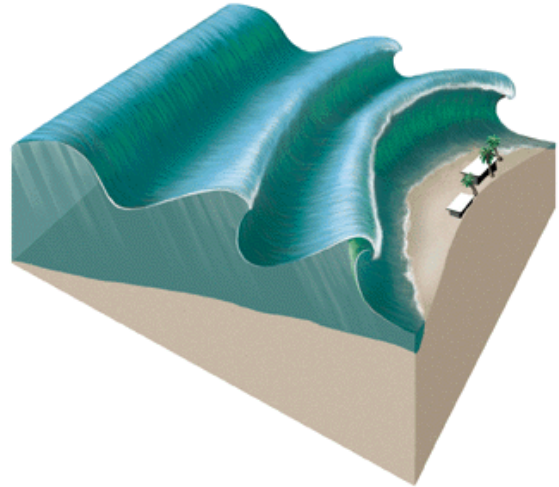


Wave-particle acceleration (“pummeling”)

- ★ Just as E/M waves carry momentum and exert pressure on matter, acoustic and MHD waves **do work on the gas** via similar net stress terms:

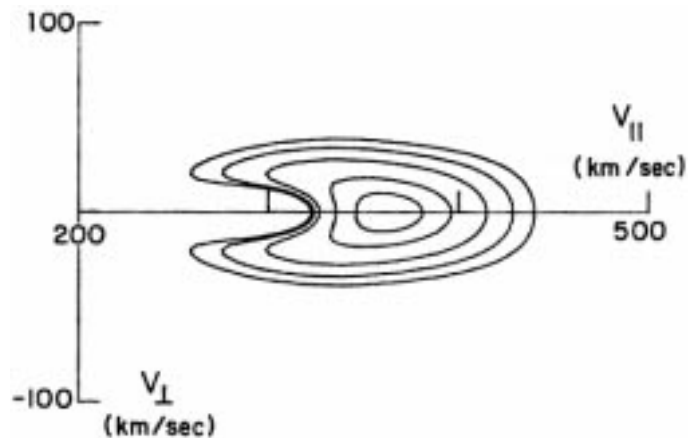
$$\rho a_{\text{wp}} = -\nabla \cdot \mathcal{P}_{\text{wp}}$$

$$\approx -\frac{\partial}{\partial r} \left(\frac{\delta B_{\perp}^2}{8\pi} \right)$$



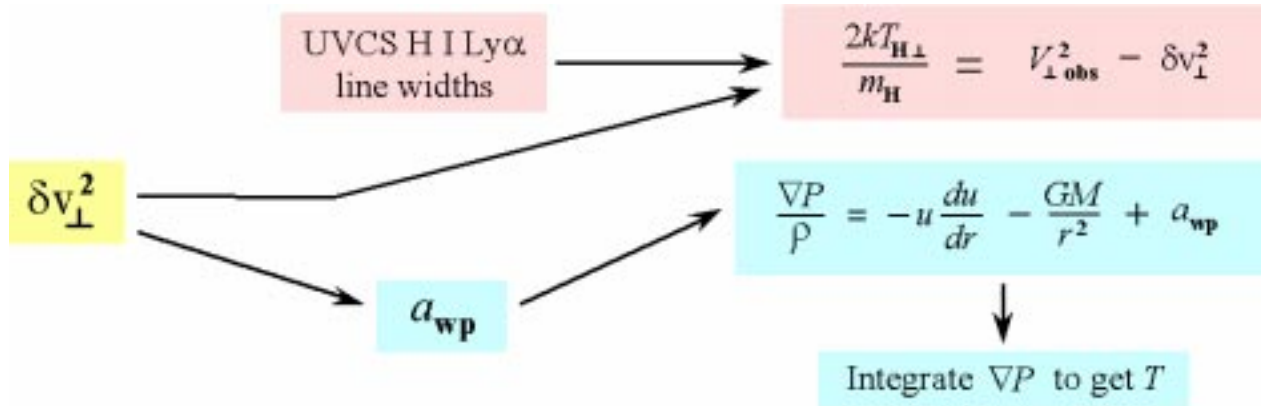
- ★ When $v_{\perp\text{up}} \gg v_{\perp\text{down}}$, the above simple WKB expression is valid. However, Laming (2004) suggests that non-WKB departures from the above may give rise to the **FIP effect** in loops.
- ★ In the extended corona, $a_{\text{wp}} \approx |g|$ (at $r \sim 2 R_{\odot}$), and can exceed $|g|$ by a factor of 3 at larger heights.

- ★ Goodrich (1978) derived the detailed “microscopic” velocity-space response of particles to a_{wp} in the collisionless solar wind. **Kinetic models should include this!**

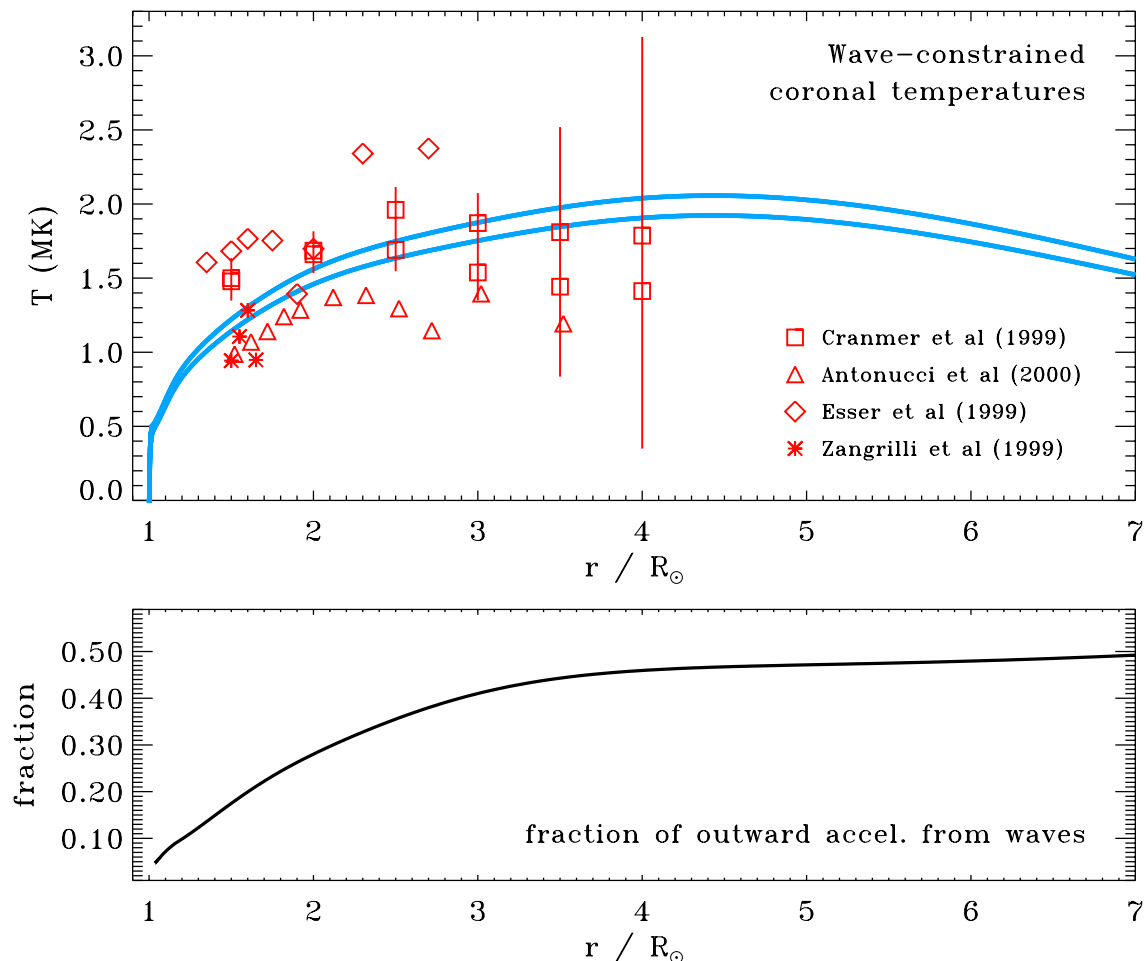


Wave pressure \longrightarrow Temperature?

- ★ There are two semi-empirical ways of using a “known” δv_{\perp} and a_{wp} to put constraints on the temperature in the extended corona:

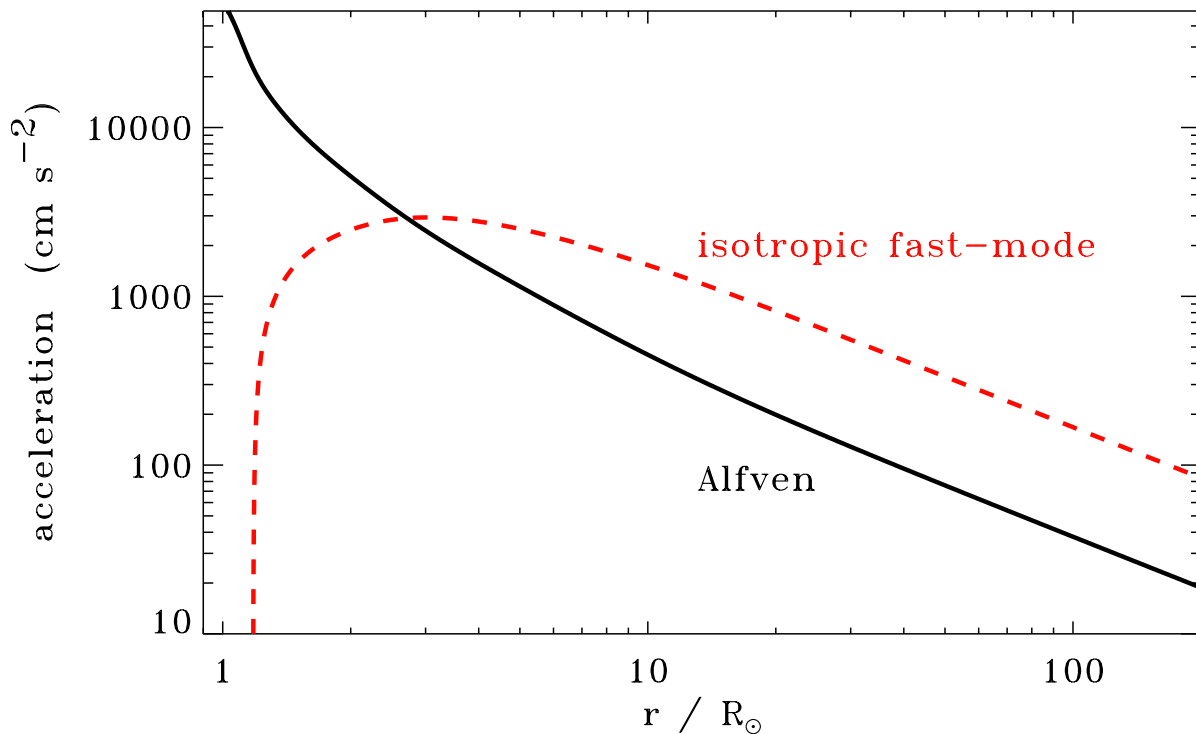


- ★ Do the two methods give the same answer?



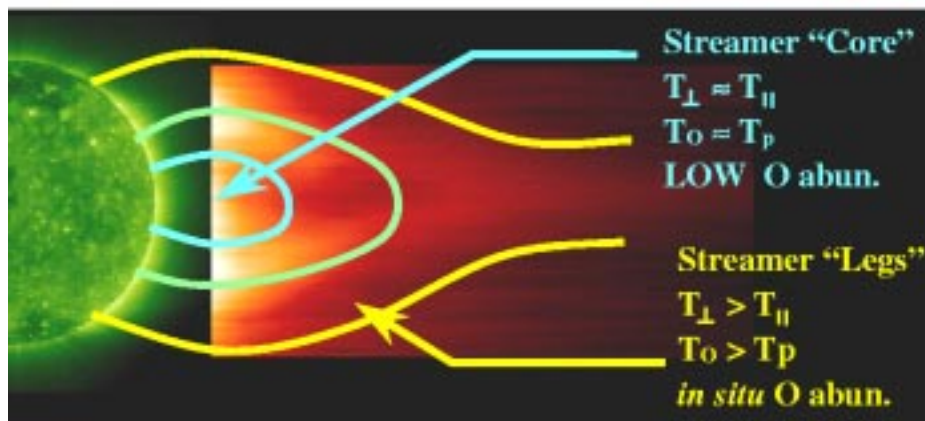
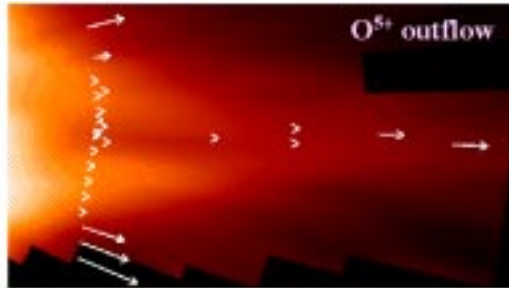
Fast-mode wave pressure?

- ★ Most solar wind models with a_{wp} include only Alfvén waves (incompressible; no linear steepening).
- ★ Fast and slow magnetoacoustic waves are probably generated in the solar atmosphere with similar fluxes as Alfvén waves . . .
 - ⇒ **slow-mode** waves steepen into shocks and damp mostly in the chromosphere;
 - ⇒ **fast-mode** waves may also steepen ($\theta \neq 0$), but their collisional damping rates are comparable to those of Alfvén waves! (Whang 1997)
- ★ For undamped Alfvén and fast-mode waves obeying wave-action conservation (and equal in energy density at $2 R_{\odot}$), we can compare their respective wave-pressure accelerations (Jacques 1977):

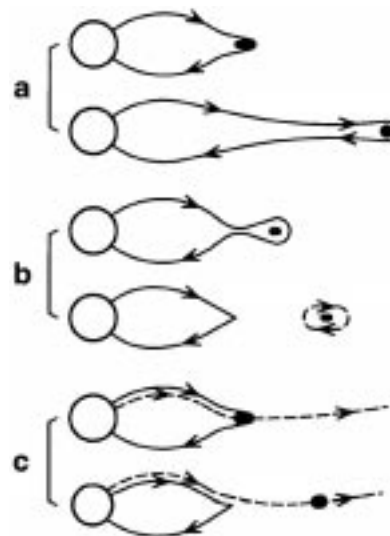
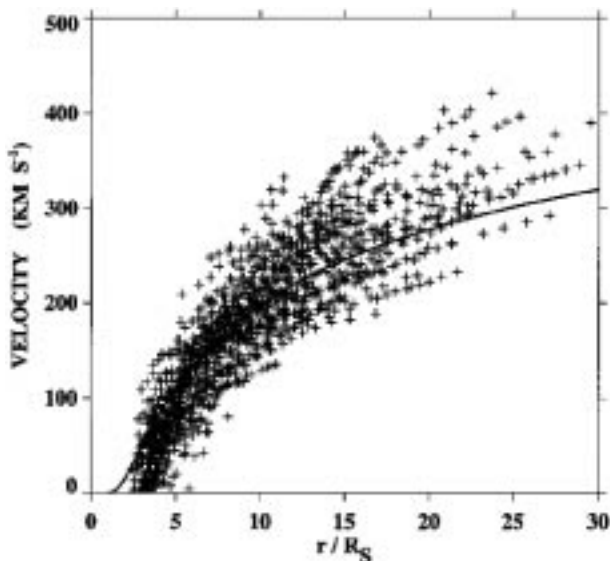


The slow solar wind: brief summary

- ★ The visible corona is dominated by bright **streamers** known for decades to be associated with the slowest solar wind streams. But what is the magnetic topology of these regions?
- ★ **UVCS spectroscopy** found outflows consistent with slow wind **only along the edges** of streamers at solar minimum:



- ★ **LASCO movies** spotlighted low-contrast "blobs" continually ejected from streamer cusps . . .



Conclusions

- ★ Our understanding of the dominant physics in the acceleration region of the solar wind is progressing rapidly . . . but so is the complexity!



What should future missions do?

- ★ We still don't know several basic plasma parameters (e.g., T_e and T_p) with sufficient accuracy in the acceleration region of the wind.
- ★ Only by better “filling out” our knowledge of **heavy ion** properties (vs. q and m) can we uniquely identify the ultimate kinetic damping mechanisms.

⇒ **Spectroscopy is key!**

- ★ The power spectrum $P(k_{\parallel}, k_{\perp}, r)$ of MHD fluctuations (near the Sun) is a strong driver of solar wind physics, but we have only very indirect constraints on its properties.

⇒ *in situ* **co-rotation may be key!** (Solar Orbiter)

- ★ The origin of coronal waves in **jostled photospheric flux-tube motions** needs to be pinned down in order to put better empirical constraints on the “lower boundary condition.”

⇒ **sub-arcsec (~ 100 km), sub-sec resolution is key!**
(near future: **ground-based only . . .**)

