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
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:

\[
\begin{align*}
\text{high-speed (500–800 km/s)} & \quad \text{low density} \quad \sim \text{laminar flow} \\
\text{low-speed (300–500 km/s)} & \quad \text{high density} \quad \text{variable, filamentary}
\end{align*}
\]

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

★ accelerate the high-speed ($v > V_{esc}$) 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: \((T_\perp/T_\parallel \approx 10\) 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.

\[
\begin{align*}
T_{\text{ion}} &\gg T_p > T_e \\
(T_{\text{ion}}/T_p) &> (m_{\text{ion}}/m_p) \\
T_\perp &\gg T_\parallel \\
u_{\text{ion}} &> u_p
\end{align*}
\]

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:

  \[
  \text{Landau damping} \quad \omega - u||k|| = 0 \\
  \quad T_e > T_p \quad \text{(low-\(\beta\))} \\
  \quad T_\parallel > T_\perp
  \]

  \[
  \text{Ion cyclotron damping} \quad \omega - u||k|| = \pm n \Omega_{\text{ion}} \\
  \quad T_{\text{ion}} \gg T_p > T_e \\
  \quad T_\perp > T_\parallel
  \]

* 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:

\[
\mathcal{E}_{\text{out}} = \frac{\rho V_{\text{edd}}^3}{\ell_{\text{edd}}} \quad \sim \sim \sim \quad Q_{\text{heat}} \approx \mathcal{E}_{\text{out}}
\]

![Diagram of power vs. wavenumber with cascade and damping annotations](image)
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-$\beta$ 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 $\mathbf{B}$.

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

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

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

$\downarrow$

$k_\perp$: cascade proceeds rapidly . . . but not to high-freq.?
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. $\ell_{\text{eddy}} \propto B_0^{-1/2}$ normalized to produce correct damping at 1 AU.

![Diagram of Alfvén wave reflection in coronal holes](image)
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.
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 . . .

**Turbulent Heating Rate (2)**

- *Wang (1994)*
- *Hansteen & Leer (1995)*
- *Allen et al. (1998)*

\[
\frac{Q}{\rho} \quad (\text{erg s}^{-1} \text{g}^{-1})
\]

\[
(r/R_{\odot}) - 1
\]
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:

\[ \rho a_{wp} = -\nabla \cdot \mathbf{P}_{wp} \]

\[ \approx -\frac{\partial}{\partial r} \left( \frac{\delta B^2_{\perp}}{8\pi} \right) \]

* When \( v_{\perp up} \gg v_{\perp down} \), 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, \( a_{wp} \approx |\mathbf{g}| \) (at \( r \sim 2R_\odot \)), and can exceed \( |\mathbf{g}| \) 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 $\rightarrow$ Temperature?

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

$$\frac{2kT_{H\perp}}{m_H} = v_{\perp,\text{obs}}^2 - \delta v_{\perp}^2$$

$$\nabla P = -u \frac{du}{dr} - \frac{GM}{r^2} + a_{wp}$$

Integrate $\nabla P$ to get $T$

* 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):

![Graph showing acceleration vs. distance from the Sun for Alfvén and isotropic fast-mode waves.](image)
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 (\( \sim 100 \) km), sub-sec resolution is key! (near future: ground-based only . . . )