Alfvénic Turbulence in the Fast Solar Wind: from cradle to grave

S. R. Cranmer, A. A. van Ballegooijen, and the UVCS/SOHO Team

Harvard-Smithsonian Center for Astrophysics
Alfvénic Turbulence in the Fast Solar Wind: from cradle to grave

Outline:
- Background
- Alfvén wave generation (thin flux tubes)
- Non-WKB wave reflection
- MHD turbulence
- Collisionless damping → ion heating

S. R. Cranmer, A. A. van Ballegooijen, and the UVCS/SOHO Team

Harvard-Smithsonian Center for Astrophysics
The need for extended coronal heating

- The basal “coronal heating problem” is well known:

- Above 2 $R_s$, **additional energy deposition** is required in order to . . .
  
  » accelerate the fast solar wind (without artificially boosting mass loss and peak $T_e$),
  
  » produce the proton/electron temperatures seen *in situ* (also magnetic moment!),
  
  » produce the strong preferential heating and temperature anisotropy of heavy ions (in the wind’s acceleration region) seen with UV spectroscopy.
Coronal heating mechanisms

- Surveys of dozens of models: Mandrini et al. (2000), Aschwanden et al. (2001)

- Where does the mechanical energy come from?

- How is this energy coupled to the coronal plasma?

- How is the energy dissipated and converted to heat?

**Diagram:**

- Waves shocks eddies (“AC”) vs. twisting braiding shear (“DC”)
- Interact with inhomog./nonlin.
- Turbulence
- Reconnection

**Collisions** (visc, cond, resist, friction) or collisionless

Alfvénic Turbulence in the Fast Solar Wind
S. R. Cranmer

Sources of the Solar Wind
Berkeley, SSL, May 10, 2005
Alfvén waves in open flux tubes


- Background plasma properties (density, flow speed, B-field strength) are fixed empirically; wave properties are modeled with virtually no “free” parameters.

- Note successive merging of flux tubes on granular & supergranular scales:

---

Alfvénic Turbulence in the Fast Solar Wind
S. R. Cranmer

Sources of the Solar Wind
Berkeley, SSL, May 10, 2005
G-band bright points (close-up)
**Photospheric power spectrum**

- The basal transverse fluctuation spectrum is specified from observed BP motions.
- The “ideal” data analysis of these motions:

\[
x(t), \ y(t)
\]

\[
\downarrow
\]

\[
v_x(t), \ v_y(t)
\]

\[
\downarrow
\]

\[
C_{xx}(\tau) = \lim_{\Delta t \to \infty} \frac{1}{\Delta t} \int_{-\Delta t/2}^{+\Delta t/2} dt \ v_x(t) v_x(t + \tau), \ \text{also for} \ C_{yy}
\]

\[
\downarrow
\]

\[
P_x(\omega) \equiv \frac{1}{2\pi} \int_{-\infty}^{+\infty} d\tau \ C_{xx}(\tau) e^{i\omega \tau}, \ \text{also for} \ P_y
\]
In practice, there are two phases of observed BP motion:

- “random walks” of isolated BPs (e.g., Nisenson et al. 2003);
- “intermittent jumps” representing mergers, fragmenting, reconnection? (Berger et al. 1998).

$P_K$ not necessarily equal to $P_B$!
**Kink-mode waves in thin flux tubes**

- Below a 600 km "merging height" we follow Lagrangian perturbations of a ~vertical flux tube (Spruit 1981):

\[
\frac{\partial^2 v_\perp}{\partial t^2} = \frac{g \Delta \rho}{\rho_{\text{tot}}} \frac{\partial v_\perp}{\partial r} + V_{\text{ph}}^2 \frac{\partial^2 v_\perp}{\partial r^2}
\]

buoyancy term
(cutoff period: 9 to 12 min.)

In reality, it’s not incompressible . . .
(Hasan et al. 2005; astro-ph/0503525)
Supergranular “funnel” cartoons

Peter (2001)

Tu et al. (2005)
Non-WKB Alfvén wave reflection

- Above the 600 km merging height, we follow Eulerian perturbations along the axis of the superradial flux tube, with wind (Heinemann & Olbert 1980; Velli 1993):

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

where \( Z_{\pm} \equiv v_\perp \pm B_\perp / \sqrt{4\pi \rho} \)
Resulting wave amplitude (with damping)

- Transport equations solved for 300 “monochromatic” periods \((3 \text{ sec to 3 days})\), then renormalized using photospheric power spectrum.
- One free parameter: base “jump amplitude” \((0 \text{ to } 5 \text{ km/s allowed}; \ 3 \text{ km/s is best})\).
**MHD turbulence**

- It is highly likely that somewhere in the outer solar atmosphere the fluctuations become turbulent and **cascade** from large to small scales:

  \[
  \mathcal{E}_{\text{out}} = \frac{\rho v_{\text{eddy}}^3}{\ell_{\text{eddy}}}, \quad Q_{\text{heat}} \approx \mathcal{E}_{\text{out}}
  \]

- With a strong background field, it is easier to **mix** field lines (perp. to \(B\)) than it is to **bend** them (parallel to \(B\)).

- Also, the energy transport along the field is far from isotropic:

  \[
  Q_{\text{heat}} = \rho \frac{\langle Z_- \rangle^2 \langle Z_+ \rangle + \langle Z_+ \rangle^2 \langle Z_- \rangle}{4L_\perp}
  \]
Turbulent heating rate

- Anisotropic heating and damping was applied to the model; $L_\perp = 1100$ km at the merging height; scales with transverse flux-tube dimension.

- The isotropic Kolmogorov law overestimates the heating in regions where $Z_- \gg Z_+$.
Anisotropic heating and damping was applied to the model; \( L_\perp = 1100 \text{ km} \) at the merging height; scales with transverse flux-tube dimension.

The isotropic Kolmogorov law **overestimates** the heating in regions where \( Z_- >> Z_+ \).

Dmitruk et al. (2002) predicted that this anisotropic heating may account for much of the expected (i.e., empirically constrained) coronal heating in open magnetic regions . . .
How is the turbulent heating “partitioned” between protons, electrons, and heavy ions?
UVCS results: solar minimum (1996-1997)

- Ultraviolet spectroscopy probes properties of ions in the wind’s acceleration region.
- In June 1996, the first measurements of heavy ion (e.g., O$^{+5}$) line emission in the extended corona revealed surprisingly wide line profiles...

Sources of the Solar Wind
Berkeley, SSL, May 10, 2005
Solar Wind: The Impact of UVCS

UVCS/SOHO has led to new views of the acceleration regions of the solar wind. Key results include:

- The fast solar wind becomes **supersonic** much closer to the Sun (~2 $R_s$) than previously believed.
- In coronal holes, heavy ions (e.g., O$^{+5}$) both flow **faster** and are **heated** hundreds of times more strongly than protons and electrons, and have **anisotropic temperatures**.

\[
\begin{align*}
T_{\text{ion}} & \gg T_p > T_e \\
(T_{\text{ion}}/T_p) & > (m_{\text{ion}}/m_p) \\
T_\perp & \gg T_\parallel \\
\nu_{\text{ion}} & > \nu_p
\end{align*}
\]
**Ion cyclotron waves in the corona?**

- UVCS observations have **rekindled theoretical efforts** to understand heating and acceleration of the plasma in the (collisionless?) acceleration region of the wind.

- Ion cyclotron waves (10 to 10,000 Hz) suggested as a natural energy source that can be tapped to preferentially heat & accelerate heavy ions.

- Dissipation of these waves produces **diffusion** in velocity space along contours of ~constant energy in the frame moving with wave phase speed:

  ![Diagram of Alfven wave's oscillating E and B fields](image1)

  ![Diagram of ion's Larmor motion around radial B-field](image2)

---

**Alfvénic Turbulence in the Fast Solar Wind**

*S. R. Cranmer*

Sources of the Solar Wind

Berkeley, SSL, May 10, 2005
Anisotropic MHD cascade

- Can MHD turbulence generate ion cyclotron waves? Many models say no!
- Simulations & analytic models predict cascade from small to large $k_{\perp}$, leaving $k_{\parallel}$ unchanged. “Kinetic Alfven waves” with large $k_{\perp}$ do not necessarily have high frequencies.
- In a low-beta plasma, KAWs are Landau-damped, heating electrons preferentially!
Anisotropic MHD cascade

- Can MHD turbulence generate ion cyclotron waves? Many models say no!
- Simulations & analytic models predict cascade from small to large $k_\perp$, leaving $k_\parallel$ unchanged. “Kinetic Alfvén waves” with large $k_\perp$ do not necessarily have high frequencies.
- In a low-beta plasma, KAWs are Landau-damped, heating electrons preferentially!
- Cranmer & van Ballegooijen (2003) modeled the anisotropic cascade with advection & diffusion in k-space and found some $k_\parallel$ “leakage” . . .
How are ions heated preferentially?

Variations on “Ion cyclotron resonance:”

- Additional unanticipated frequency cascades (e.g., Gomberoff et al. 2004)
- Impulsive plasma micro-instabilities that locally generate high-freq. waves (Markovskii 2004)
- Non-linear/non-adiabatic KAW-particle effects (Voitenko & Goossens 2004)
- Larmor “spinup” in dissipation-scale current sheets (Dmitruk et al. 2004)

Other ideas:

- KAW damping leads to electron beams, further (Langmuir) turbulence, and Debye-scale electron phase space holes, which heat ions perpendicularly via “collisions” (Ergun et al. 1999; Cranmer & van Ballegooijen 2003)
- Collisionless velocity filtration of suprathermal tails (Pierrard et al. 2004)
Conclusions

- Our understanding of the dominant physics in the acceleration region of the solar wind is growing rapidly . . . But so is the complexity!

- **Preliminary**: It does seem possible to heat & accelerate the high-speed wind via mainly incompressible Alfvénic turbulence.

- We still don’t know several key plasma parameters (e.g., $T_e$ and $T_p$) with sufficient accuracy, as a function of $r$, $\theta$, and solar cycle.

- Upcoming missions (SDO, STEREO, Solar-B) will help build a more complete picture, but we really need next-generation UVCS and LASCO, as well as Solar Probe!

- Lines of communication between {solar/stellar/plasma/astro} physicists must be kept open.