Turbulent Origins of the Sun’s Hot Corona and the Solar Wind

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Turbulent Origins of the Sun’s Hot Corona and the Solar Wind

Outline:
1. Solar overview: Our complex “variable star”
2. How do we measure waves & turbulence?
3. Coronal heating & solar wind acceleration
The Sun’s overall structure

Core:
• Nuclear reactions fuse hydrogen atoms into helium.

Radiation Zone:
• Photons bounce around in the dense plasma, taking millions of years to escape the Sun.

Convection Zone:
• Energy is transported by boiling, convective motions.

Photosphere:
• Photons stop bouncing, and start escaping freely.

Corona:
• Outer atmosphere where gas is heated from \( \sim 5800 \, \text{K} \) to several million degrees!
Everywhere one looks, the plasma is “out of equilibrium!”
The solar photosphere

- In visible light, we see the top of the convective zone (wide range of time/space scales):
  - \( \beta << 1 \)
  - \( \beta \sim 1 \)
  - \( \beta > 1 \)
The solar chromosphere

- After $T$ drops to $\sim4000$ K, it rises again to $\sim20000$ K over 0.002 $R_{\text{sun}}$ of height.

- Observations of this region show shocks, thin “spicules,” and an apparently larger-scale set of convective cells (“super-granulation”).

- Most… but not all… material ejected in spicules appears to fall back down.
The solar corona

- Plasma at $10^6$ K emits most of its spectrum in the UV and X-ray...
The coronal heating problem

- We still do not understand the physical processes responsible for heating up the coronal plasma. A lot of the heating occurs in a narrow “shell.”

- Most suggested ideas involve 3 general steps:
  1. Churning convective motions that tangle up magnetic fields on the surface.
  2. Energy is stored in tiny twisted & braided “magnetic flux tubes.”
  3. Something releases this energy as heat.
     - Particle-particle collisions?
     - Wave-particle interactions?
A small fraction of magnetic flux is OPEN

Peter (2001)

Tu et al. (2005)
The solar wind: discovery

- 1860–1950: Evidence slowly builds for **outflowing magnetized plasma** in the solar system:
  - solar flares → aurora, telegraph snafus, geomagnetic “storms”
  - comet ion tails point anti-sunward (no matter comet’s motion)

- 1958: Eugene Parker proposed that the **hot corona** provides enough gas pressure to counteract gravity and accelerate a “solar wind.”

$$\left( \frac{\partial}{\partial t} + \mathbf{v} \cdot \nabla \right) \mathbf{v} = -\frac{\nabla P}{\rho} + \mathbf{g} + \mathbf{a}_{\text{other}}$$
In situ solar wind: properties


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

- 1990s: *Ulysses* left the ecliptic; provided first 3D view of the wind’s source regions.

- 1970s: *Helios* (0.3–1 AU). 2007: *Voyagers* @ term. shock!

<table>
<thead>
<tr>
<th></th>
<th>fast</th>
<th>slow</th>
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<tbody>
<tr>
<td><strong>speed (km/s)</strong></td>
<td>600–800</td>
<td>300–500</td>
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<tr>
<td><strong>density</strong></td>
<td>low</td>
<td>high</td>
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<tr>
<td><strong>variability</strong></td>
<td>smooth + waves</td>
<td>chaotic</td>
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<tr>
<td><strong>temperatures</strong></td>
<td>$T_{\text{ion}} \gg T_p &gt; T_e$</td>
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<td><strong>abundances</strong></td>
<td>photospheric</td>
<td>more low-FIP</td>
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Waves & turbulence in the photosphere

• **Helioseismology:** direct probe of wave oscillations below the photosphere (via modulations in intensity & Doppler velocity)

• How much of that wave energy “leaks” up into the corona & solar wind?

  ➡ Still a topic of vigorous debate!

• Measuring **horizontal** motions of magnetic flux tubes is more difficult . . . but may be more important?
Waves in the corona

- Remote sensing provides several direct (and indirect) detection techniques:
  
  - Intensity modulations . . .
    \[ \delta I \propto (\delta \rho)^{1-2} \]
  - Motion tracking in images . . .
    \[ \delta V_{\text{POS}} \]
  - Doppler shifts . . .
    \[ \delta \lambda \propto \delta V_{\text{LOS}} \]
  - Doppler broadening . . .
    \[ \delta \lambda \rightarrow <\delta V_{\text{LOS}}> \]
  - Radio sounding . . .
    \[ \delta n \rightarrow \delta \rho, \delta B \rightarrow \delta V \]

SOHO/LASCO (Stenborg & Cobelli 2003)
Wavelike motions in the corona

- Remote sensing provides several direct (and indirect) detection techniques:

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- Motion tracking in images . . .

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- Doppler broadening . . .

  \[ \delta \lambda \rightarrow \langle \delta V_{\text{LOS}} \rangle \]

- Radio sounding . . .

  \[ \delta \bar{n} \rightarrow \delta \rho, \delta B \rightarrow \delta V \]
Wavelike motions in the corona

- Remote sensing provides several direct (and indirect) detection techniques:

- The Ultraviolet Coronagraph Spectrometer (UVCS) on SOHO has measured plasma properties of protons, ions, and electrons in low-density collisionless regions of the corona (1.5 to 10 solar radii).

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

- Ion cyclotron waves (10–10,000 Hz) have been suggested as a “natural” energy source that can be tapped to preferentially heat & accelerate the heavy ions, as observed.
In situ fluctuations & turbulence

- Fourier transform of $B(t)$, $v(t)$, etc., into frequency:

The inertial range is a “pipeline” for transporting magnetic energy from the large scales to the small scales, where dissipation can occur.
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What processes drive solar wind acceleration?

Two broad paradigms have emerged . . .

• Wave/Turbulence-Driven (WTD) models, in which flux tubes “stay open”
• Reconnection/Loop-Opening (RLO) models, in which mass/energy is injected from closed-field regions.

• There’s a natural appeal to the RLO idea, since only a small fraction of the Sun’s magnetic flux is open. Open flux tubes are always near closed loops!
• The “magnetic carpet” is continuously churning.
• Open-field regions show frequent coronal jets (SOHO, Hinode/XRT).
Waves & turbulence in open flux tubes

- Photospheric flux tubes are shaken by an observed spectrum of horizontal motions.
- Alfvén waves propagate along the field, and partly reflect back down (non-WKB).
- Nonlinear couplings allow a (mainly perpendicular) cascade, terminated by damping.

Results of wave/turbulence models

- Cranmer et al. (2007) computed self-consistent solutions for waves & background plasma along flux tubes going from the photosphere to the heliosphere.

- **Only free parameters:** radial magnetic field & photospheric wave properties. (No arbitrary “coronal heating functions” were used.)

- Self-consistent coronal heating comes from gradual Alfvén wave reflection & turbulent dissipation.

- Is Parker’s “critical point” above or below where most of the heating occurs?

- Models match most observed trends of plasma parameters vs. wind speed at 1 AU.
Understanding physics reaps practical benefits

Self-consistent WTD models

\[ Q_{\text{heat}} = |\nabla \cdot \mathbf{F}_{\text{heat}}| = \rho \mathcal{F} \frac{(Z_-)^2(Z_+)}{4L_\perp} \]

3D global MHD models

Real-time “space weather” predictions?
Conclusions

- It is becoming easier to include “real physics” in 1D → 2D → 3D models of the complex Sun-heliosphere system.

- Theoretical advances in MHD turbulence continue to help improve our understanding about coronal heating and solar wind acceleration.

• We still do not have complete enough observational constraints to be able to choose between competing theories.

For more information:  http://www.cfa.harvard.edu/~scranmer/