Coronal heating and SW acceleration: thoughts on scaling parameters

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Outline

• MHD turbulence as a coronal heating paradigm: scaling results, problems and perspectives

• Open corona and SW acceleration

• Conclusions
Magnetic field: confinement and energization

(a) White light eclipse 2007 March 29 corona made by a 1600 mm telescope in Libya and SOHO EIT He II (30.4 nm). The resolution of the image is 1-2” and its effective wavelength within 400 - 650 nm. (b) Edge-enhanced Druckmüller-Aniol eclipse picture Libya, 2006, cropped at r 1/4 2:2 Rs joined to a LASCO C2 image recorded at 10:46 UT. An unsharp mask has been applied to the LASCO white-light image by subtracting from it a smoothed version of itself. Image rotated about 30° cc compared to (a), From Pasachoff et al. (2007) and Wang et al. (2007).
Source of heliospheric energy flux

Photospheric motions produce field line tangling and emerging flux resulting in a Poynting flux crossing the photosphere:

\[ \mathbf{S} = \frac{c}{4\pi} \mathbf{E} \times \mathbf{B} \]

\[ \mathbf{E} = -\frac{1}{c} \mathbf{V}_{ph} \times \mathbf{B} \]

\[ \mathbf{S} \cdot \mathbf{n}_{ph} = \frac{B^2}{4\pi} \mathbf{V}_{ph} \cdot \mathbf{n}_{ph} - \frac{\mathbf{B} \cdot \mathbf{n}_{ph}}{4\pi} \mathbf{V}_{ph \perp} \cdot \mathbf{B} \]

Emerging Flux Waves and Turbulence
Heating the confined corona

Parker

Model

“Reality”
Towards a scaling

\[ F = \frac{B \cdot B}{4\pi}. \]

\[ \tan\Theta = \frac{vt}{L}. \]

\[ W = vF, \]
\[ = v\frac{B^2}{4\pi} \tan\Theta. \]

\[ F_H = q \frac{B^2}{4\pi} \delta v, \]
Parker scenario has considerable heritage....


A loop model

\[ \frac{B_0}{\sqrt{4\pi \rho}} \approx 1000 \frac{km}{s} \]
\[ \sqrt{\langle u_{ph}^2 \rangle} \approx 1 \frac{km}{s} \]
\[ L \approx 10^4 km \]
\[ \frac{l_\perp}{L} = \epsilon \approx \frac{1}{10} \]
\[ \frac{l_\perp V_a}{Lu_{ph}} = f \]
Full RMHD simulations

J^2/R    Red = 1000    Yellow = 350    Max = 2.7x10^4    min = 0
Full RMHD simulations

Perpendicular spectra as a function of the control parameter $f = IV_a/L u_{ph}$
Shorter loops, or loops with a STRONGER axial field, have STEEPER spectral slopes and more energy. One may derive a combined scaling law for coronal heating

\[ S_z = \rho v_A u_{ph}^2 \left( \frac{\ell_c v_A}{L u_{ph}} \right)^{\frac{\alpha+1}{\alpha+2}} \]
Lower boundary condition
Full 3D simulations Gudiksen Nordlund and Oslo crowd

Exponential decrease of heating/currents with height
Heating and driving the fast solar wind

Invoke either REFLECTION of ALFVÉN WAVES (Velli et al. 1989, Matthaeus et al 2000, Verdini et al. 2006, Verdini & Velli 2007) or COMPRESSIBLE PARALLEL CASCADE (Suzuki ‘06, ‘07)

Generation of waves by foot point motion

Reflection of the waves due to variation of Va

Turbulent cascade, plasma heating and wind acceleration in perpendicular planes
Reflection has two effects:
- Limits the outward flux
- Triggers non-linear interactions

Wave Equations

\[
\frac{\partial z^\pm}{\partial t} + [(U \pm V_a) \cdot \nabla] z^\pm + (z^\mp \cdot \nabla)(U \mp V_a) + \frac{1}{2} (z^- - z^+) \left[ \nabla \cdot V_a \mp \frac{1}{2} (\nabla \cdot U) \right] = - (z^\mp \cdot \nabla) z^\pm - \frac{1}{\rho} \nabla p_{tot}
\]
Shell model cascade and heating
Outward and inward Alfvén mode spectra at various heights in the corona
Some papers:


Buchlin, E.; Cargill, P. J.; Bradshaw, S. J.; Velli, M. Profiles of heating in turbulent coronal magnetic loops A&A 2007
\[
\n\n\left\{ \rho \nabla \left( \frac{V^2}{2} + \frac{\gamma p}{(\gamma - 1)\rho} - \frac{GM_o}{R} \right) - \frac{(V \times B) \times B}{4\pi} + \frac{r}{F_c} \right\} + q_R = 0
\]

\[
F_c = -\kappa \nabla T \text{ or some other prescription (collisionless)}
\]

\[
q_R \text{ radiative loss} \quad F_0 = F_m + F_q + F_{rad} + F_{sw}
\]
SW acceleration: Energy Balance Along a Flux Tube

\[ F_{sw} = \dot{M} \left( \frac{V^2}{2} - \frac{V_g^2}{2} + \frac{5kT}{m_p} \right) \]

\[ V_g = 618 \text{ km/s} \]

\[ F_0 = F_{m,0} + F_{q,0} + F_{rad,0} - \dot{M} \frac{V_g^2}{2} \]

\[ F_0 = F_{rad,\infty} + \dot{M} \frac{V_\infty^2}{2} \]

\[ F_{m,0} = \dot{M} \left( \frac{V_\infty^2}{2} + \frac{V_g^2}{2} \right) + F_{rad,\infty} \]

\[ \frac{V_\infty^2}{2} = \frac{1}{\dot{M}} \left( F_{m,0} - F_{rad,\infty} \right) - \frac{V_g^2}{2} \]

Hammer, Holzer & Leer, Hansteen et al, et.c.
Interchange reconnection as source of EM energy and mass flux to the wind


\[ \frac{V^2}{2} = \frac{C_1}{T} + C_2 \]

[Graph and diagram showing interconnection of solar wind and magnetic field structures]
Fisk, 2005 Scaling Law

Flux tube breaks open in reconnection releasing 50% of its mass

\[ \rho = \rho_0 \exp\left(-\frac{zGM_0m_p}{2r_0^2kT}\right) \]

\[ M_{\text{loop}} = \rho_0 S \left( 2r_0^2kT/GM_0m_p \right) \left[ 1 - \exp\left(-1.75 h_0 GM_0m_p/2r_0^2kT\right) \right] \]

\[
\frac{V_{SW}^2}{2} = \left( \frac{B_{\text{loop}}}{\rho_{\text{loop}}} \right) \left( \frac{\int B_{\text{open}} \cdot dh}{4\pi r_0} \right) \left( \frac{GM_0m_p}{2r_0kT} \right) \beta(h_{\text{loop}},T) - \frac{GM_0}{r_0}
\]

\[
\beta(h_{\text{loop}},T) = \left\{ 1 - \exp\left[-(1.75h_{\text{loop}} GM_0m_p)/(2r_0^2kT)\right] \right\}^{-1}.
\]
Schwadron & McComas Scaling Law

Apply Conservation Laws 2 Times:
\( a) \) from photosphere to 1 AU
\( b) \) from photosphere to \( T_{\text{max}} \)

\[
\frac{m v_f^2}{2} = \frac{c}{4\pi} \int dS_0 \cdot (E \times B)_0 \frac{\int f_0^r dV \langle \dot{E}_{\text{rad}} \rangle}{\delta N} - \frac{GM_{\odot} m}{R_{\odot}}. 
\]

\[
\langle F_E \rangle_0 \approx \frac{c}{4\pi} \langle E \times B \rangle_0 - \langle \rho u \rangle_0 \frac{GM_{\odot}}{R_{\odot}}. 
\]

\[
\frac{\partial}{\partial z} \left( \frac{\gamma}{\gamma - 1} u p \right) + \frac{\partial q_e}{\partial z} = \dot{E}_H - \dot{E}_R, 
\]

\[
f_0^L dV \langle \dot{E}_{\text{rad}} \rangle = \int f_0^L dV \dot{E}_R - \frac{GM_{\odot}}{R_{\odot}} \frac{\kappa_0 T_{\text{max}}^{7/2}}{f_0 L} = C_1 k T_{\text{max}}.
\]

**Energy**

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<td>Scaling Law</td>
<td>( m v_{\text{Ho}}^2 )</td>
<td>( \left( C_0 \frac{K_0 T_m^{7/2}}{f_0^L} - C_1 k T_m \right) )</td>
<td>( \frac{GM_{\odot} m}{R_{\odot}} )</td>
<td>( \frac{m v_f^2}{2} )</td>
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SOHO 23  September 24  2009
Schwadron & McComas Scaling Law 2

\[ \frac{m u_f^2}{2} \approx m v_{A0}^2 - \left( C_0 \frac{\kappa_0 T_{\text{max}}^{7/2}}{f_0 L} - C_1 k T_{\text{max}} \right) - \frac{G M_{\odot} m}{R_{\odot}}. \]

Fig. 1.—Solar wind mass flux vs. the magnitude of the magnetic flux density, \(|\mathbf{B}|\), in the Ulysses polar regions for latitudes above \(\pm 40^\circ\) and for solar wind speeds \(>710 \text{ km s}^{-1}\). We have included the solar wind \(\text{He}^{++}\) flux in these estimates. The left-hand vertical scale shows the radially normalized average mass flux, while the right-hand scale multiplies by the area of a sphere at 1 AU to form the total mass-loss rate. Similarly, the lower horizontal scale applies to the magnetic flux density, while the upper scale applies to the total magnetic flux. The black line from the model of Schwadron & McComas (2003) model with a mass-loss rate per magnetic flux of 1.25 mg s\(^{-1}\) Wb\(^{-1}\) matches the observations remarkably well.
Suzuki et al ‘05 - ‘07

Comparison of fast and slow winds obtained with circularly polarized Alfvén wave forcing.

Alfvén waves drive and reflect off density gradients, parametric decay et c. generate compressive motions which shock and heat. So Alfvén waves push and shock waves push and heat.
Suzuki 2006 Scaling Law: confirms Wang and Sheeley

\[
\rho v r^2 f_{\text{tot}} \frac{v^2}{2} \bigg|_{r=1 \text{ AU}} = \left[ r^2 \left( -\frac{B_r \langle \delta B_{\perp} \delta v_{\perp} \rangle}{4\pi} + F_H - \rho v \frac{GM_{\odot}}{r} \right) \bigg]_{r=1 \text{ AU}} \right.
\]

\[
- \int_{1 \text{ AU}}^{r_{\odot}} dr \ r^2 f_q r,
\]

\[
\rho v r^2 f_{\text{tot}} \frac{v^2}{2} \bigg|_{r=1 \text{ AU}} = \left\{ \left. r^2 \left[ -\frac{B_r \langle \delta B_{\perp} \delta v_{\perp} \rangle}{4\pi} + \rho v \left( \frac{\gamma}{\gamma - 1} \frac{RT_C}{r} - \frac{GM_{\odot}}{r} \right) \right] \right\}_{r=1 \text{ AU}} \right.
\]

\[
v_{1 \text{ AU}} = \left\{ 2 \left[ -\frac{R_{\odot}^2}{4\pi (\rho v r^2)_{1 \text{ AU}}} r_{\odot} \langle \delta B_{\perp} \delta v_{\perp} \rangle_{\odot} \right. \right.
\]

\[
+ \left. \frac{\gamma}{\gamma - 1} \frac{RT_C}{R_{\odot}} - \frac{GM_{\odot}}{R_{\odot}} \right) \right\}^{1/2}
\]

\[
= 300 \text{ km s}^{-1} \left[ 5.9 \left( \frac{\langle \delta B_{\perp} \delta v_{\perp} \rangle_{\odot}}{8.3 \times 10^5 \text{ cm s}^{-1} \text{ G}} \right) \left( \frac{B_{r,\odot}[\text{G}]}{f_{\text{tot}}} \right) \right.
\]

\[
+ 3.4 \left( \frac{\gamma}{1.1} \right) \left( \frac{0.1}{\gamma - 1} \right) \left( \frac{T_C}{10^6 \text{ K}} \right) - 4.2 \right]^{1/2}
\]
Can a turbulence theory work in coronal holes to heat and drive the solar wind? Incompressible: invoke REFLECTION of ALFVEN WAVES (Velli et al. 1989, Matthaeus et al 2000, Verdini et al. ‘05, Cranmer et al. ‘05)
Compressible: +

Nonlinear Steepening

- Generation of waves by foot point motion
- Reflection of the waves due to variation of Va
- Turbulent cascade, plasma heating and wind acceleration in perpendicular planes
Evolution of waves in turbulence from coronal holes into the fast wind

Evolution of waves in turbulence from coronal holes into the fast wind

Energies/mass as a function of heliocentric distance

Rms u and b as a function of heliocentric distance
Global magnetic field connectivity

Cranmer & van Ballegooijen (‘07,’05) models of the global properties of incompressible non-WKB Alfvenic turbulence along an open flux tube.

Lower boundary condition: observed horizontal motions of G-band bright points. Along the flux tube, wave/turbulence properties should be computed consistently.
High-speed wind: strong connections to the largest coronal holes

Low-speed wind: still no agreement on the full range of coronal sources:

- hole/streamer boundary (streamer “edge”)
- streamer plasma sheet (“cusp/stalk”)
- small coronal holes
- active regions
The Slow Solar Wind

Time difference images showing flow of material in streamers
Sheeley, et al., 1997

Corresponding velocity profiles
Origins of the slow wind

Depending on heating partition, no stationary state is found.
Conclusion

• Scaling laws summarize empirical results (but are not a predictive tool: as complex as a full SW model)

• Slow solar wind plasma physics and transport in the low to moderate/high beta regions needs to be considered