The Heating & Acceleration of the Solar Wind

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Overview

- Brief Background
- Solar Wind Heating by KAW Turbulence
  - 'stochastic heating' by low freq. fluctuations, not ion cyclotron heating
- Global Solar Wind Modeling
Empirical Constraints on Heating

- Heating → acceleration of solar wind
- *In situ:* Fast vs Slow Wind
  - **Fast** $T_{\text{ion}} \gtrsim T_p \gtrsim T_e$ & $T_{\perp,i} \gtrsim T_{\parallel,i}$
  - **Slow** $T_e \gtrsim T_p$

- $\sim 1.4 R_\odot$: UVCS/SOHO constraints
  - $T_{\perp,i} \gg T_{\parallel,i}$ (e.g., $O^{5+}$, p)

- preferential minor ion htg

Kohl et al. 1997, 1998; Cranmer et al. 1999

*often interpreted as ion cyclotron resonant heating in bulk of solar wind*
low turbulence

\[ \omega \gg \omega_{nl} \quad \text{MHD Scales} \]

\[ \omega \approx \Omega_p \quad \text{ion cyclotron frequency} \]

\[ \omega_{nl} \gg \omega \]

\[ \text{critical balance: } k_p k_{\perp} (\omega - \omega_{nl}) \]

\[ \text{kinetic scales} \]

\[ \omega \ll \Omega_p \]

\[ \text{ion Larmor radius} \]
Alfvénic fluctuations

Strong KAW Turbulence (sans damping)

\[ E_B \propto k^{-7/3} \]

\[ k_\parallel \propto k_{\perp}^{1/3} \]

Biskamp et al. 1999; Cho & Lazarian 2004; Schekochihin et al. 2007
Howes et al. 2008

Nonlinear GyroKinetic Simulations

Nonlinear GyroKinetic Simulations

anisotropic low frequency turbulence both above & below \( \rho_i \) can be quantitatively modeled using a low freq. expansion of the Vlasov eqn

Howes et al. 2006; Schekochihin et al. 2007
In Situ Measurements of E & B-fields consistent with a transition to KAWs but not with the onset of ion cyclotron damping

In Situ Measurements in the Solar Wind
(Bale et al. 2005)
Heating by the Anisotropic Cascade
Quataert 1998; Leamon et al. 1998; Quataert & Gruzinov 1999; Cranmer & van Ballegooijen 2003; Gary & Nishimura 2004

- Linear theory; if $\omega \approx \Omega_i$
  - no cyclotron resonance
  - magnetic moment $\mu \propto T_\perp / B$ is conserved
  - $\rightarrow$ heating can only increase $T_\parallel$
    - primarily e- htg for $\beta \lesssim \text{few}$ and p htg for $\beta \gtrsim \text{few}$

- Strong Turbulence:
  - role of current sheets
  - finite amplitude fluctuations violate $\mu$ conservation
Stochastic Ion Heating by Low-Frequency Turbulence

- E-field fluctuations at $\sim \rho$ can disrupt the smooth ion gyromotion, violating conservation of magnetic moment $\mu = (mv_{\perp}^2)/2B$.
  (e.g. McChesney et al 1987, Johnson & Cheng 2001, Chen, Lin, & White 2001)

- $\mu$-conservation requires both $\omega << \Omega_p$ and $\delta v_\rho << v_{\perp}$

$\gamma_s = 0.18 \epsilon \Omega_p \exp \left( -\frac{\epsilon^2}{\epsilon} \right)$

$\epsilon = \frac{\delta v_\rho}{v_{\perp}}$

Based on Test-Particle Calculations

Note: this hsg not directly captured by gyrokinetics; requires test particles, hybrid ... though GK can likely still model the fluctuations
Stochastic heating is inherently self-limiting

\[ Q_\perp \sim \frac{(\delta v_\rho)^3}{\rho} \exp[-c_2 \epsilon] \]

\[ T_\perp \uparrow \Rightarrow \epsilon = \delta v_\rho / v_\perp \downarrow \Rightarrow Q_\perp \downarrow \]

saturates when \( t_{\text{heat}} \sim t_{\text{expansion}} \)
consistent w/ minor ion htg
(e.g., O\(^{+5}\) in corona)

slide adapted from Ben Chandran
Global Solar Wind Modeling

- 8 1D PDEs for p & e- fluid eqns solved in flux tube (no rotation)
- flux tube w/ ’super-radial’ expansion as in coronal holes
- $T_\perp$ & $T_\parallel$ evol for protons w/ fluxes of both; e- isotropic
  - $\parallel$ p & e- htg from linear theory KAW damping; $\perp$ stochastic p htg
  - e- heat flux; p $\perp$ and $\parallel$ heat fluxes evolved w/ $<v^4> = 0$; Coulomb collisions

- Low Freq Alfvén Waves Generated by Photospheric Convection
  e.g., Matthaeus et al. 1999; Cranmer & van Ballegooijen 2005
Global Solar Wind Modeling

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  - \( e^- \) heat flux; \( p \ \perp \) and \( \parallel \) heat fluxes evolved w/ \( \langle v^4 \rangle = 0 \); Coulomb collisions

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- AW turbulence due to non-WKB reflection of outgoing waves
  - wave kinetic eqn for wave energy density
    \[ \text{Htg Rate} \sim \frac{E_{\text{waves}}}{L_\perp} \]
    - energy mostly in outgoing AWs
    - rms amplitude of ingoing/reflected AWs (solved for)
    - input correlation length for waves \( \sim 10^{8-9} \text{ cm} \)
Density and Velocity Profiles

Data: white light scattering in corona & in situ measurement

Data: coronal spectroscopy & in situ measurements

slide adapted from Ben Chandran
Temperature Profiles

Data: spectroscopic (corona) and in situ

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Partitioning of Turbulent Htg Btw $Q_e$, $Q_{||p}$, and $Q_{\perp p}$

$\perp$ stochastic p htg dominates for most radii

$T_{\perp}$ profile set by $t_{\text{heat}} \sim t_{\text{exp}}$

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Electron Heating and Electron Heat Flux

Te profile set by 
$\tau_{\text{cond}} \sim \tau_{\text{heat}}$

also sometimes true for $T_\parallel$ proton
Summary

• Alfvenic Turbulence: Htg in Extended Corona and Solar Wind
• Strong MHD Turbulence (Alfvenic)
  ✓ Anisotropic Kolmogorov Turbulence
  ✓ $k \cdot \rho_i \sim 1$: Alfven Wave Cascade $\rightarrow$ Kinetic Alfven Wave Cascade
  • not cyclotron damping: $\omega \ll \Omega_i$ even at $k \cdot \rho_i \sim 1$
  • confirmed by in situ measurements
  ✓ Stochastic Htg by KAWs $\rightarrow$ Primarily $\perp$ proton heating
• Global (Fluid) Modeling Reproduces Solar Wind From First Principles