The Heating & Acceleration of the Solar Wind

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Overview

• Brief Observational & Theoretical Background

• Alfvenic Turbulence Theory (weak & strong)
  • Comparison to In Situ Observations at ~ AU
  • Transition to Kinetic Alfven Wave Cascade at ~ the Ion Larmor Radius

• Particle Heating by Alfvenic Turbulence
  • Comparison to the Fast & Slow Winds
  • The Puzzle of the High Frequency Cascade (or the lack thereof ....)
  • Possible Solutions
Background

- Heating required to accelerate the solar wind
  
  * Park 1958

- Early models invoked $e^{-}$ conduction but $T_p \gtrsim T_e$ in fast wind

- Local ($r \sim R_\odot$) & extended ($r \sim \text{few-}10^3 R_\odot$) heating required

- Extended heating favors waves

- Alfven waves: primary observed fluctuation & least damped MHD mode in collisionless plasmas
  
  * e.g., Belcher & Davis 1971; Barnes 1956

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Voyager Temp Profile

Matthaeus et al. 1999
**Thermodynamic Constraints on Heating**

- **In situ:** must dist. btw. Fast & Slow Wind
- **Fast:** \( T_{\text{ion}} \gtrsim T_p \gtrsim T_e \) \& \( T_{\perp,i} \gtrsim T_{\parallel,i} \)
- **Slow:** \( T_e \gtrsim T_p \) \& \( T_{\parallel,i} \gtrsim T_{\perp,i} (?) \)

- \(~1-4 R_\odot\): constraints from UVCS/SOHO (in Coronal Holes = **Fast**)
- \( T_{\perp,i} \gg T_{\parallel,i} \) (e.g., \( O^{5+}, p \))
- \( T_i \gg T_p \gtrsim T_e \); preferential minor ion heating

*Newbury et al. 1998*

*Kohl et al. 1997, 1998; Cranmer et al. 1999*
Wave Excitation/Launching

- **Small-scale Magnetic Activity → High Freq. Alfven Waves**
  - ~ Hz and higher; $f^{-1}$ spectrum often assumed
  - damp by ion cyclotron resonance: lower freq. waves damp at larger $r$ (lower $B$)
  - Axford & McKenzie 1992
  - e.g., Matthaeus et al. 1999; Cranmer & van Ballegooijen 2005

- **Photospheric/Convective Motions → Low Freq. Alfven Waves**
  - ~ min & shorter
  - damp by **turbulent cascade** to small scales/high frequency
MHD Turbulence

- Hydro: $P(k) \sim k^{-5/3}$
- MHD: B-field defines local direction
- $k = ??; P(k) \sim k^{-??}$
- Focus on Incompressible MHD
- Slow & Alfven waves
- Balanced Turbulence

How Does Turbulent Power Fill k-space?
Incompressible MHD Turbulence

- View as interaction of Alfven wave packets traveling at $v = \pm v_A \ (\omega = |k_\parallel|v_A)$
  
- a single Alfven wave packet is an exact non-linear soln of incompressible MHD
  
  → turbulence requires oppositely directed waves

- solar wind: inward propagating waves generated by reflection of long-wavelength ($\gtrsim$ density scale-height) outward propagating waves
  
  e.g., Matthaeus et al. 1999; Cranmer & van Ballegooijen 2005; Verdini & Velli 2007

- **weak** turbulence: non-linear (cascade) timescale $\gg$ linear wave period
  
  $\omega_{nl} \ll \omega_{lin}$

- **strong** turbulence: non-linear (cascade) timescale $\sim$ linear wave period
  
  $\omega_{nl} \sim \omega_{lin}$
Weak MHD Turbulence

- non-linear time $>>$ linear wave period $\sim (|k_\parallel| v_A)^{-1}$
- Momentum & Energy Conservation $\rightarrow$

$$k_1 + k_2 = k \quad \omega_1 + \omega_2 = \omega$$

$\rightarrow k_{\parallel,1} - k_{\parallel,2} = k_{\parallel}$ & $k_{\parallel,1} + k_{\parallel,2} = k_{\parallel}$

- $k_{\parallel}$ cannot increase: energy flows in the perp. direction

\[ \begin{align*}
\begin{array}{cc}
\text{isotropic} & \text{driving} \\
\end{array}
\end{align*}\]
Strong MHD Turbulence

Higdon 1984; Goldreich & Sridhar 1995

- non-linear interactions $\sim (\mathbf{v} \cdot \nabla) \mathbf{v}$

- $\omega_{nl} \sim k_\perp \delta v_\perp \uparrow$ during weak turb.; $\omega_{lin} = |k|| v_A$ unchanged

- weak turbulence becomes strong: $\omega_{nl} \sim \omega_{lin}$

- “critical balance”: assume turbulence maintains $\omega_{nl} \sim \omega_{lin}$

Goldreich & Sridhar 1995

$\rightarrow E(k_\perp) \propto k_\perp^{-5/3} \rightarrow \delta v_\perp \propto k_\perp^{-1/3}$

Anisotropic Kolmogorov

critical balance $\rightarrow k_\parallel \propto k_\perp^{2/3}$

Scale-Dependent Anisotropy
\( \omega \gg \omega_{nl} \) weak turbulence

MHD Scales

\( \omega \sim \Omega_p \) ion cyclotron frequency

\( \omega \ll \Omega_p \) kinetic scales

\( \omega \ll \Omega_p \) ion Larmor radius

Critical balance: \( k_i \propto k_i^{2/3} (\omega - \omega_{nl}) \)
MHD Simulations Support the Goldreich-Sridhar (GS) Model

Cho & Vishniac 2000

Compressible Sims show that Alfven & Slow Modes Follow the GS Cascade
Some Fast Mode Energy Cascades to High Freq

Cho & Lazarian 2003; see also Chandran 2005
Solar Wind Fluctuations

Magnetic field power spectrum consistent w/ Kolmogorov (above the ion Larmor radius)

\[ <\text{slope}> = 1.6 \pm 0.1 \]

Smith et al. 2006

~ 90% of the Energy in \( \perp \) fluctuations

~ 10% in \( \parallel \) fluctuations

Slow wind: more \( \perp \) fluctuations

Fast wind: more \( \parallel \) fluctuations

Dasso et al. 2005
Towards the Dissipation Range: The Transition to a Kinetic Alfven Wave Cascade at $\sim \rho_i$

At $k_\perp \rho_i \simeq 1$, $\frac{\omega}{\Omega_i} \simeq \left(\frac{\rho_i}{L}\right)^{1/3} \beta_i^{-1/2}$ \quad L \equiv \text{outer scale of turbulence}

- **Solar Wind at 1 AU:** $\omega/\Omega_i \simeq 0.04$ at $k_\perp \rho_i \simeq 1$ ($L \simeq 10^{11}$ cm)
- **Corona at $\sim 2 R_\odot$:** $\omega/\Omega_i \simeq 0.03$ at $k_\perp \rho_i \simeq 1$ ($L \simeq 10^9$ cm)
  (fluctuations already anisotropic at the outer scale)

- $k_\perp \rho_i \gtrsim 1$ \& $\omega \lesssim \Omega_i$, Alfven waves $\rightarrow$ Kinetic Alfven Waves (KAWs)

  strong Alfven wave turbulence $\rightarrow$ strong KAW turbulence
Strong KAW Turbulence (sans damping)

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

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

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

Nonlinear (Gyro)Kinetic 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

“gyrokinetics”
In Situ Measurements in the Solar Wind

(Bale et al. 2005)

In Situ Measurements of E & B-fields with Cluster are consistent with a transition to KAWs at small scales but not with the onset of ion cyclotron damping.
Collisionless Damping of the Anisotropic Cascade

- so long as $\omega \lesssim \Omega_i$
- no cyclotron resonance
- magnetic moment $\mu \propto T_\perp/B$ is conserved
- $\to$ heating can only increase $T_\parallel$
- cyclotron damping is strongly suppressed at $k_\perp \rho_i \gtrsim 1$

$\to$ for cycl. damping to be impt, $\omega \to \Omega_i$ at $k_\perp \rho_i \lesssim 1$
Collisionless Damping of the Anisotropic Cascade
Quataert 1998; Leamon et al. 1998; Quataert & Gruzinov 1999; Cranmer & van Ballegooijen 2003; Gary & Nishimura 2004

- parallel heating via the Landau resonance: \( \omega = k_{||} v_{||} \)
- both Landau damping (\( \delta E_{||} \)) & transit-time damping (\( \delta B_{||} \))
  \( \beta \lesssim 1 \) \( \beta \gtrsim 1 \)

- **primarily e\(^-\) heating for \( \beta \lesssim 10 \)**
- dominant source of e\(^-\) heating
  in solar wind (?); consistent with
  \( T_e \gtrsim T_p \) in slow wind
The Puzzle ...

• How to get $T_{\text{ion}} \gtrsim T_p \gtrsim T_e$ & $T_{\perp,i} \gtrsim T_{\parallel,i}$? (Fast Wind)

• Outer scale $< < \text{Assumed Values (unlikely ...?)}; \text{Coupling of KAWs to Ion Bernstein, fast waves (unlikely)}$

\[ \text{at } k_{\perp} \rho_i \sim 1, \quad \frac{\omega}{\Omega_i} \sim \left( \frac{\rho_i}{L} \right)^{1/3} \beta_i^{-1/2} \quad L \equiv \text{outer scale of turbulence} \]

• Fast Waves Cascade to High Frequencies for $\beta \ll 1$ (Chandran ‘05)

• but Alfvenic fluctuations

dominate at $\sim \text{AU}$ ...

• Imbalanced Turbulence?

anisotropy is the same

cascade slows down

$\rightarrow \text{less}$ likely to reach $\sim \Omega_i$
The Puzzle ...

- How to get $T_{\text{ion}} \gtrsim T_p \gtrsim T_e$ & $T_{\perp,i} \gtrsim T_{\parallel,i}$? (Fast Wind)

- Imbalanced Turbulence: cascade slows down

- other non-linearities impt?

- e.g., Alfven waves steepen on a timescale $\sim \omega_{\text{lin}}^{-1} (B/\delta B)^2$

- Secondary Instabilities

- electron-ion: $T_e \rightarrow T_i$ (e.g., e- beams)
  Cranmer & van Ballegooijen 2003; Gary & Nishimura 2004

- velocity space: $T_{\perp} \leftrightarrow T_{\parallel}$
Velocity-Space Instabilities

**proton || anisotropy limited by firehose**

Kasper et al. 2002

Electron Anisotropy

whistler

Stuart Bale

proton || anisotropy limited by firehose

Kasper et al. 2002
Summary

- Alfvenic Turbulence is the Most Promising Source of Heating in the Extended Corona and Solar Wind

- Strong MHD Turbulence (Alfvenic)
  - ✓ Anisotropic Kolmogorov Turbulence: critical balance $\rightarrow k_{\parallel} \propto k_{\perp}^{2/3}$
  - ✓ $k_{\perp} \rho_i \sim 1$: Alfven Wave Cascade $\rightarrow$ Kinetic Alfven Wave Cascade

  - **NOT** cyclotron damping: $\omega \sim 0.03-0.2 \Omega_i$ even at $k_{\perp} \rho_i \sim 1$

  - Confirmed by Cluster Electric Field Measurements

    - KAW Cascade $\rightarrow$ Electron $\parallel$ Heating at $k_{\perp} \rho_i \sim 0.3-10$ ($\beta \sim 10^{-3}-1$)

- Puzzle: $T_{\text{ion}} \gtrsim T_p \gtrsim T_e$ & $T_{\perp,i} \gtrsim T_{\parallel,i}$ (Fast Wind)

- Smaller Outer Scale? Fast Waves? Secondary Instabilities? Addtl non-linearities? Sweep + Cascade in $\omega$? ...