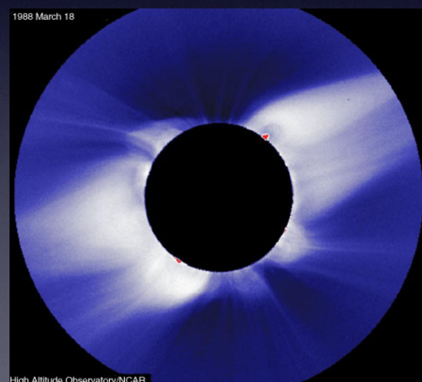
The Heating & Acceleration of the Solar Wind

Eliot Quataert (UC Berkeley)

work led by Ben Chandran (UNH)

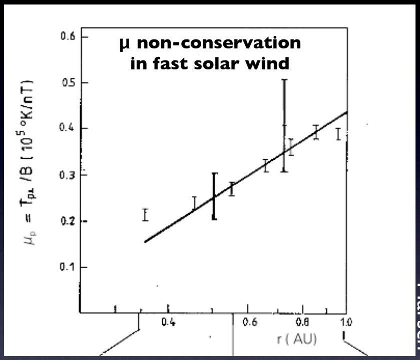


Overview

- 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

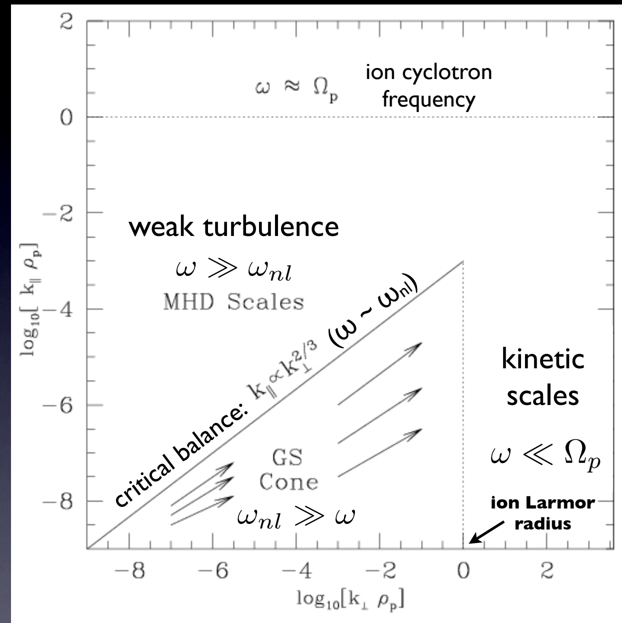
- Heating → acceleration of solar wind
- *In situ*: Fast vs Slow Wind
- **Fast** $T_{ion} \gtrsim T_p \gtrsim T_e$ & $T_{\perp,i} \gtrsim T_{||,i}$
- **Slow** $T_e \gtrsim T_p$



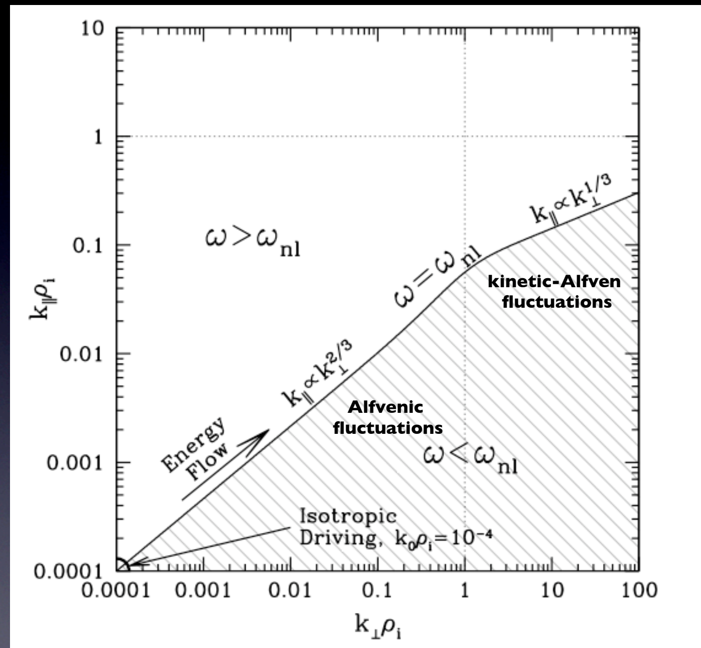
Marsch

- ~1-4 $R_\odot$: UVCS/SOHO constraints
- $T_{\perp,i} >> T_{||,i}$ (e.g., O^{5+}, p)
- $T_i >> T_p \gtrsim T_e$; 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



$\omega \approx \Omega_p$ ion cyclotron frequency
weak turbulence
$\omega \gg \omega_{nl}$
MHD Scales
critical balance: $k_\parallel \propto k_\perp^{2/3}$ ($\omega \sim \omega_{nl}$)
GS Cone
$\omega_{nl} \gg \omega$
kinetic scales
$\omega \ll \Omega_p$
ion Larmor radius
$\log_{10}[k_\parallel \rho_p]$
$\log_{10}[k_\perp \rho_p]$

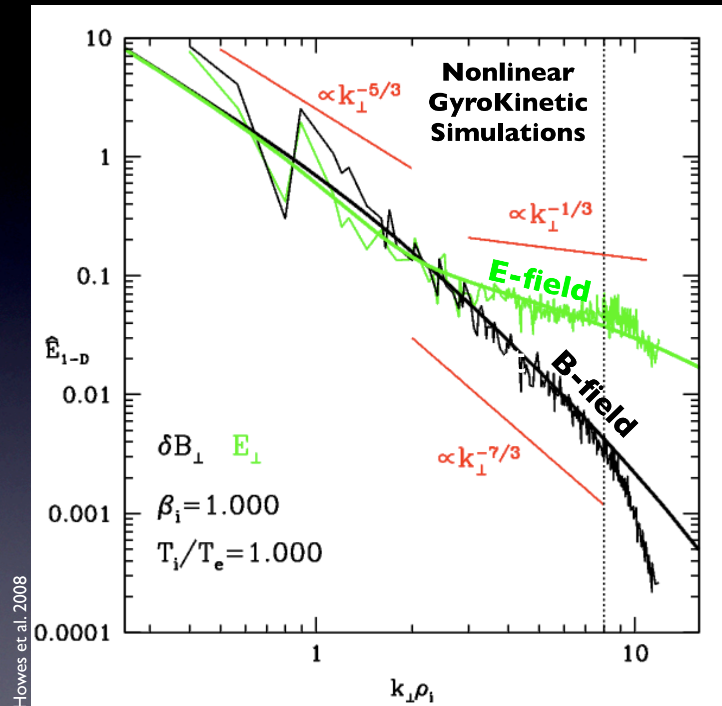


Strong KAW Turbulence
(sans damping)

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

$$k_\parallel \propto k_\perp^{1/3}$$

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

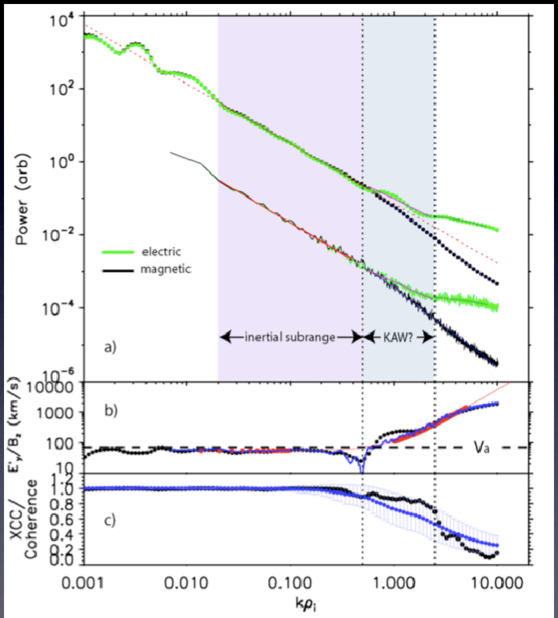


anisotropic
low frequency
turbulence
both above & below ρ_i can be
quantitatively
modeled using a
low freq. expansion
of the Vlasov eqn

Howes et al. 2006; Schekochihin et al. 2007

In Situ Measurements in the Solar Wind

(Bale et al. 2005)



In Situ Measurements of E & B-fields consistent with a transition to KAWs but *not* with the onset of ion cyclotron damping

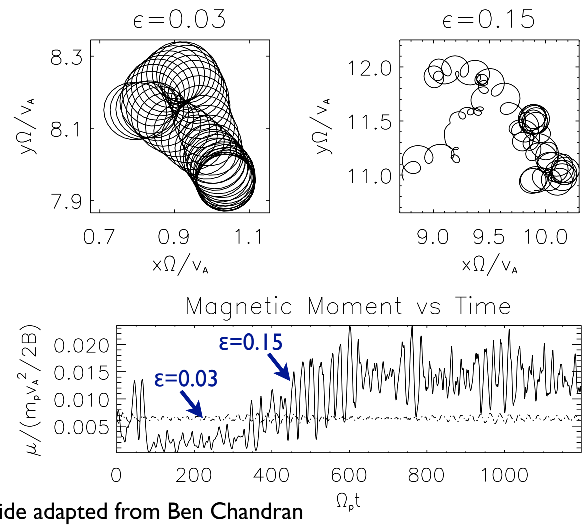
Heating by the Anisotropic Cascade

Quataert 1998; Leamon et al. 1998; Quataert & Gruzinov 1999; Cranmer & van Ballegooijen 2003; Gary & Nishimura 2004

- Linear theory; if $\omega \lesssim \Omega_i$
  - no cyclotron resonance
  - magnetic moment $\mu \propto T_\perp/B$ is conserved
  - $\rightarrow$ heating can only increase $T_{||}$
    - primarily e- htg for $\beta \lesssim$ few and p htg for $\beta \gtrsim$ few
- Strong Turbulence:
  - role of current sheets
  - finite amplitude fluctuations violate μ conservation

Stochastic Ion Heating by Low-Frequency Turbulence

- E-field fluctuations at ~ρ 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)
- ***μ-conservation requires <u>both</u> $\omega \ll \Omega_p$ <u>and</u> $\delta v_\rho \ll v_\perp$***



slide adapted from Ben Chandran

Based on Test-Particle Calculations

$$\gamma_s = 0.18\,\epsilon\,\Omega_p \exp\left(-\frac{c_2}{\epsilon}\right)$$

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

(Chandran, Li, Rogers, Quataert, & Germaschewski, ApJ, 720, 503, 2010)

Note: this htg not directly captured by gyrokinetics; requires test particles, hybrid .... though GK can likely still model the fluctuations

Stochastic heating is inherently self-limiting

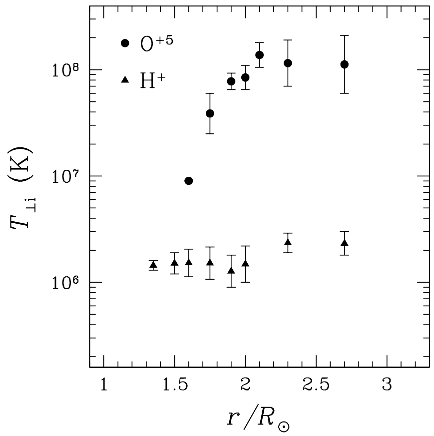
$$Q_\perp \sim \frac{(\delta v_\rho)^3}{\rho} \exp[-c_2\,\epsilon]$$

$T_\perp \uparrow \Rightarrow \varepsilon = \delta v_\rho / v_\perp \downarrow \Rightarrow Q_\perp \downarrow$

saturates when $t_{heat} \sim t_{expansion}$

consistent w/ minor ion htg

(e.g., O^{+5} in corona)

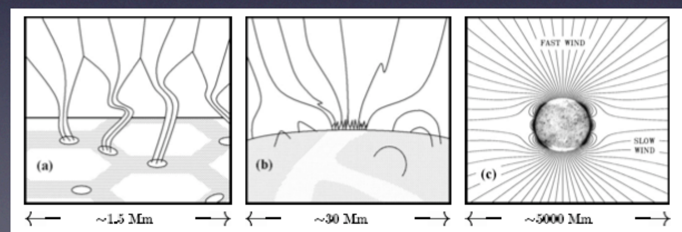


(Esser et al 1999)

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
  - $T_\perp$ & $T_{||}$ evol for protons w/ fluxes of both; e- isotropic
    - || p & e- htg from linear theory KAW damping; $\perp$ stochastic p htg
    - e- heat flux; p $\perp$ and || heat fluxes evolved w/ $\langle v^4 f \rangle = 0$; Coulomb collisions
- Low Freq Alfven Waves Generated by Photospheric Convection
  e.g., Matthaeus et al. 1999; Cranmer & van Ballegooijen 2005



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
  - $T_\perp$ & $T_{||}$ evol for protons w/ fluxes of both; e- isotropic
    - || p & e- htg from linear theory KAW damping; $\perp$ stochastic p htg
    - e- heat flux; p $\perp$ and || heat fluxes evolved w/ $\langle v^4 f \rangle = 0$; Coulomb collisions
- Low Freq Alfven Waves Generated by Photospheric Convection
  e.g., Matthaeus et al. 1999; Cranmer & van Ballegooijen 2005
- AW turbulence due to non-WKB reflection of outgoing waves
  - wave kinetic eqn for wave energy density

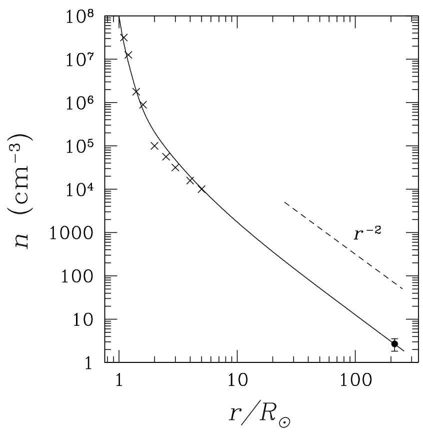
rms amplitude of
ingoing/reflected AWs
(solved for)

$$\mathrm{Htg\,Rate} \sim E_{waves}\,\frac{z_-}{L_\perp}$$

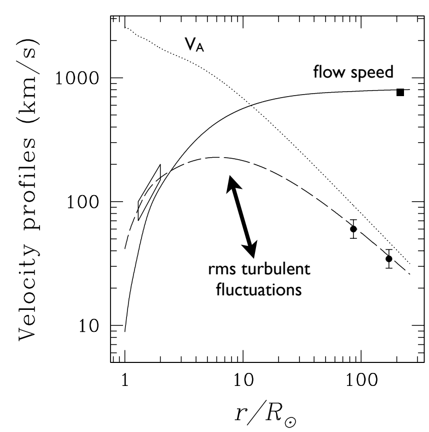
energy mostly in
outgoing AWs

input correlation length
for waves ~$10^{8\text{-}9}$ cm

Density and Velocity Profiles



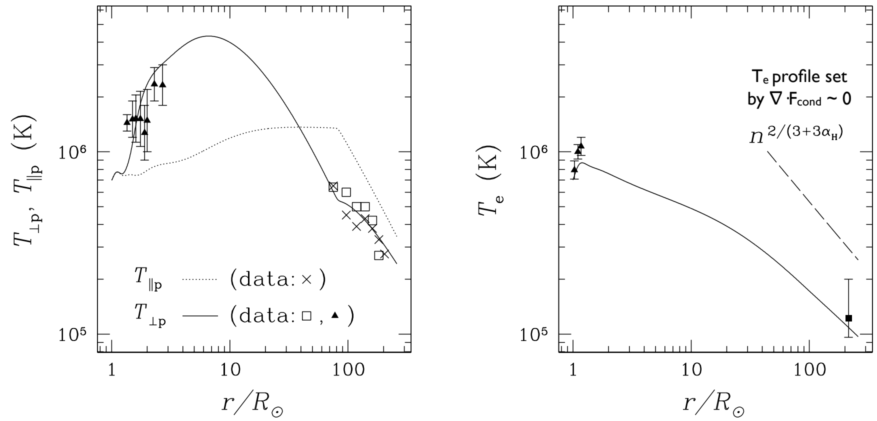
Data: white light scattering in corona & in situ measurement



Data: coronal spectroscopy & in situ measurements

slide adapted from Ben Chandran

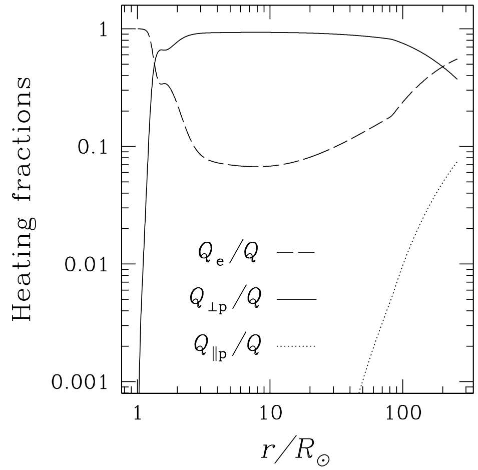
Temperature Profiles



Data: spectroscopic (corona) and in situ

slide adapted from Ben Chandran

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

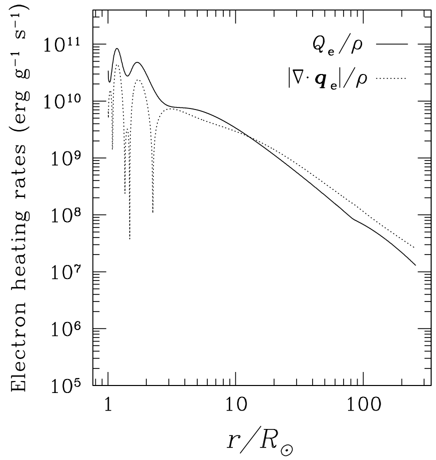


$\perp$ stochastic p htg dominates for most radii

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

slide adapted from Ben Chandran

Electron Heating and Electron Heat Flux



T_e profile set by $t_{cond} \sim t_{heat}$

also sometimes true for $T_{||}$ proton

slide adapted from Ben Chandran

Summary

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