Kinetic Scale Turbulence Near the Sun

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The Solar Wind at 1 AU

- Broad spectrum of magnetic fluctuations
- 1/f range: waves, structures, or...
- Inertial range: Alfvenic turbulence energy cascade to small scales
- Transition in properties at kinetic scales
- Kinetic range: kinetic Alfven turbulence
- Energy dissipated: heating solar wind and corona?
Radial Variation

- Spectrum changes: amplitude and break scales
- Due to changes in various turbulence/plasma parameters

Bruno & Trenchi 2014 ApJL

Bruno & Carbone 2013 LRSP
Plasma Parameters

- $\beta$ decreases towards the Sun (in particular $\beta_e$)
- Also in numerical models, e.g., $\beta_i \sim 0.1$, $\beta_e \sim 0.02$ at $10 \text{ R}_S$ (Chandran et al. 2011)
Kinetic Turbulence Ranges

- Kinetic scales related by beta: $\beta_s = (\rho_s/d_s)^2$
- At 1 AU: $\beta_i \sim \beta_e \sim 1 \rightarrow$ scales for each species same
- Close to Sun, $\beta_e < \beta_i < 1$, new ranges

**1 AU**

- Ion inertial scale
- Electron inertial scale
- Ion gyroscale
- Electron gyroscale

**Near Sun**

- Ion inertial scale
- Electron inertial scale
- Ion gyroscale
- Electron gyroscale

\[ k^{-1.6} \quad k^{-2.8} \]

Range 1

Range 2
Range 2: Inertial Kinetic Alfvén Waves

• Standard kinetic Alfvén wave is derived assuming $\omega \ll k_{||}v_{th,e}$

$$\omega^2 = \frac{k_{||}^2 v_A^2 k_{\perp}^2 \rho_i^2}{\beta_i + 2/(1 + T_e/T_i)}$$

• But this breaks down halfway between ion and electron gyroscales at

$$k_{\perp}^2 \rho_e^2 \sim \beta_i (2 + \beta_i) (T_e/T_i)^2$$

• For frequencies $k_{||}v_{th,e} \ll \omega \ll k_{\perp}v_{th,i}$ there is a new mode

$$\omega^2 = \frac{k_{||}^2 v_A^2 k_{\perp}^2 \rho_i^2}{\beta_i(1 + k_{\perp}^2 d_e^2)(1 + 2/\beta_i + k_{\perp}^2 d_e^2)}.$$  \textit{inertial kinetic Alfvén wave}

[note this is different to standard inertial Alfvén wave valid for $\beta_e \ll m_e/m_i$]

• We expect a new range of iKAW turbulence to develop in Range 2
iKAW Turbulence Near Earth

- In the solar wind at 1 AU: $\beta \sim 1$, $T_i/T_e \sim 1$
- In the magnetosheath: shock “heats” ions more strongly, $\beta \gtrsim 1$, $T_i/T_e \gg 1$
- Magnetosheath conditions (in some ways) similar to near-Sun solar wind
- Use to investigate the turbulence here
Magnetosheath Data Interval

- Search MMS data for period
  - burst mode
  - high SNR
  - no instrument artefacts (spin/wake/etc.)
  - steady conditions
  - no other phenomena (mirrors/whistlers/etc.)

- Find 73 s period
  - quasi-perp sheath
  - near dusk m/pause
  - s/c sep ~10 km

  $\beta = 0.79, \frac{T_i}{T_e} = 9.1$
Overview of Interval

- Time series shows steady conditions, and $T_i \gg T_e$
- Spectra: both $B$ and $E$ spectra change at transition through plasma scales
- Range 2 not large, but can begin to probe the physics

![Graph showing time series and PSD](image)
Range 1: KAW Turbulence

- The two possible plasma modes
  - kinetic Alfvén wave
    \[ \omega^2 = \frac{k^2 v_A^2 k^2 \rho_i^2}{\beta_i + 2/(1 + T_e/T_i)} \]
  - whistler wave
    \[ \omega^2 = k^2 v_A^2 k^2 d_i^2 \]
- Distinguish by \( \delta n - \delta B \) correlation
  - KAW: negative
  - whistler: positive
- Strong anti-correlation
  \( \rightarrow \) KAW (as in solar wind)
- Other tests give similar result

Range 2: iKAW Turbulence

- Observational feature is increase in magnetic compressibility
  \[
  \frac{\delta B_{||}^2}{\delta B_{\perp}^2} = \frac{1 + k_{\perp}^2 d_{e}^2}{1 + 2/\beta_i + k_{\perp}^2 d_{e}^2}
  \]

- In general, increases as electron inertial scale is crossed

- Matches observations well

- Consistent with transition to iKAW turbulence

Spectrum of iKAW Turbulence

- To understand nonlinear properties, derive the dynamical equations

\[
\frac{\partial}{\partial t} \left( 1 - \nabla_\perp^2 \right) \psi + \left( (\hat{z} \times \nabla n) \cdot \nabla \right) \nabla_\perp^2 \psi = -\nabla_\parallel n \nabla_\perp n
\]

\[
\frac{\partial}{\partial t} \left( 1 + \frac{2}{\beta_i} - \nabla_\perp^2 \right) n + \left( (\hat{z} \times \nabla n) \cdot \nabla \right) \nabla_\perp^2 n = \nabla_\parallel \nabla_\perp n
\]

- note dimensionless variables [ \( \delta B_\perp = \hat{z} \times \nabla \psi, \ \nabla_\parallel = \partial/\partial z + (\hat{z} \times \nabla \psi) \cdot \nabla \) ]
- without nonlinear terms: iKAW

- Equations conserve the energy \( E = \int \left[ \delta n \left( 1 + \frac{2}{\beta_i} - \nabla_\perp^2 \right) \delta n - \nabla_\perp^2 \psi \left( 1 - \nabla_\perp^2 \psi \right) \right] d^3 x \)

- For \( k_\perp \gg \sqrt{1 + 2/\beta_i} \) nonlinear time estimated as \( \tau \sim \lambda^2/\delta n_\lambda \)

- Constant energy flux through scales \( \varepsilon \sim (\delta n^2_\lambda/\lambda^2)/\tau \sim \delta n^3_\lambda/\lambda^4 \)

- Fluctuation scaling \( \delta n_\lambda \sim \psi_\lambda/\lambda \sim \varepsilon^{1/3} \lambda^{4/3} \)

- Fourier spectrum \( E_{n,B}(k_\perp) \propto k_\perp^{-11/3} \)
Anisotropy of iKAW Turbulence

- Critical balance: equate linear and nonlinear terms
  \[ \psi_{\lambda}/(l_{||}\lambda^2) \sim \delta n_{\lambda}^2/\lambda^4 \]
- Anisotropy \( k_{||} \propto k_{\perp}^{5/3} \), should get less anisotropic towards smaller scales
- Transition to iWhistler turbulence?...

standard AW/KAW turbulence  
iKAW turbulence
Predictions for PSP / SO

- $\beta$ decreases as we go in
- New range opens up at electron kinetic scales
- Transition to iKAW cascade here
  - increased compressibility
  - steeper -11/3 spectrum
  - less anisotropic smaller scales
  - possible transition to iWhistlers
- Future studies
  - more magnetosheath studies
  - numerical simulations
  - investigate dissipation / heating
  - observe with PSP / SO!