Anisotropy of Solar Wind Turbulence



CHK Chen, O Alexandrova, SD Bale, S Boldyrev, JW Bonnell, TS Horbury, GG Howes, KG Klein, A Mallet, JJ Mitchell, FS Mozer, JC Perez, CS Salem, AA Schekochihin, RT Wicks, Q Xia, TA Yousef



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Outline

- Why is anisotropy important?
- How can we measure anisotropy in the solar wind?
- Inertial range anisotropy: critical balance (?!)
- 3D anisotropy: Alfvénic and compressive fluctuations
- Anisotropy at kinetic scales
- Other recent results...



Why Anisotropy?

- Hydrodynamic turbulence:
 - usually no special directions
 - flow eliminated by Galilean transform
 - isotropy assumed
- Plasma turbulence:
 - B cannot be transformed away
 - large fluctuations can provide mean field for small ones
 - special direction \rightarrow anisotropy
- Anisotropy is often central prediction / assumption of theories → important to measure





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Types of Anisotropy

- Variance anisotropy: $\delta B_{\perp} \neq \delta B_{\parallel}$ (aka power anisotropy)
- Power anisotropy: $P(k_{\perp}) \neq P(k_{\parallel})$
- Wavevector anisotropy: $k_{\perp} \neq k_{\parallel}$
- Spectral index anisotropy: $\alpha_{\perp} \neq \alpha_{\parallel}$
- Imbalance: E⁺ ≠ E⁻

[Horbury, Wicks & Chen 2012 SpaceSciRev]



Anisotropy in Weak Turbulence

- Weak Alfvénic turbulence (Iroshnikov 1963; Kraichnan 1965)
 - Isotropic Alfvénic packets along field
 - Assume weak interactions: $\tau_A \ll \tau_{nl}$
 - $E(k) \sim k^{-3/2}$
- But 3 wave interactions produce anisotropy (Shebalin et al. 1983 JPP)

$$\mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}_3$$

$$\omega_1 + \omega_2 = \omega_3,$$

$$\omega^2 = v_A^2 k_{\parallel}^2,$$



$$\begin{array}{rcl} k_{\parallel 1}+k_{\parallel 2} &=& k_{\parallel 3},\\ \\ k_{\parallel 1}-k_{\parallel 2} &=& \pm k_{\parallel 3}. \end{array}$$

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Anisotropy in Strong Turbulence

- Strong Alfvénic turbulence (Goldreich & Sridhar 1995 ApJ)
 - Reach critical balance: $\tau_{\text{A}}\approx\tau_{\text{nl}}$
 - $k_{\parallel} \sim k_{\perp}^{2/3}$ eddies get elongated
 - $E(k_{\perp}) \sim k_{\perp}^{-5/3} \& E(k_{\parallel}) \sim k_{\parallel}^{-2}$
- Scale dependent alignment (Boldyrev 2006 PRL)
 - $\delta v \& \delta b$ align to an angle $\phi \sim \lambda^{1/4}$
 - $\mathsf{E}(\mathsf{k}_{\lambda}) \sim \mathsf{k}_{\lambda}^{-3/2} \qquad \mathsf{E}(\mathsf{k}_{\xi}) \sim \mathsf{k}_{\xi}^{-5/3} \qquad \mathsf{E}(\mathsf{k}_{\parallel}) \sim \mathsf{k}_{\parallel}^{-2}$
 - Eddies are ribbon-like rather than filament-like,
 δb direction special







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Measuring Solar Wind Spectra

- Spacecraft makes measurements as plasma flows past
- Can usually assume changes happen slowly → spatial cut (Taylor)
- 1D cut gives you a 1D (reduced) spectrum
- Parameter dependence:
 - we have great measurements
 - but can't control the conditions
 - so we wait





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Spacecraft Data





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Correlation Function Anisotropy

- Can measure the correlation between 2 spacecraft for different B angles
- Find better correlation along the field
- Anisotropic structures
- Can do with single spacecraft: correlation as a function of scale at different angles
- "Maltese cross"



Crooker et al. 1982 JGR



Space Physics Research Group University of California, Berkeley

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Power Anisotropy

- An alternative way is to measure power at a given scale for different angles
- Power increases with angle to B
- Consistent with $k_{\perp} > k_{\parallel}$
- "Solved" cosmic ray scattering problem





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Local Mean Field

- Previous measurements, local field fluctuations not tracked
- But we expect Alfvén waves / turbulent eddies to be sensitive to the mean field at (or just above) their scale
- Seen in minimum variance directions
- Also proposed to be important in simulations (Cho & Vishniac 2000, Maron & Goldreich 2001, Milano et al. 2001)







Cho & Vishniac 2000 ApJ



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Wavelets and Structure Functions

- Need a technique to measure energy in fluctuations and track local mean field
- Wavelets:
 - power spectrum as a function of scale and time
 - mean field is wavelet envelope
- Structure function:
 - 2 point differences
 - mean field is average of points







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Spectral Index Anisotropy

- Power anisotropy as before (but smoother and more anisotropic)
- Spectral index anisotropic: matches critical balance prediction
- Best evidence so far for CB
- Not universally accepted (higher order, 2 component model, discontinuities)



Horbury et al. 2008 PRL



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Multi-Spacecraft Measurement

- Cluster: group of 4 s/c, multiple angles simultaneously
- Shorter intervals, better for the more inhomogeneous slow wind
- Slow wind → same results
- Different technique \rightarrow same results
- Different local field \rightarrow same results







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Local vs Global Mean Field

- Applied same technique to simulations (by Mallet, Yousef, Schekochihin)
- Scaling is anisotropic to the local mean field only (Cho & Vishniac 2000, Maron & Goldreich 2001)
- Using global or local mean field makes a difference, even when dB/ B small
- Explains the previous contradictory results (Sari & Valley 1976, Tessein et al. 2009, Grappin & Muller 2010)





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Energy Injection Scales



Wicks et al. 2010 MNRAS



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3D Anisotropy

- Same technique but track local dB direction as well as B₀
- Pick constant power and plot variation of scale with angle
- Get a surface of constant power for different power levels
- Statistical "eddy shape"
- Movie shows how shape changes as turbulence cascades to smaller scales





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3D Anisotropy



- Large scales: elongated in δB direction, 1/f Alfvén waves from Sun
- Turbulent range: eddy elongates in B₀ direction due to critical balance
- Eddy is anisotropic in the perpendicular plane. Why? Not fully understood but related to dynamic alignment, solenoidality, intermittency...



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Compressive Fluctuations

- Schekochihin 2009:
 - Transform kinetic equation of KRMHD to Lagrangian frame of Alfvénic turbulence
 - d/dt $\rightarrow \partial/\partial t$ and b. $\nabla \rightarrow \partial/\partial s$ so equation becomes linear
 - no parallel cascade along field lines
 - small k_{\parallel} so small damping
- Lithwick & Goldreich 2001
 - Magnetic field not completely frozen due to dissipation
 - Passive scalar follows velocity so decorrelates as Alfvénic turbulence
 - Could be undamped if beta low enough

$$\frac{\partial \Psi}{\partial t} = v_A \hat{\mathbf{b}} \cdot \nabla \Phi, \qquad (155)$$

$$\frac{d}{dt}\nabla_{\perp}^{2}\Phi = v_{A}\mathbf{\hat{b}}\cdot\nabla\nabla_{\perp}^{2}\Psi,$$
(156)

$$\frac{dg}{dt} + v_{\parallel} \, \hat{\mathbf{b}} \cdot \nabla \left[g + \left(\frac{Z}{\tau} \frac{\delta n_e}{n_{0e}} + \frac{v_{\perp}^2}{v_{\text{th}i}^2} \frac{\delta B_{\parallel}}{B_0} \right) F_{0i} \right]$$

$$= \left\langle C_{ii} \left[g + \frac{v_{\perp}^2}{v_{\text{th}i}^2} \frac{\delta B_{\parallel}}{B_0} F_{0i} \right] \right\rangle_{\mathbf{R}_i}, \qquad (157)$$

$$\frac{\delta n_e}{n_{0e}} = -\left[\frac{Z}{\tau} + 2\left(1 + \frac{1}{\beta_i}\right)\right]^{-1} \frac{1}{n_{0i}} \int d^3 \mathbf{v} \left[\frac{v_\perp^2}{v_{\text{th}i}^2} - 2\left(1 + \frac{1}{\beta_i}\right)\right] g,\tag{158}$$

$$\frac{\delta B_{\parallel}}{B_0} = -\left[\frac{Z}{\tau} + 2\left(1 + \frac{1}{\beta_i}\right)\right]^{-1} \frac{1}{n_{0i}} \int d^3 \mathbf{v} \left(\frac{v_{\perp}^2}{v_{\text{th}i}^2} + \frac{Z}{\tau}\right) g,\tag{159}$$



Schekochihin et al. 2009 ApJS



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Compressive Fluctuations

- Use local field tracking technique to measure local structure of |B| eddies
- They are axisymmetric, more anisotropic than Alfvénic turbulence
- Since damping is $\gamma \sim k_{\parallel}$, this could be why they are not damped, why the sw is slightly compressive
- cf inner solar wind (Armstrong, Grall, Woo)
- Alternative explanations? Maybe the less anisotropic ones are just damped?







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Kinetic Scale Turbulence

- What happens at kinetic scales?
- B and n spectra steepen: spectral indices in the range -2.7 to -2.9
- Damping? Heating? Further Cascade? Current sheets? Instabilities?
- What are the relevant waves? KAW? Whistlers? Ion cyclotron? Bernstein?





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Dispersive Cascade Predictions

- Biskamp et al. 1996: scaling for strong EMHD turbulence is E ~ k_⊥^{-7/3}
- Cho & Lazarian 2004: critically balanced EMHD cascade gives $k_{\parallel} \sim k_{\perp}^{-1/3}$, E ~ k_{\parallel}^{-5}
- Boldyrev & Perez 2012: increased intermittency of strong KAW turbulence leads to E ~ k₁-^{8/3} and E ~ k₁-^{7/2}
- Several other possibilities to explain the steep spectra:
 - Ion entropy cascade (Schekochihin et al. 2009)
 - Electron Landau damping (Howes et al. 2011)
 - Wave-particle scattering (Rudakov et al. 2011)
 - Ion cyclotron damping (Smith et al. 2012)





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Small Scale Anisotropy

- Multi-spacecraft anisotropy measurement at $1/\rho_i < k < 1/\rho_e$
- Contours are elongated in parallel direction
 - Anisotropic eddies
 - $k_{\perp} > k_{\parallel}$
- Perp spectral index steepens at small angles
 - suggests critically balanced cascade
- Parallel spectral index shallow: reason unknown (instabilities? transitory?)
- So perp mode but which one?



Chen et al. 2010 PRL



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Ion Scale Flattening

- KAW become compressive as the ion scales are reached
- Density spectrum can be modeled as passive scalar + active KAW turbulence
- Leads to "bulge" in spectrum before ion scales
- Flattening is enhanced for
 - smaller passive component
 - lower β_i



Chandran et al. 2009 ApJ



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Ion Scale Flattening

- Compare flattening to cascade model (provided by Greg Howes)
- Lower β_i interval has bigger "bulge"
- Consistent with shape of cascade model
- Will be a feature to look for with Solar Orbiter / Probe where $\beta_i << 1$





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E Parallel Spectrum

- Parallel electric field spectrum hard to measure: 3 intervals in 10 years of data
- It steepens in the kinetic scale range: -2.1 to -2.8 (similar to simulations)
- E_{\parallel} is comparable to E_{\perp}
- Any explanations?
- Lots of E_{II} available for Landau damping



Mozer & Chen 2013 ApJL (in press) arXiv:1304.1189



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Evidence for Kinetic Alfvén Turbulence

- -2.8 spectrum of b (Alexandrova et al. 2009 PRL)
- -2.75 spectrum of n (Chen et al. 2012 PRL)
- Anisotropic $k_{\perp} > k_{\parallel}$ (Chen et al. 2010 PRL)
- $\delta \tilde{n} \approx \delta \bar{D}_{\perp}$ (Chen et al. in prep)
- Significant δE_{\parallel} spectrum (Mozer & Chen 2013 arXiv:1304.1189)
- Bigger ion scale density bulge at lower β (Chen et al. 2013 arXiv:1210.0127)



Summary

- Anisotropy is central to diagnosing and understanding plasma turbulence
- With a single spacecraft we can measure spatial anisotropy k_\perp > k_\parallel and scaling anisotropy
- Measurements generally support critical balance
- Eddies are 3D anisotropic, not fully understood
- Compressive fluctuations more anisotropic than Alfvénic, therefore not damped?
- Sub ion gyroscale turbulence kinetic Alfvén and possibly critically balanced



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