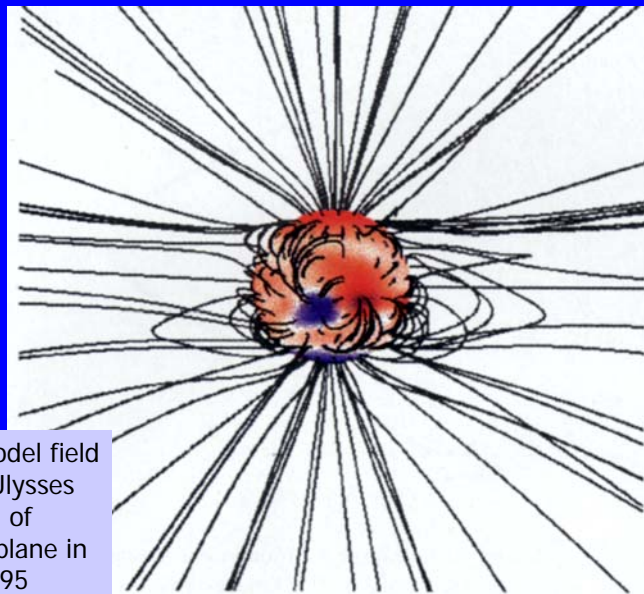


Structures, waves and turbulences in the solar wind

- Solar wind and heliospheric magnetic field
- The heliosphere, structure and dynamics
- Fluctuations: scales and parameters
- Magnetoacoustic and Alfvénic fluctuations
- Turbulence spectra and radial evolution
- Ideal MHD invariants and dissipation
- Cross-helicity, anisotropy, compressibility
- Scaling and intermittency

The Sun's open magnetic field lines



MHD model field during Ulysses crossing of ecliptic plane in early 1995

Mikic & Linker, 1999

Length scales in the solar wind

Macrostructure - fluid scales

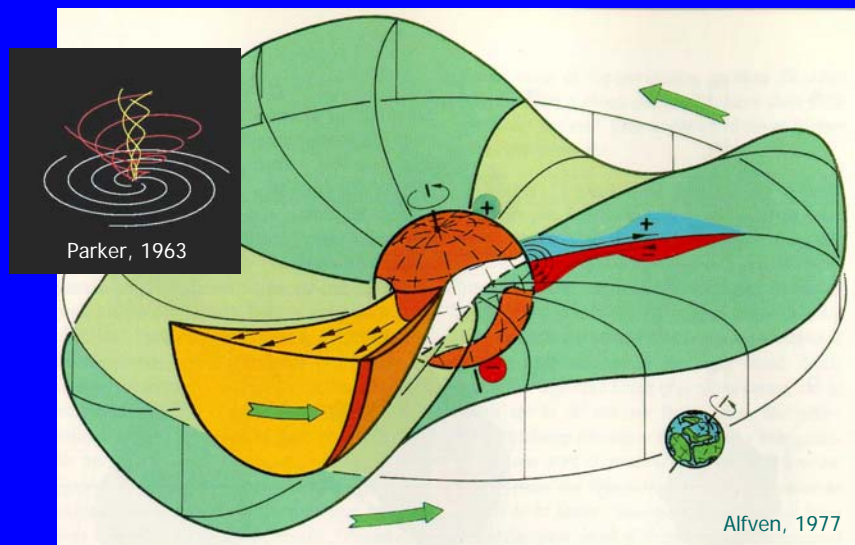
- Heliocentric distance: r 150 Gm (1AU)
- Solar radius: R_s 696000 km (215 R_s)
- Alfvén waves: λ 30 - 100 Mm

Microstructure - kinetic scales

- Coulomb free path: l ~ 0.1 - 10 AU
- Ion inertial length: V_A/Ω_p (c/ω_p) ~ 100 km
- Ion gyroradius: r_L ~ 50 km
- Debye length: λ_D ~ 10 m
- Helios spacecraft: d ~ 3 m

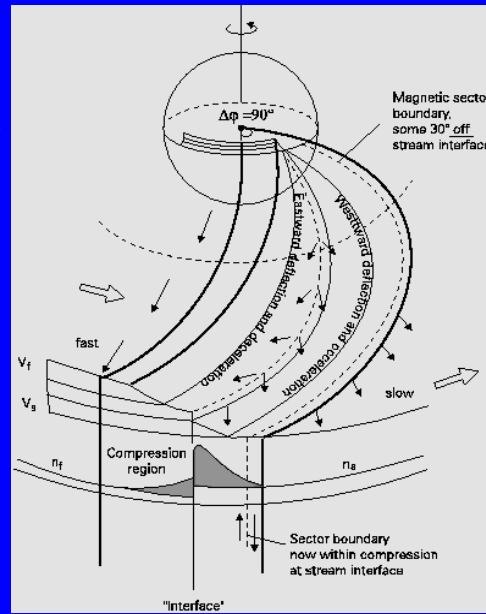
Microscales vary with solar distance!

Solar wind stream structure and heliospheric current sheet



Stream interaction region

Dynamic processes in inter-planetary space



- Wave amplitude steepening ($n \sim r^{-2}$)
- Compression and rarefaction
- Velocity shear
- Nonlinearity by advection ($\underline{V} \cdot \nabla \underline{V}$)
- Shock formation (co-rotating)

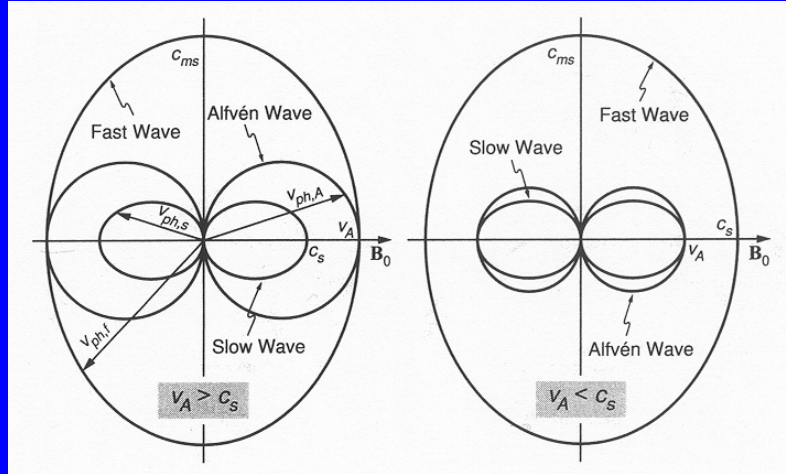
Schwenn, 1990

Spatial and temporal scales

Phenomenon	Frequency (s ⁻¹)	Period (day)	Speed (km/s)
Solar rotation:	$4.6 \cdot 10^{-7}$	25	2
Solar wind expansion:	$5 - 2 \cdot 10^{-6}$	2 - 6	800 - 250
Alfvén waves:	$3 \cdot 10^{-4}$	1/24	50 (1AU)
Ion-cyclotron waves:	1 - 0.1	1 (s)	(V_A) 50

Turbulent cascade: generation + transport
→ inertial range → kinetic range + dissipation

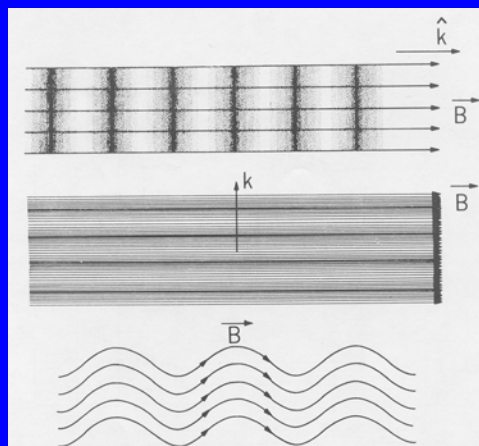
Phase velocities of MHD modes



$$\omega^4 - \omega^2 (kc_{ms})^2 + (kc_s)^2 (\mathbf{k} \cdot \mathbf{V}_A)^2 = 0$$

$$\omega = \mathbf{k} \cdot \mathbf{V}_A$$

Weak turbulence, superposition of magnetohydrodynamic waves



- Magnetosonic waves compressible
- parallel slow and fast
- perpendicular fast

$$c_{ms} = (c_s^2 + V_A^2)^{-1/2}$$

- Alfvén wave incompressible
- parallel and oblique

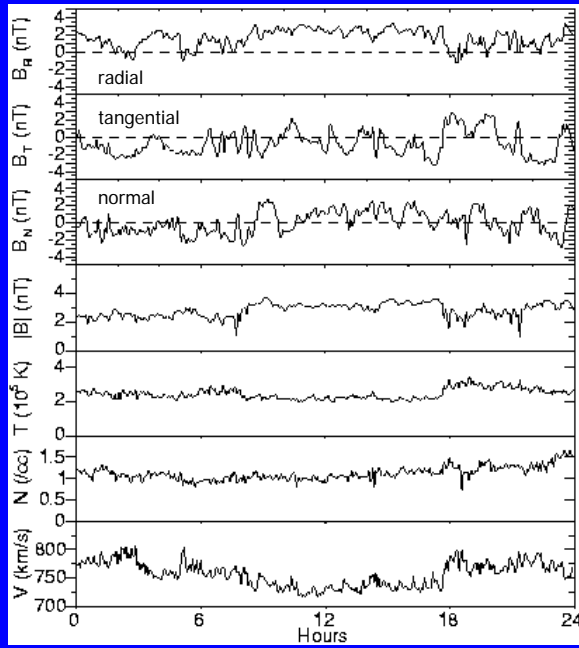
$$V_A = B / (4\pi\rho)^{1/2}$$

Broad band in \mathbf{k} and random phases

Fluctuations

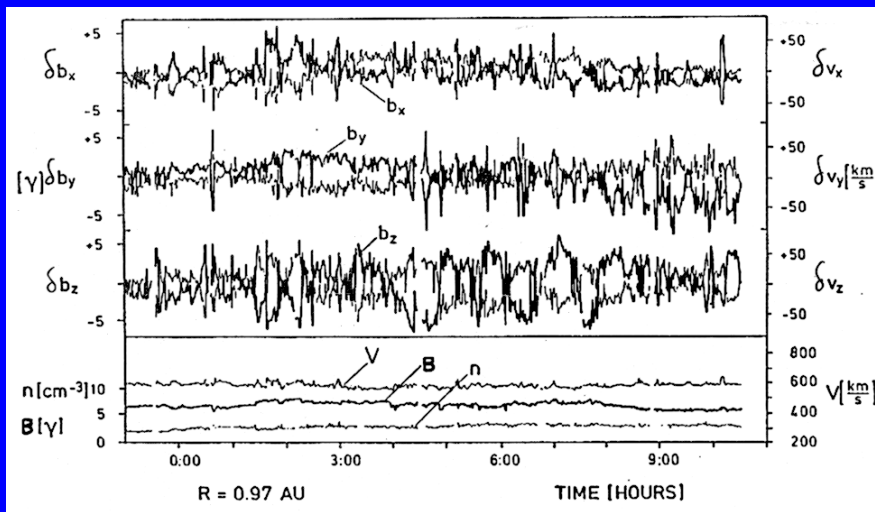
Typical day in April 1995 of Ulysses plasma and field observations in the polar (42° north) heliosphere at 1.4 AU

- Sharp changes in field direction
- Large Component variations
- Weak compressive fluctuations



Horbury & Tsurutani, 2001

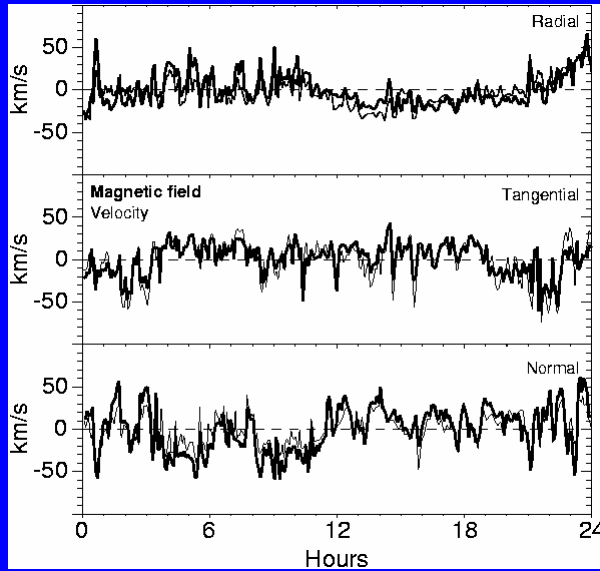
Alfvénic fluctuations (Helios)



Neubauer et al., 1977

$$\delta V = \pm \delta V_A$$

Alfvénic fluctuations (Ulysses)



Elsässer variables:

$$\mathbf{Z}^{\pm} = \mathbf{V} \pm \mathbf{V}_A$$

Turbulence energy:

$$e^{\pm} = 1/2 (\mathbf{Z}^{\pm})^2$$

Cross helicity:

$$\sigma_c = (e^+ - e^-)/(e^+ + e^-)$$

Horbury & Tsurutani, 2001

Alfvénic fluctuations

Ulysses observed many such waves (4-5 per hour) in fast wind over the poles:

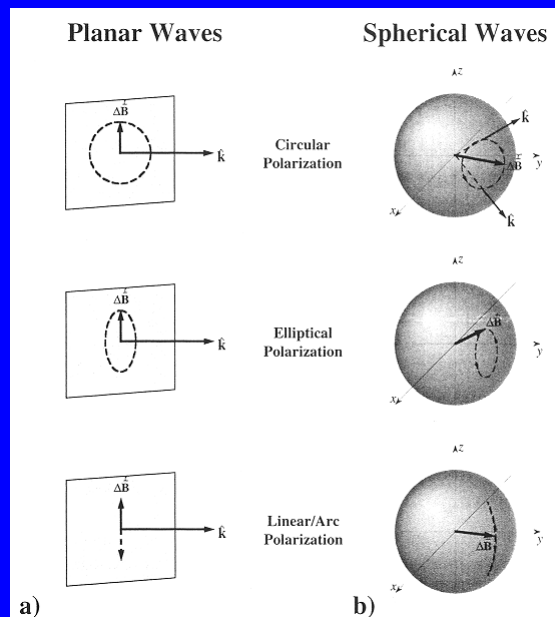
- Arc polarized waves
- Phase-steepened

Rotational discontinuity:

$$\Delta \mathbf{V} = \pm \Delta \mathbf{V}_A$$

Finite jumps in velocities over gyrokinetic scales

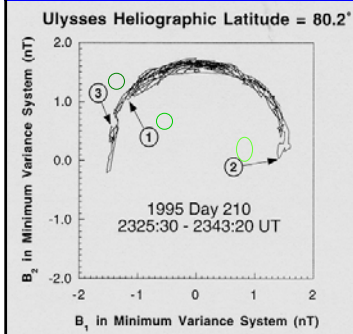
Tsurutani et al., 1997



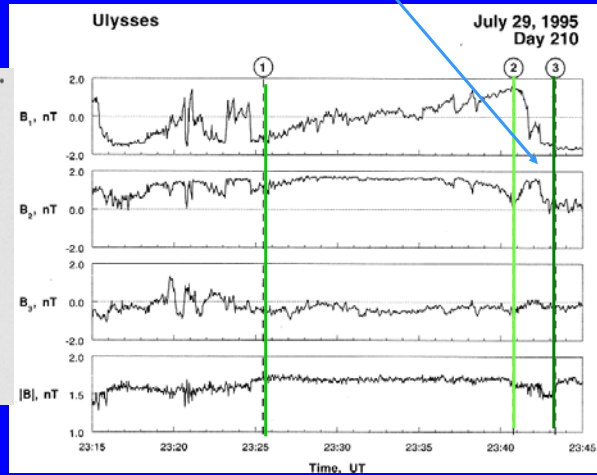
Arc-polarized Alfvén waves

Slowly rotating Alfvén wave lasts about 15 minutes

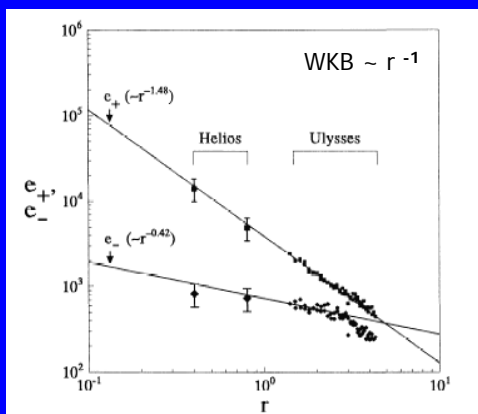
Rotational discontinuity RD lasts only 3 minutes



Tsurutani et al., 1997



Alfvén waves in polar solar wind

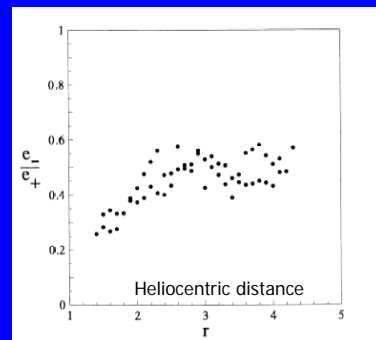


Radial variation of $e^\pm(r)$; wave amplitude at 1-h period is not sufficient to drive fast wind!

Elsässer variables: $Z^\pm = V \pm V_A$

Turbulence energy: $e^\pm = 1/2 (Z^\pm)^2$

Elsässer ratio: $r_e = e^-/e^+$



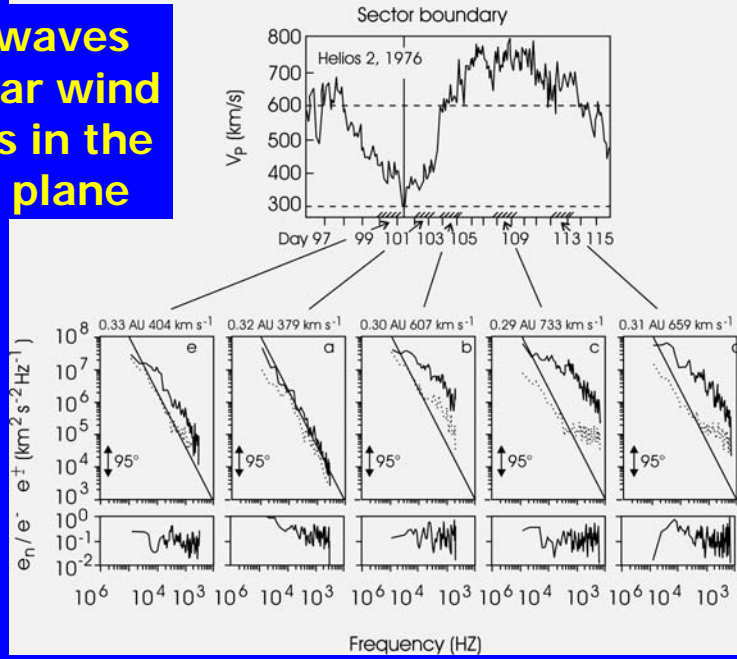
Average values over 0.1 AU wide intervals of hourly variances of Z^\pm

Bavassano et al., JGR, **105**, 15959, 2001

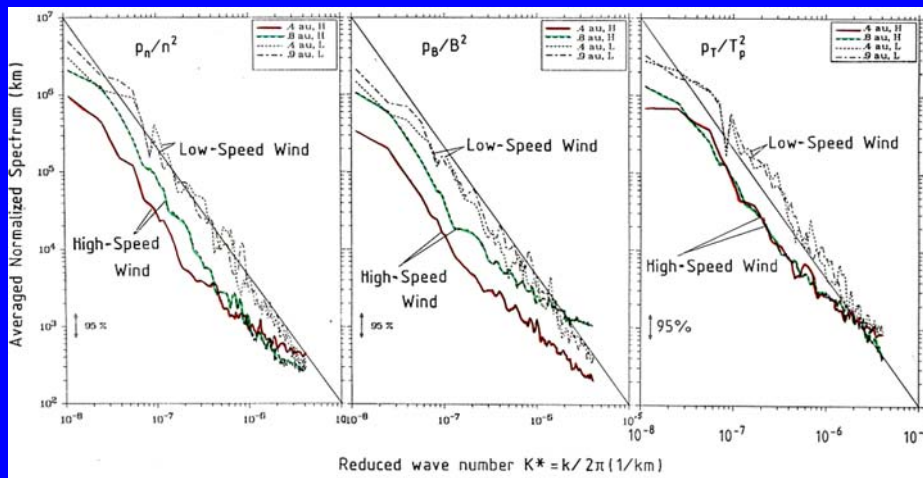
Alfvén waves and solar wind streams in the ecliptic plane

- High Alfvén wave flux in fast streams
- Developed isotropic turbulence in slow streams

Tu et al., GRL, 17, 283, 1990



Compressive fluctuations in the solar wind

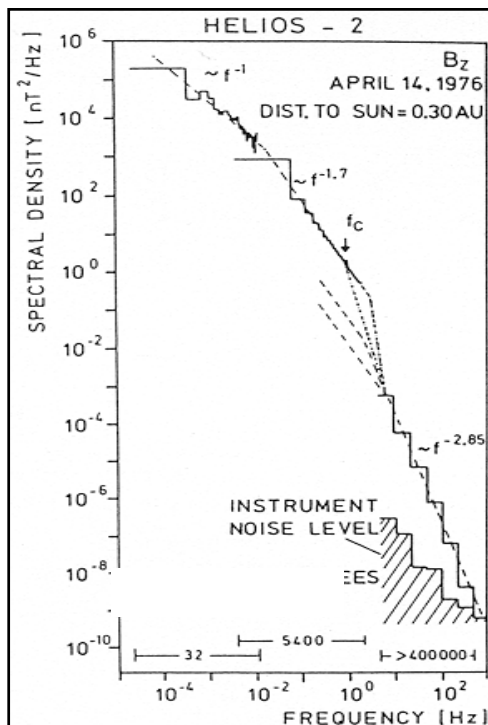


Marsch and Tu, JGR, 95, 8211, 1990

Kolmogorov-type turbulence

Solar wind turbulence

Parameter	Coronal Hole (open)	Current sheet (closed)
Alfvén waves:	yes	no
Density fluctuations:	weak (<3%)	intense (>10%)
Magnetic/kinetic turbulent energy:	$\cong 1$	> 1
Spectral slope:	flat (-1)	steep (-5/3)
Wind speed:	high	low
T_p (T_e):	high (low)	low (high)
Wave heating:	strong	weak



Magnetic field power spectrum

- Power laws with index of about -1, -5/3 and -3
- Abrupt decline at f_c indicates cyclotron absorption
- Steep spectrum at high frequencies above 2 Hz is mainly due to whistler waves

Denskat et al., JGR **54**, 60, 1983

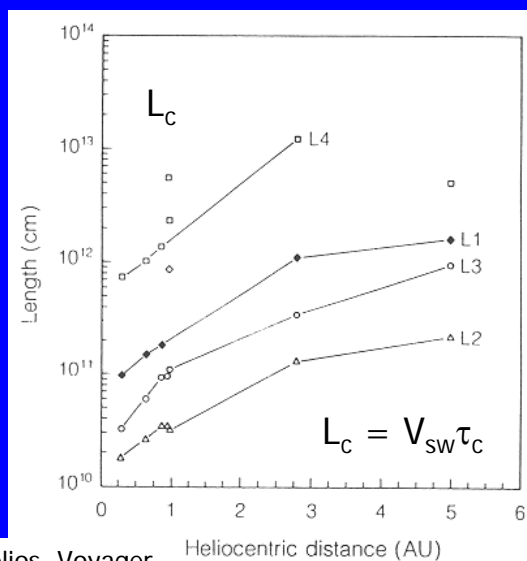
Integral invariants of ideal MHD

$$\begin{aligned}
 E &= \frac{1}{2} \int d^3x (V^2 + V_A^2) && \text{Energy} \\
 H_c &= \int d^3x (\mathbf{V} \cdot \mathbf{V}_A) && \text{Helicity} \\
 H_m &= \int d^3x (\mathbf{A} \cdot \mathbf{B}) && \text{Magnetic helicity} \\
 \mathbf{B} &= \nabla \times \mathbf{A}
 \end{aligned}$$

Elsässer variables: $\mathbf{Z}^\pm = \mathbf{V} \pm \mathbf{V}_A$

$$E^\pm = \frac{1}{2} \int d^3x (\mathbf{Z}^\pm)^2 = \int d^3x e^\pm(\mathbf{x})$$

Correlation length of turbulence



Helios, Voyager

Correlation function:

$$C_{AA'}(\mathbf{x}, t, \mathbf{x}', t') = \langle A(\mathbf{x}, t) A(\mathbf{x}', t') \rangle$$

for any field $A(\mathbf{x}, t)$.

If stationarity and homogeneity, then $\tau = t - t'$, $\mathbf{r} = \mathbf{x} - \mathbf{x}'$

$$\begin{aligned}
 C_{AA'}(\mathbf{x}, t, \mathbf{x}', t') &= \\
 C_{AA'}(\mathbf{r}, \tau) &
 \end{aligned}$$

Turbulence in the heliosphere

Questions and problems:

- *Nature and origin of the fluctuations*
- *Distribution and spectral transfer of turbulent energy*
- *Spatial evolution with heliocentric distance*
- *Intermittency and microphysics of dissipation*

Alfvénic correlations: Alfvénicity (cross helicity)

$$\sigma_c = (e^+ - e^-)/(e^+ + e^-) = 2 \langle \delta \mathbf{V} \cdot \delta \mathbf{V}_A \rangle / \langle (\delta V)^2 + (\delta V_A)^2 \rangle$$

Magnetic versus kinetic energy: Alfvén ratio

$$r_A = e_V/e_B = \langle (\delta V)^2 \rangle / \langle (\delta V_A)^2 \rangle$$

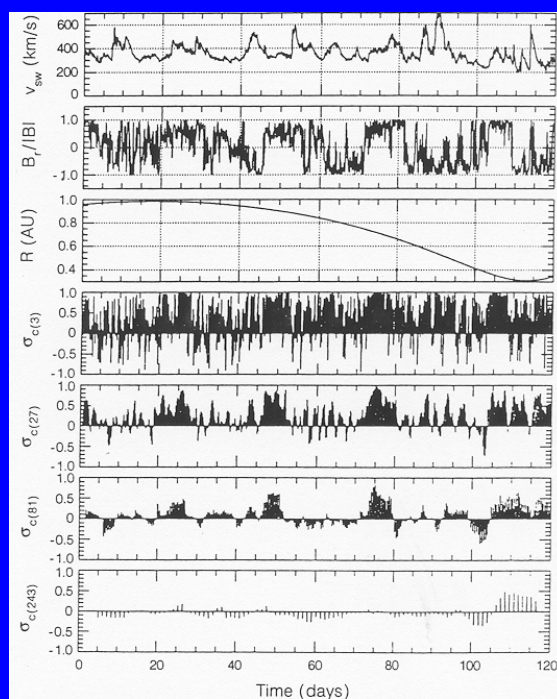
Scaling, non-linear couplings and cascading?

Evolution of cross helicity

$$\begin{aligned} \sigma_c &= 2 \langle \delta \mathbf{V} \cdot \delta \mathbf{V}_A \rangle / \langle (\delta V)^2 + (\delta V_A)^2 \rangle \\ &= (e^+ - e^-)/(e^+ + e^-) \end{aligned}$$

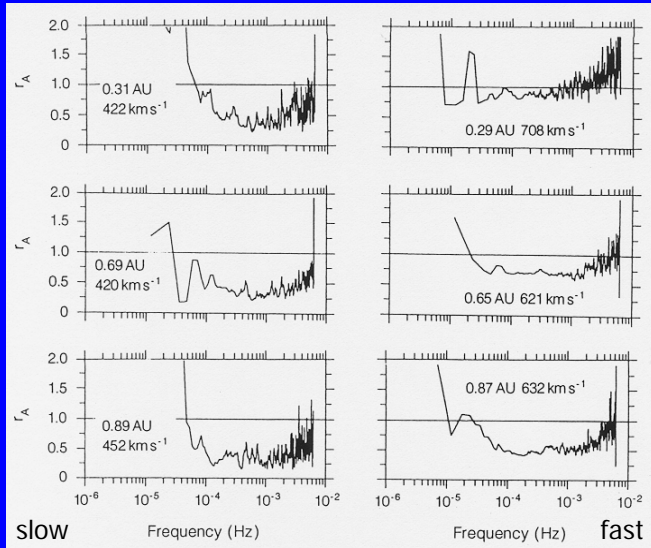
Alfvénic correlations decay radially!

Roberts et al., J. Geophys. Res. **92**, 12023, 1987



Alfvén ratio

$$r_A(\mathbf{k}) = \frac{e_V(\mathbf{k})}{e_B(\mathbf{k})}$$

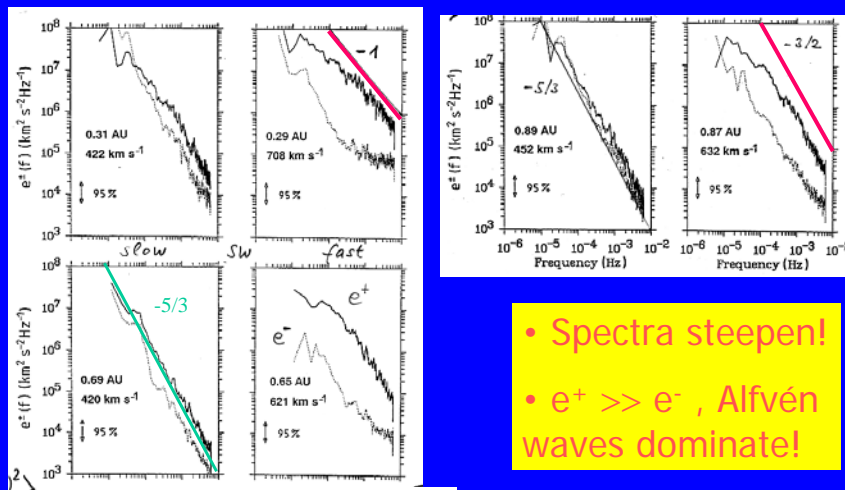


$$e_A(\mathbf{k}) = 1/2 \int d^3k e^{-i\mathbf{k}\cdot\mathbf{r}} \langle \mathbf{A}(\mathbf{0}) \cdot \mathbf{A}(\mathbf{r}) \rangle$$

Spectrum

Marsch and Tu, J. Geophys. Res., 95, 8211, 1990

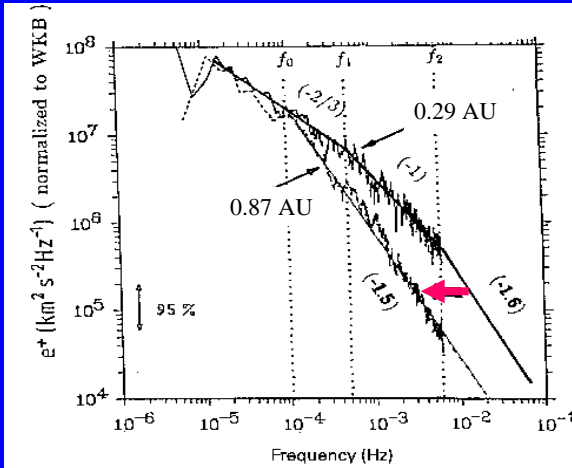
Spectral indices and spatial evolution of turbulence



slow <-> fast wind

Marsch and Tu, JGR, 95, 8211, 1990

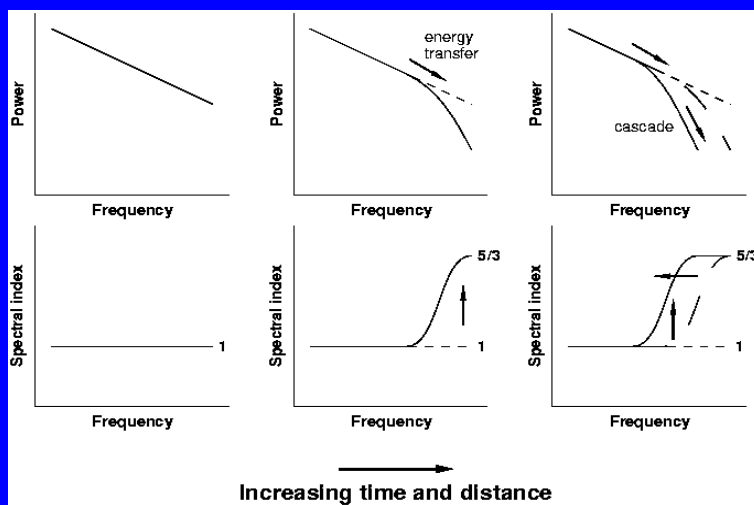
Spectral evolution of Alfvénic fluctuations



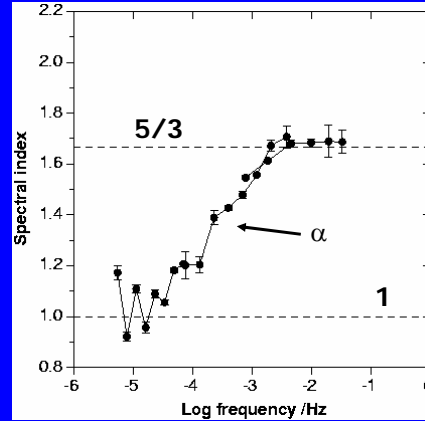
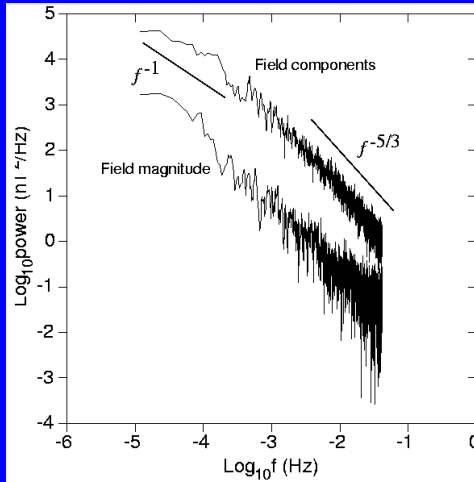
- Steepening by cascading
- Ion heating by wave sweeping
- Dissipation by wave absorption

Tu and Marsch, J. Geophys. Res., **100**, 12323, 1995

Spectral evolution and turbulent cascade: slope steepening



Power spectrum evolution

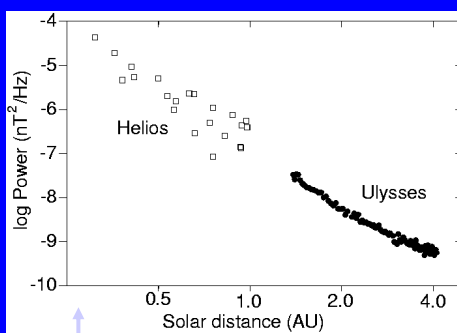


Turbulence spectrum:

$$e^{\pm}(f) = 1/2 (\delta Z^{\pm})^2 \sim (f/f_0)^{-\alpha}$$

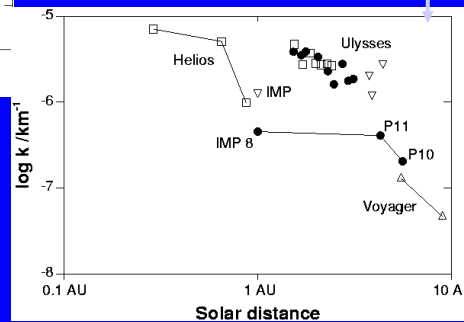
Horbury et al., JGR 101, 405, 1996

Radial variation of spectral features



- Variation of spectral breakpoint (decreases) as measured by various S/C
- Slower radial evolution of spectra over the poles

- Turbulence intensity declines with solar distance
- Wave amplitudes are consistent between Helios and Ulysses in fast streams from coronal holes



Horbury & Tsurutani, 2001

Kolmogorov phenomenology for isotropic homogeneous turbulence

Energy cascade:

Turbulent energy (per unit mass density), $e_t \approx (\delta Z)^2$, at scale l is transported by a hierarchy of turbulent eddies of ever decreasing sizes to the dissipation range at scale l_0 .

energy transfer rate: $\varepsilon_l \sim (\delta Z)^2 / \tau$

turnover time: $\tau \sim l / \delta Z_l$

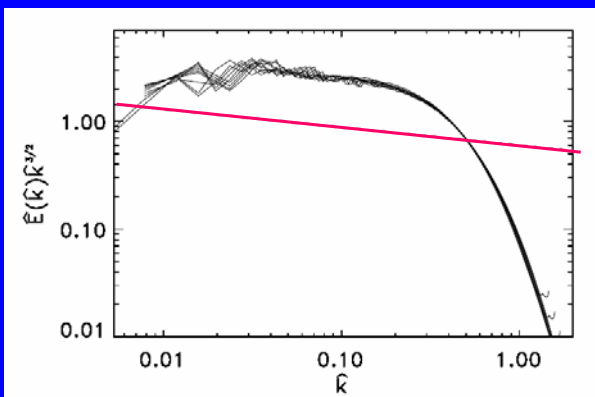
wavenumber: $k \sim 1/l$

energy spectrum: $E_k k \sim (\delta Z)^2$

$$\varepsilon_l \sim \delta Z / l (\delta Z)^2 \sim E_k^{3/2} k^{5/2}$$

Scale invariance: $\varepsilon_l = \varepsilon$ (dissipation rate) $\rightarrow E_k \sim k^{-5/3}$

Spectral properties of 3-D magnetohydrodynamic turbulence



Direct numerical simulation with a spectral code with 512^3 modes

Compensated normalized spectrum shows Kolmogorov scaling and sheet-like dissipative structures

$E_k \sim \varepsilon^{2/3} k^{-5/3}$ Kolmogorov, 1941

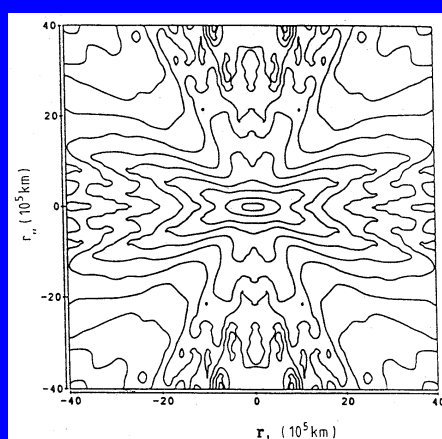
$E_k \sim (\varepsilon V_A)^{1/2} k^{-3/2}$ Kraichnan, 1965

Müller and Biskamp, Phys. Rev. Lett., **84**, 475, 2000

MHD turbulence dissipation through absorption of dispersive kinetic waves

- Viscous and Ohmic dissipation in collisionless plasma (coronal holes and fast solar wind) is hardly important
- Waves become dispersive (at high frequencies beyond MHD) in the multi-fluid or kinetic regime
- Turbulence dissipation involves absorption (or emission by instability) of kinetic plasma waves!
- Cascading and spectral transfer of wave and turbulence energy is not well understood in the dispersive dissipation domain!

Anisotropy and dimension



„Maltese cross“

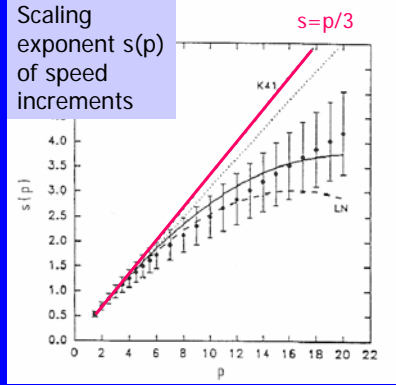
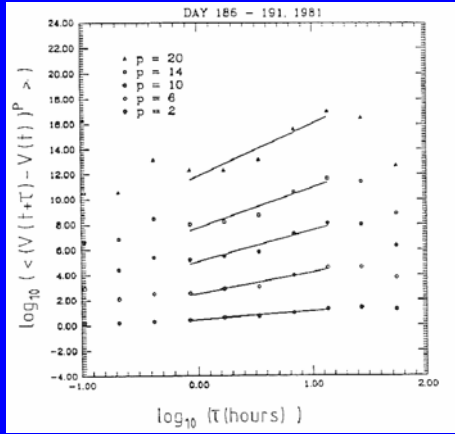
- Particle pitch-angle scattering is weaker than for isotropic MHD consistent with observations of ESPs and CRs
- Compressible fluctuations are described by 2-D MHD

Correlations: \longrightarrow
Alfvén waves and 2-D turbulence

Matthaeus et al., J. Geophys. Res., 95, 20673, 1990

Structure function and scaling

Voyager 2 near 8.5 AU

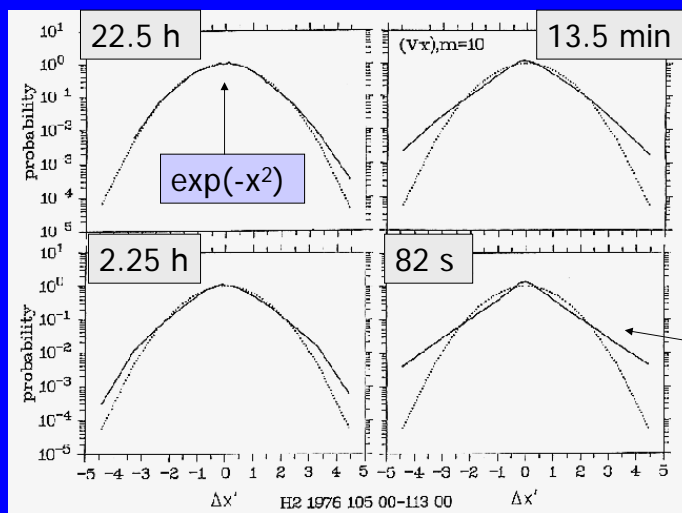


$$S^p(\tau) = \langle |V(\tau) - V(0)|^p \rangle = \tau^{s(p)}$$

$$s(p) = 1 - \ln[P^{p/3} + (1-P)^{p/3}] \quad \text{P-model of fractal cascade; } P=1/2 \text{ no intermittency}$$

Burlaga, JGR, 96, 5847, 1991

Probability distribution functions



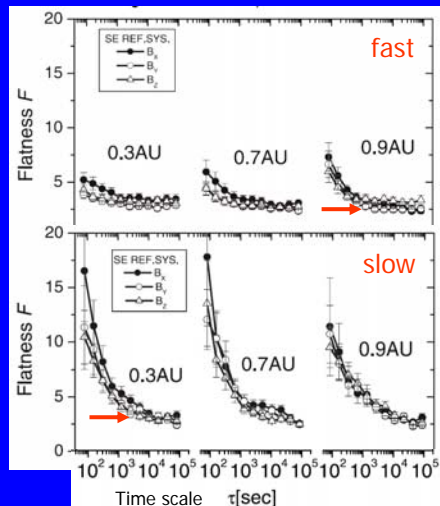
Helios:
fast SW,
 V_x radial
component
of flow
velocity

$$\exp(-x)$$

Non-Gaussian statistics at small scales!

Marsch and Tu, Annales
Geophys., 12, 1127, 1994

Radial evolution of intermittency



Slow wind more intermittent !

Helios, fast solar wind:
 B_x radial component of magnetic field, B_y , B_z .

Flatness (Gaussian, 3):

$$\mathcal{F}(\tau) = \frac{\langle S_\tau^4 \rangle}{\langle S_\tau^2 \rangle^2}$$

Structure function:

$$S_\tau^p = \langle |V(t + \tau) - V(t)|^p \rangle$$

Bruno et al., J. Geophys. Res., **108**, 1130, 2003

Summary

- Solar wind is an almost isotropic turbulent magnetofluid
- Alfvénic fluctuations dominate, with an admixture of weak compressive (magnetosonic) fluctuations
- Turbulence develops towards Kolmogorov spectra, but intermittency prevails at small (below hourly) scales
- Alfvén ratio, cross-helicity, anisotropy evolve radially, as does the average energy spectrum
- Origin of the fluctuations: coronal sources for Alfvén waves, compressive waves from pressure imbalances and stream interactions, cascading by velocity shear
- Structure functions and probability distribution reveal non-gaussian statistics