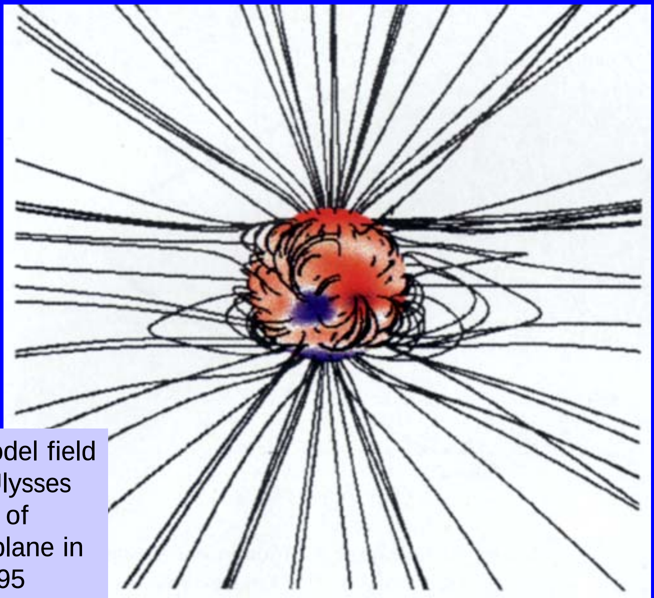
Structures, waves and turbulences in the solar wind

- 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

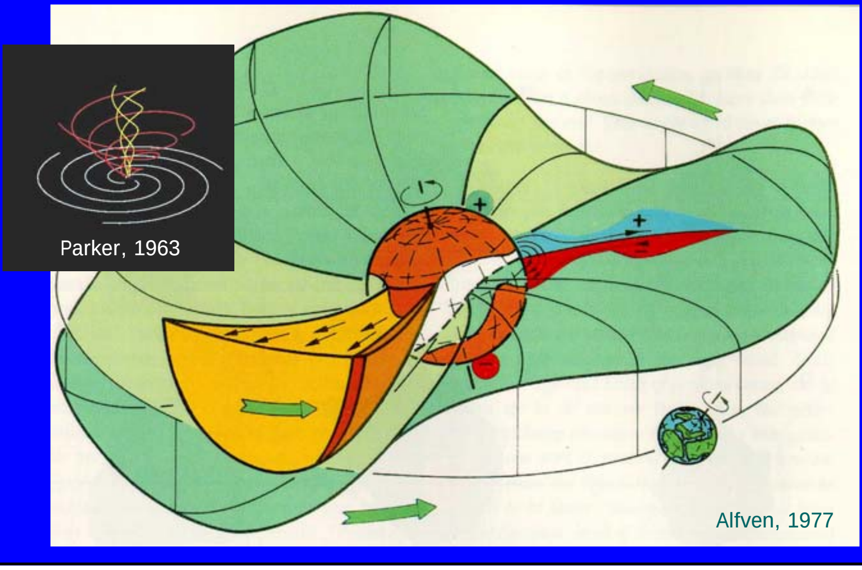
• Heliocentric distance:	r	150 Gm (1AU)
• Solar radius:	R_s	696000 km (215 R_s)
• Alfvén waves:	λ	30 - 100 Mm

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

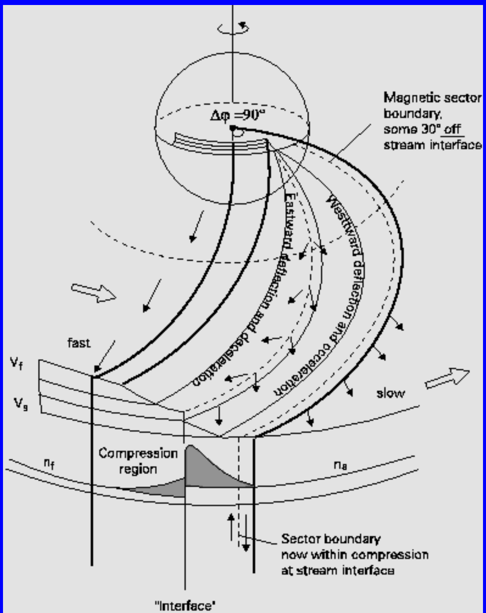


Parker, 1963

Alfven, 1977

Stream interaction region

Dynamic processes in interplanetary space



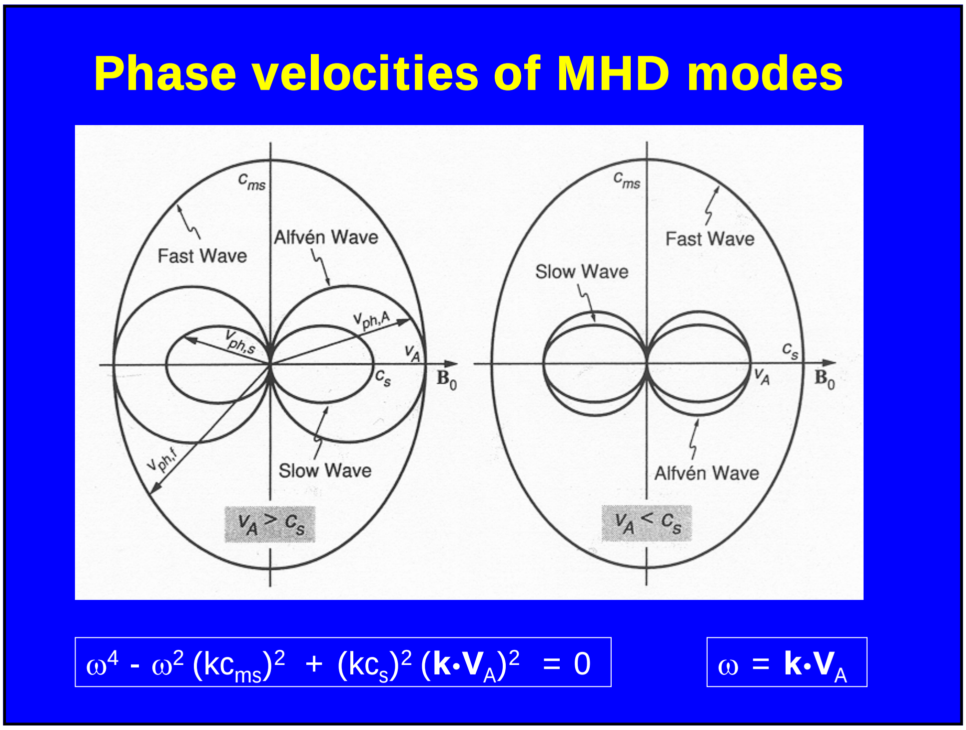
- **Wave amplitude steepening (n~ r^{-2})**
- **Compression and rarefaction**
- **Velocity shear**
- **Nonlinearity by advection ($(\underline{V}\bullet\underline{\nabla})\underline{V}$)**
- **Shock formation (co-rotating)**

Schwenn, 1990

Spatial and temporal scales

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

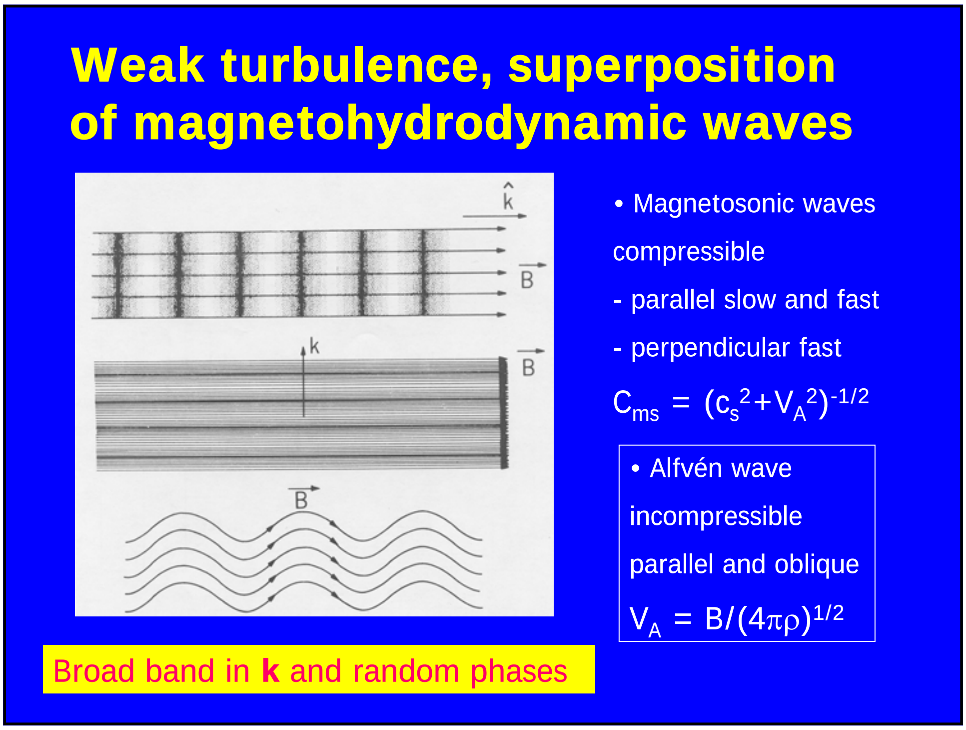
Turbulent cascade: generation + transport
→ inertial range → kinetic range + dissipation



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

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

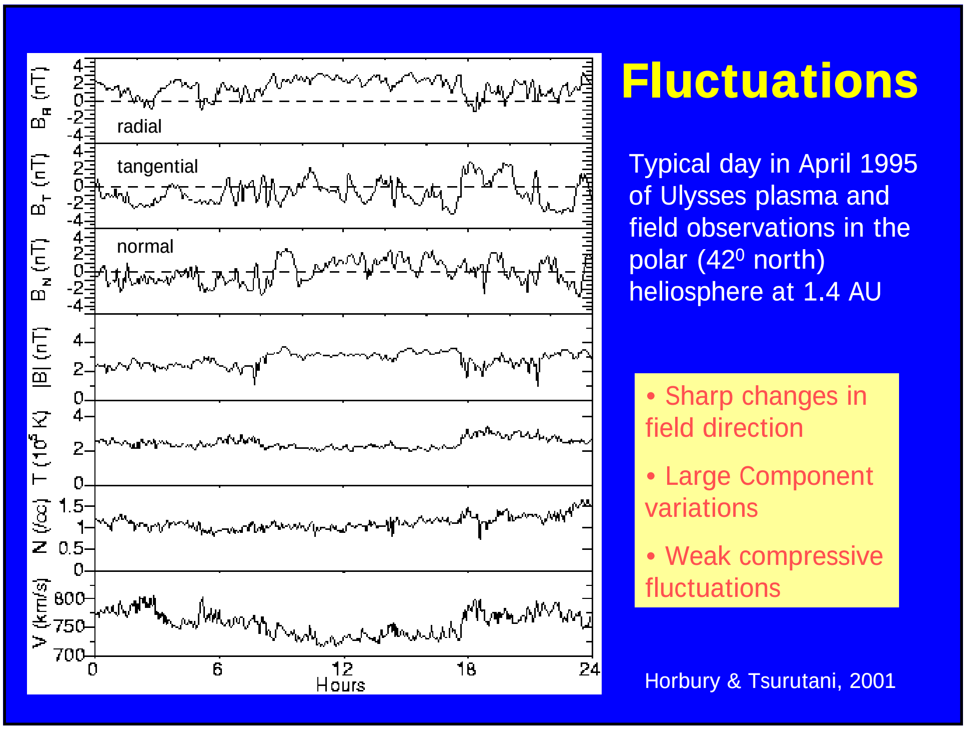
- Alfvén wave

incompressible

parallel and oblique

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

Broad band in **k** and random phases

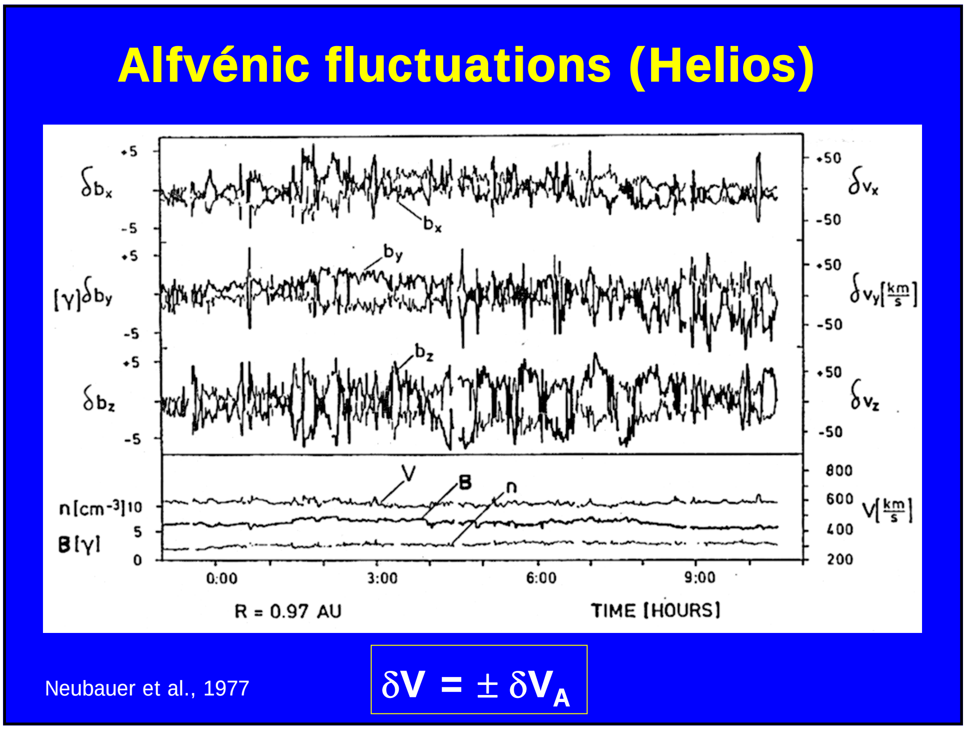


Fluctuations

Typical day in April 1995 of Ulysses plasma and field observations in the polar (42^0 north) heliosphere at 1.4 AU

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

Horbury & Tsurutani, 2001

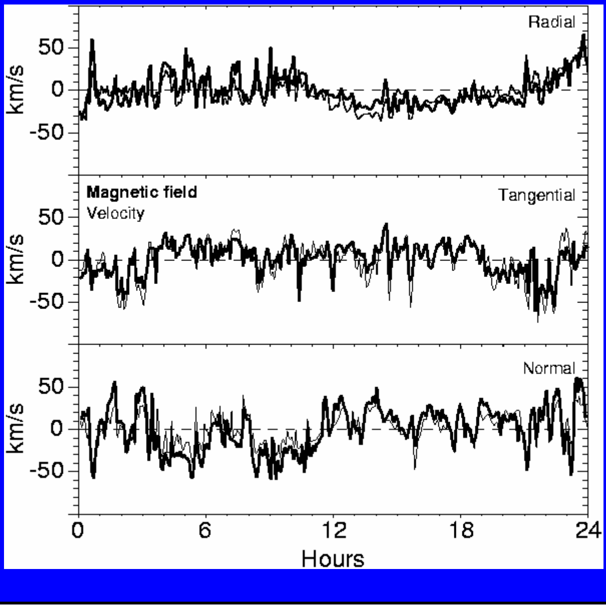


Alfvénic fluctuations (Helios)

Neubauer et al., 1977

$\delta V = \pm \delta V_A$

Alfvénic fluctuations (Ulysses)



Elsässer variables:

$\mathbf{Z}^{\pm} = \mathbf{V} \pm \mathbf{V}_{\mathbf{A}}$

Turbulence energy:

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

Cross helicity:

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

Horbury & Tsurutani, 2001

Alfvénic fluctuations

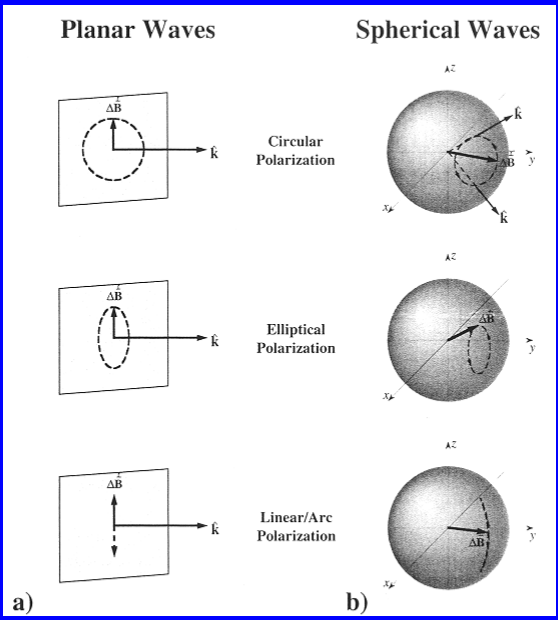
Ulysses observed many such waves (4-5 per hour) in fast wind over the poles:

- Arc polarized waves
- Phase-steepened

Rotational discontinuity:

$\Delta \mathbf{V} = \pm\, \Delta \mathbf{V}_{\mathbf{A}}$

Finite jumps in velocities over gyrokinetic scales

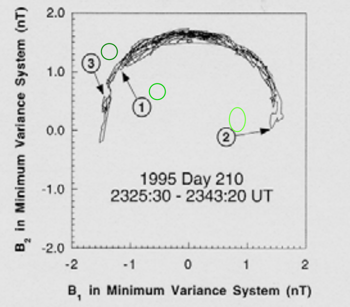


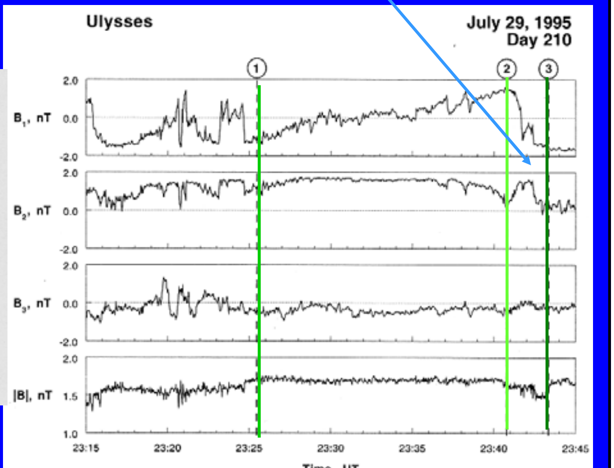
Tsurutani et al., 1997

Arc-polarized Alfvén waves

Slowly rotating Alfvén wave lasts about 15 minutes

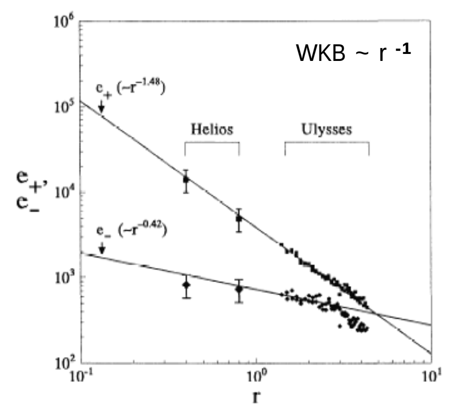
Rotational discontinuity RD lasts only 3 minutes





Tsurutani et al., 1997

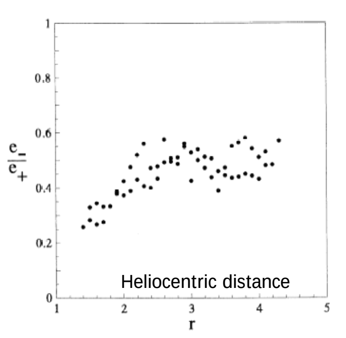
Alfvén waves in polar solar wind



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

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

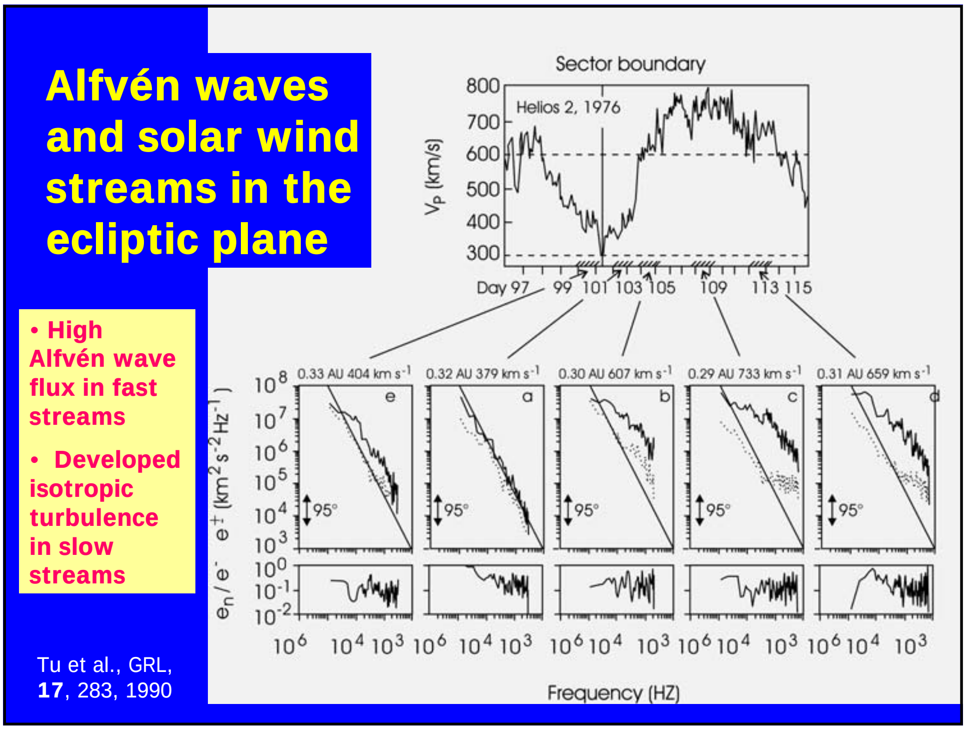
Elsässer ratio: $r_e = e^-/e^+$



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

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

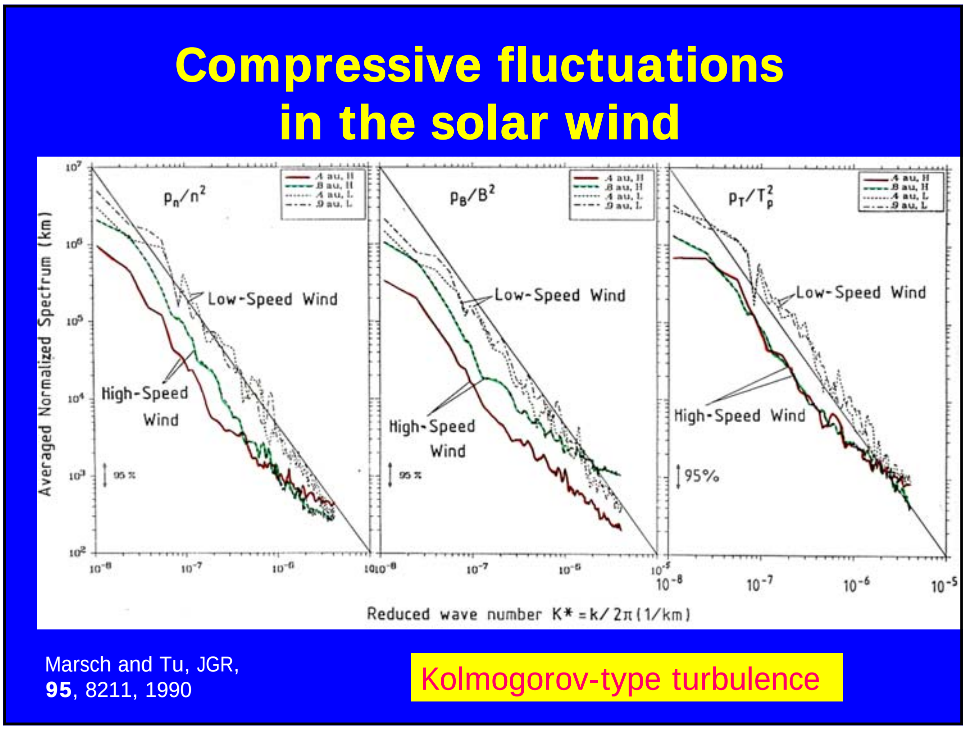
Average values over 0.1 AU wide intervals of hourly variances of $Z^{\pm}$



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



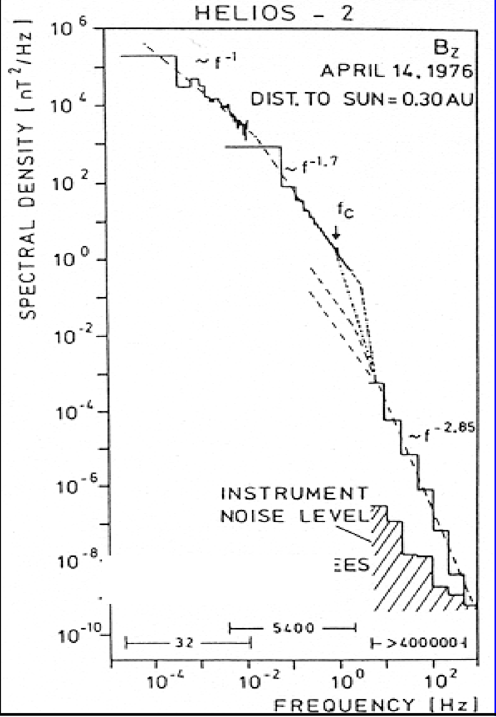
Compressive fluctuations in the solar wind

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

$E = 1/2 \int d^3x \, (V^2 + V_A^2)$ Energy

$H_c = \int d^3x \, (\mathbf{V} \cdot \mathbf{V}_A)$ Helicity

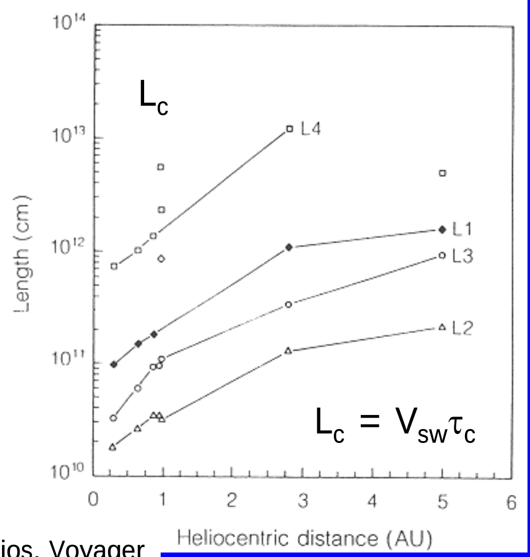
$H_m = \int d^3x \, (\mathbf{A} \cdot \mathbf{B})$ Magnetic helicity

$\mathbf{B} = \nabla \times \mathbf{A}$

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

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

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 $\tau = t - t'$, $\mathbf{r} = \mathbf{x} - \mathbf{x}'$

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

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)

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

Magnetic versus kinetic energy: Alfvén ratio

$r_A = e_V / e_B = < (\delta V)^2 > / < (\delta V_A)^2 >$

Scaling, non-linear couplings and cascading?

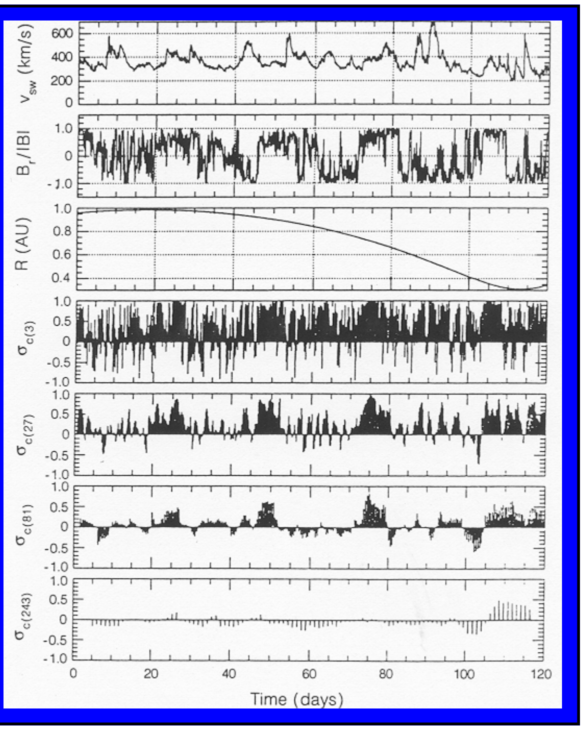
Evolution of cross helicity

$\sigma_c = 2 < \delta \mathbf{V} \cdot \delta \mathbf{V}_A >$
$/ (\delta \mathbf{V}^2 + \delta \mathbf{V}_A{}^2)$

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

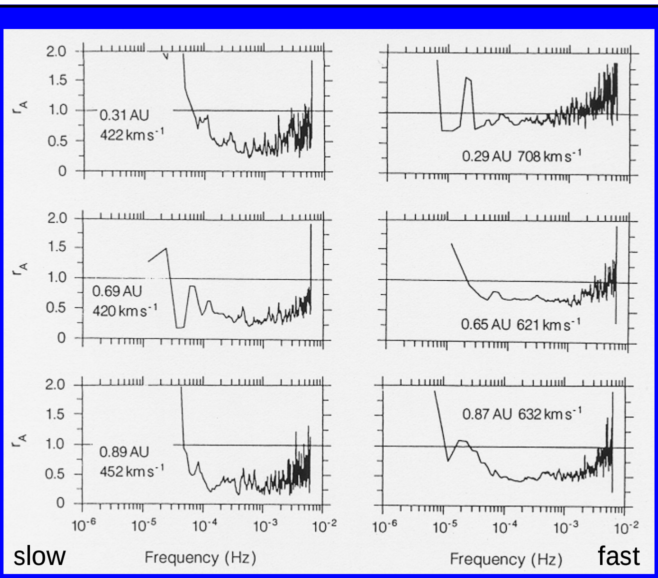
Alfvénic correlations decay radially!

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



Alfvén ratio

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

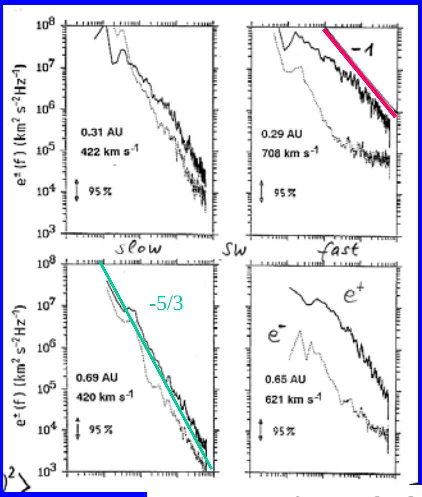


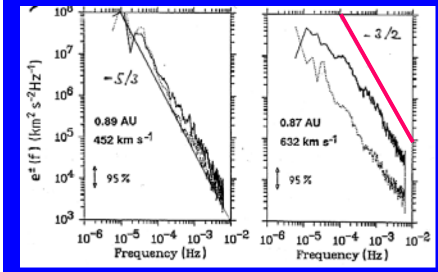
$$e_A(\mathbf{k}) = 1/2 \int d^3k\, e^{-i\,\mathbf{k}\cdot\mathbf{r}} \langle \mathbf{A}(\mathbf{0})\cdot\mathbf{A}(\mathbf{r})\rangle$$

Spectrum

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

Spectral indices and spatial evolution of turbulence



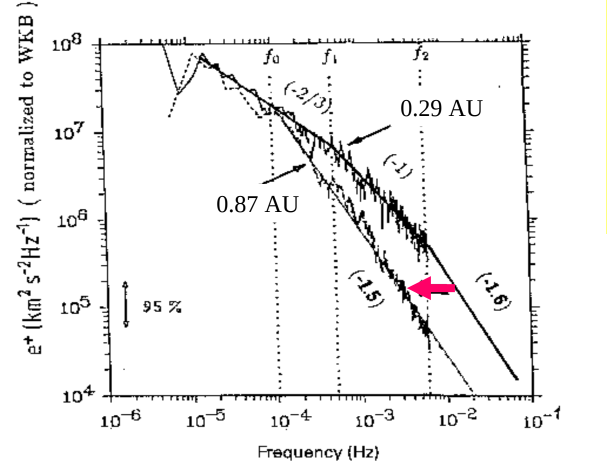


- Spectra steepen!
- $e^+ >> e^-$, Alfvén waves dominate!

slow <-> fast wind

Marsch and Tu, JGR, **95**, 8211, 1990

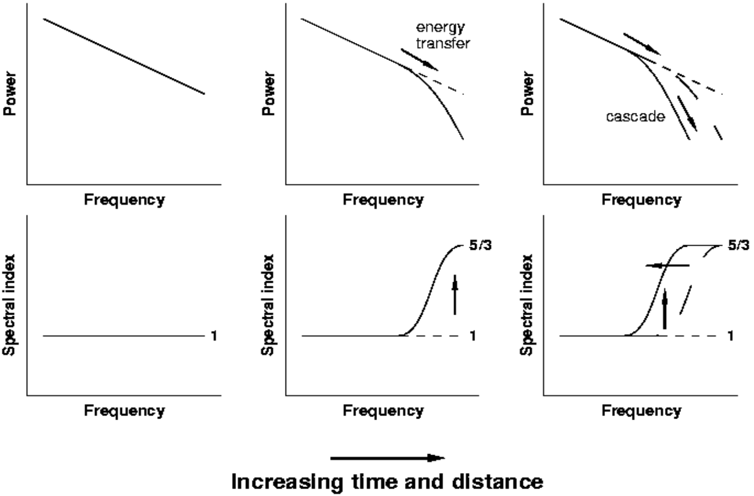
Spectral evolution of Alfvénic fluctuations

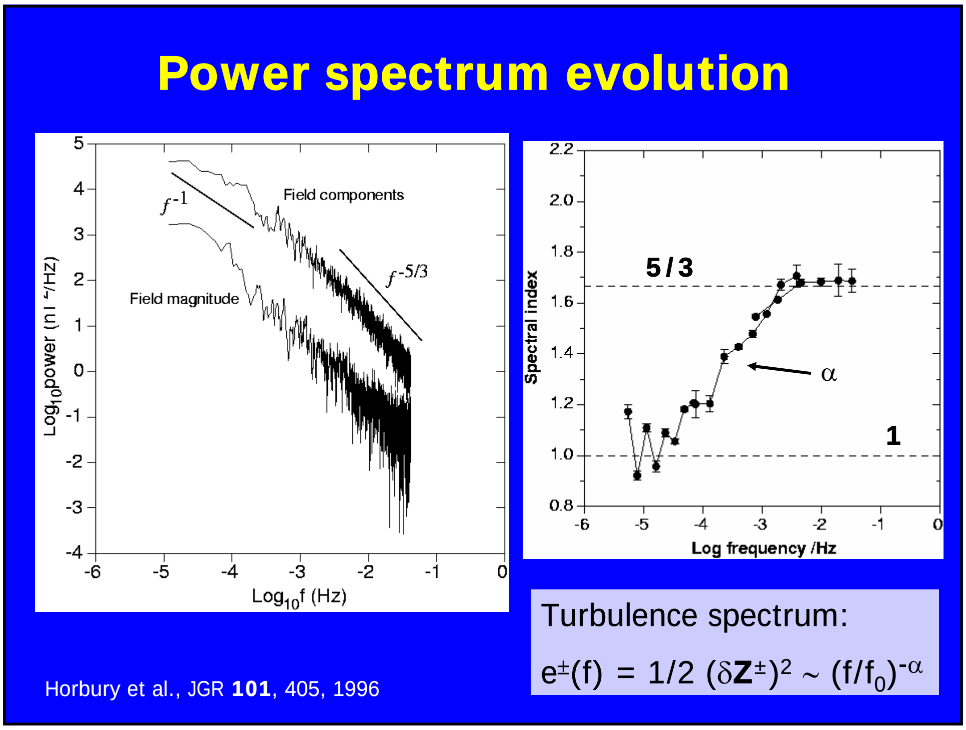


- **Steepening by cascading**
- **Ion heating by wave sweeping**
- **Dissipation by wave absorption**

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

Spectral evolution and turbulent cascade: slope steepening



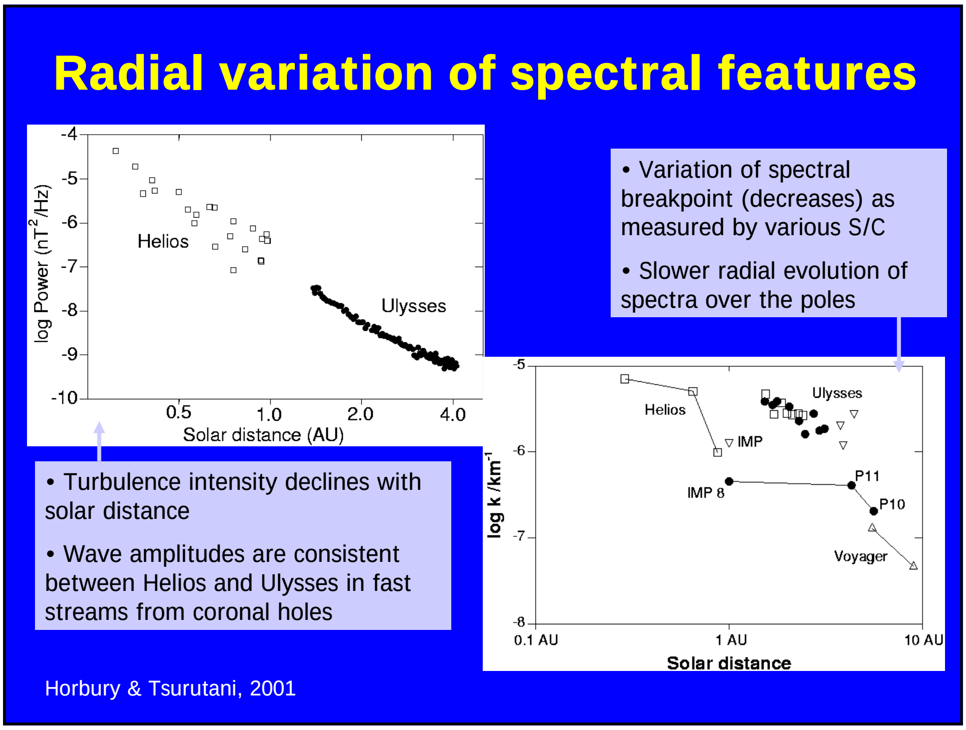


Power spectrum evolution

Turbulence spectrum:

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

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:

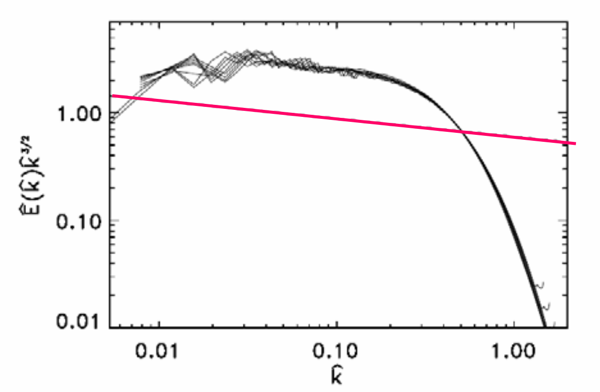
Turbulent energy (per unit mass density), $e_\ell \approx (\delta Z)^2$, at scale ℓ is transported by a hierarchy of turbulent eddies of ever decreasing sizes to the dissipation range at scale ℓ_D.

energy transfer rate:	$\varepsilon_\ell \sim (\delta Z_\ell)^2/\tau$
turnover time:	$\tau \sim \ell / \delta Z_\ell$
wavenumber:	$k \sim 1/\ell$
energy spectrum:	$E_k k \sim (\delta Z_\ell)^2$

$$\varepsilon_\ell \sim \delta Z/\ell \, (\delta Z)^2 \sim E_k^{3/2} k^{5/2}$$

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

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

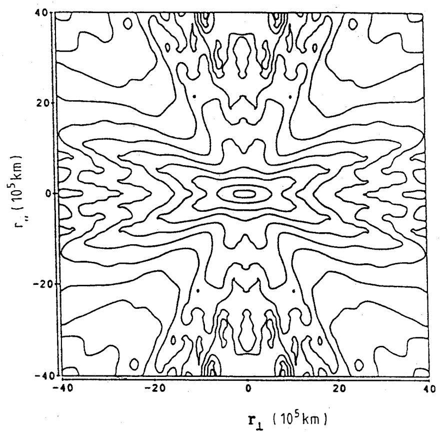
Müller and Biskamp, Phys. Rev. Lett., **84**, 475, 2000

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

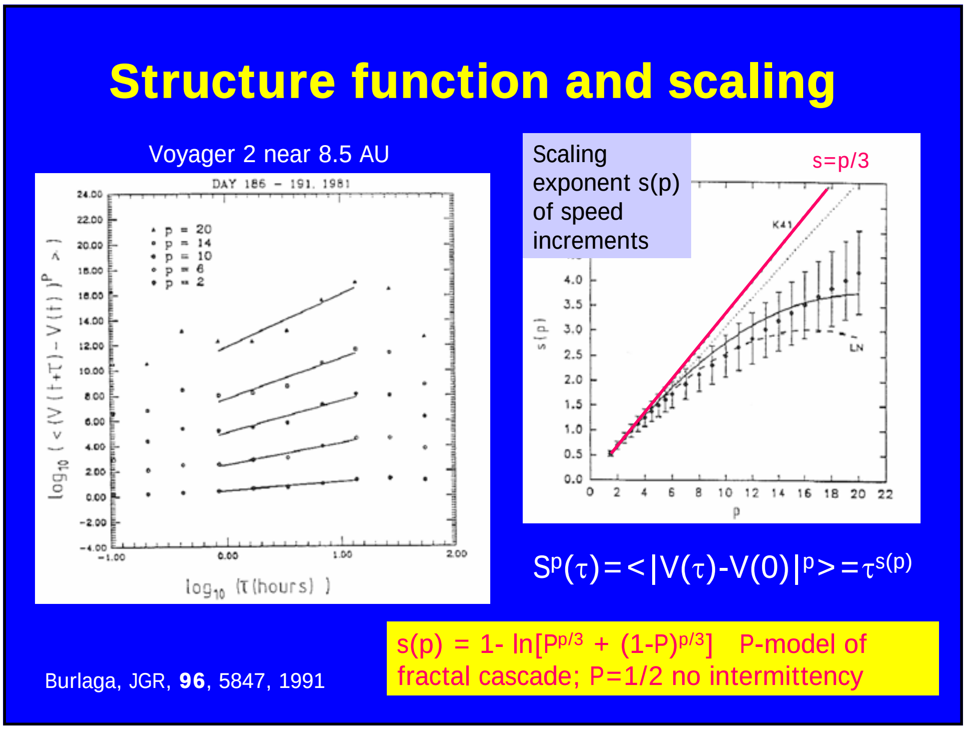


„Maltese cross“

- 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:
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

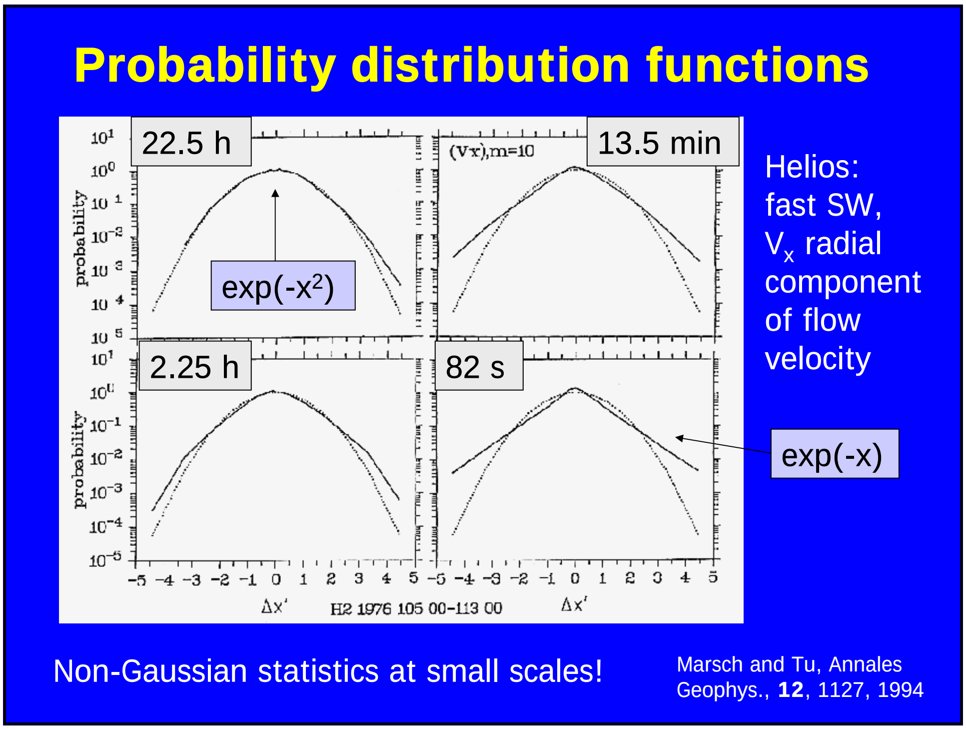
Scaling exponent s(p) of speed increments

s=p/3

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

Burlaga, JGR, **96**, 5847, 1991

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



Probability distribution functions

exp(-x^2)

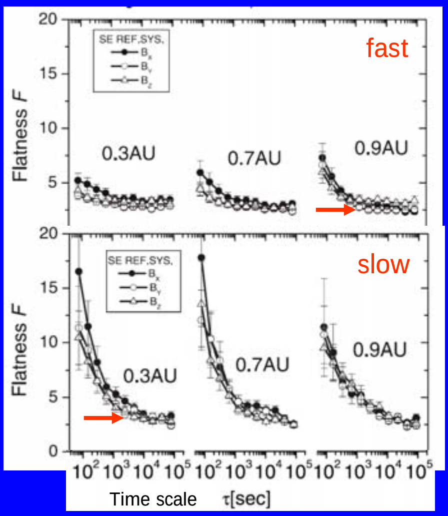
exp(-x)

Helios: fast SW, V_x radial component of flow velocity

Non-Gaussian statistics at small scales!

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

Radial evolution of intermittency



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:

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

Slow wind more intermittent !

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