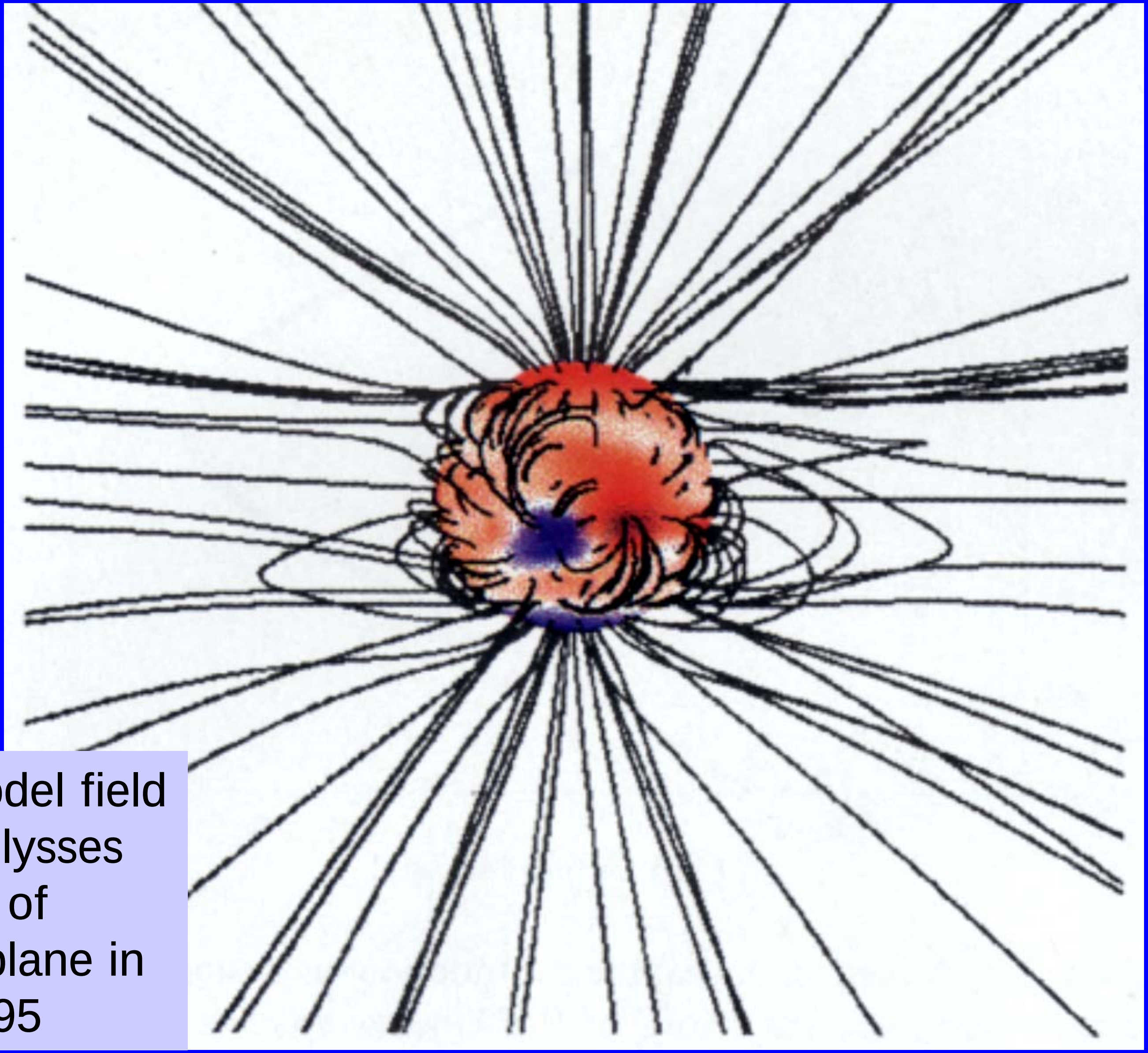
Structures, waves and turbulence in the heliosphere

- The inner 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

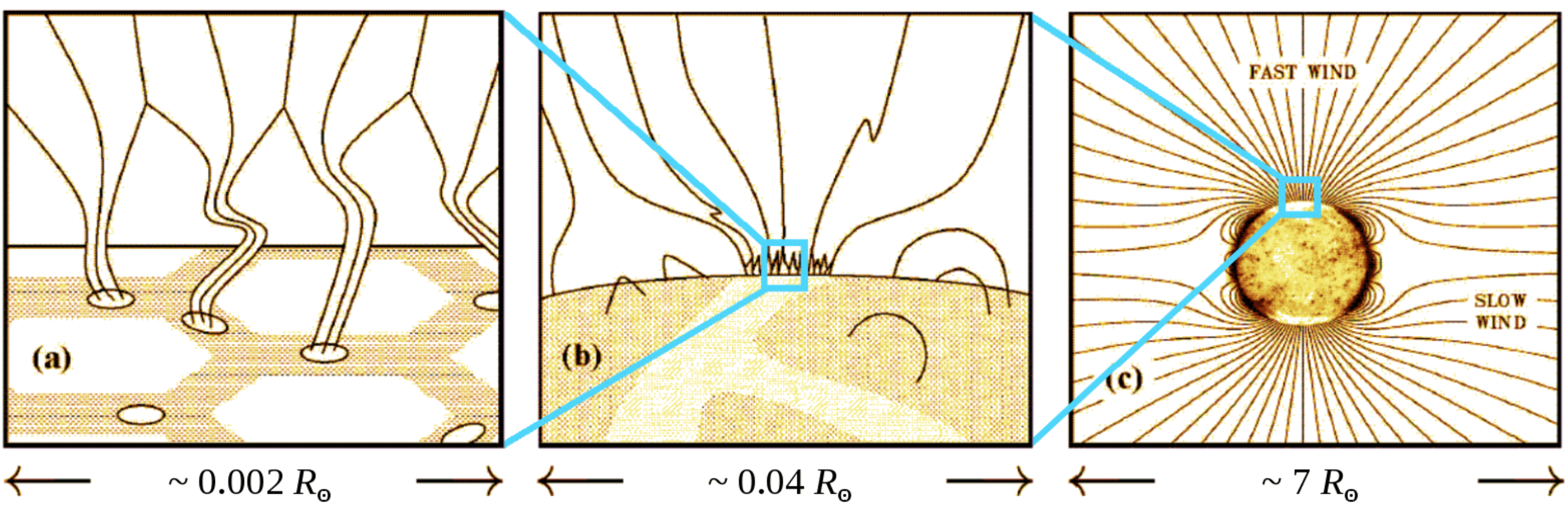


MHD model field during Ulysses crossing of ecliptic plane in early 1995

Mikic & Linker, 1999

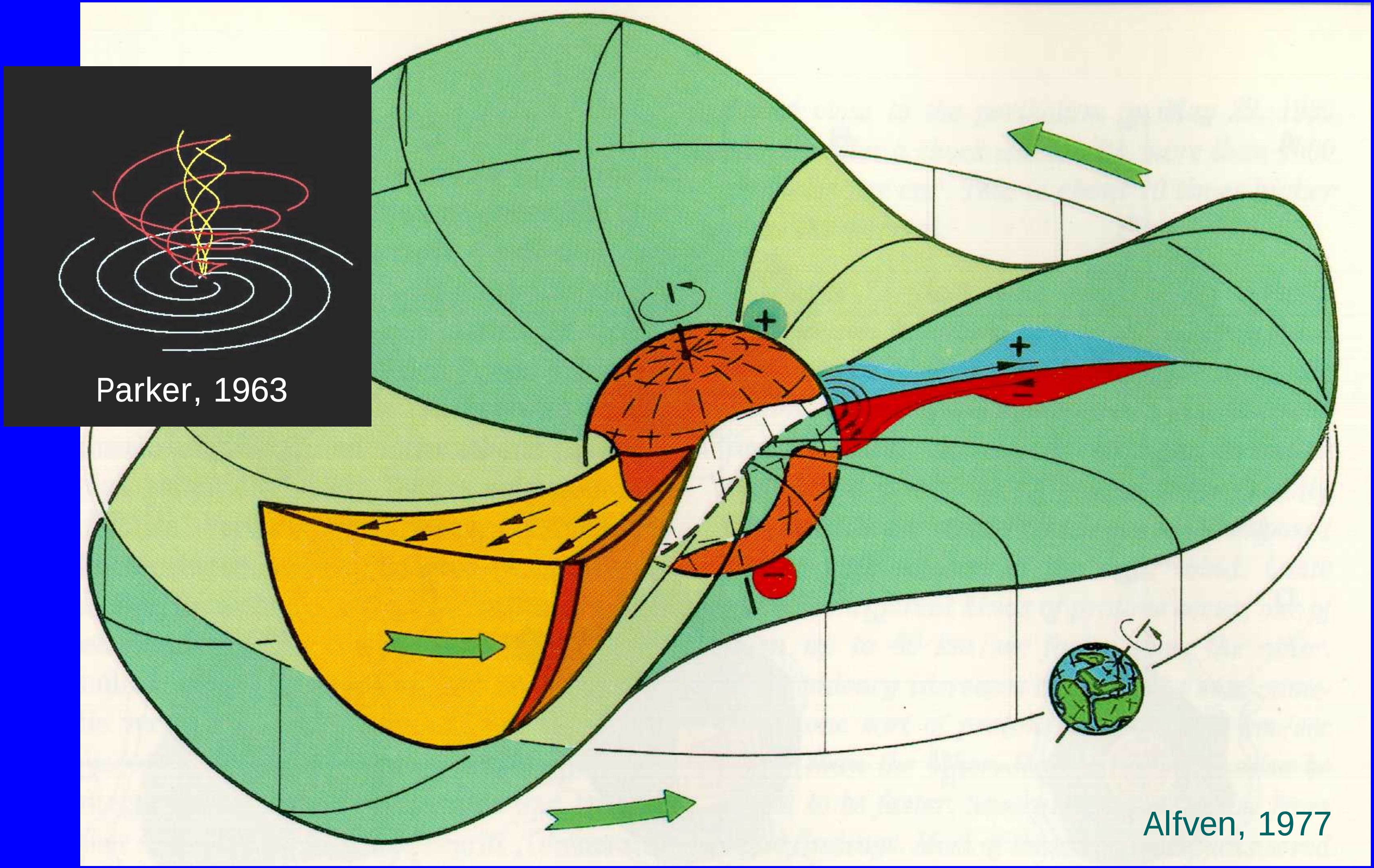
Waves and turbulence on open fields

- Photospheric flux tubes are **shaken** by an observed spectrum of horizontal motions.
- Alfvén waves propagate along the field, and may partly **reflect** back down.
- Nonlinear couplings force a (perpendicular?) **cascade**, terminated by damping.



(Heinemann & Olbert 1980; Hollweg 1981, 1986; Velli 1993; Matthaeus et al. 1999; Dmitruk et al. 2001, 2002; Cranmer & van Ballegooijen 2003, 2005; Verdini et al. 2005; Oughton et al. 2006; many others)

Solar wind stream structure and heliospheric current sheet

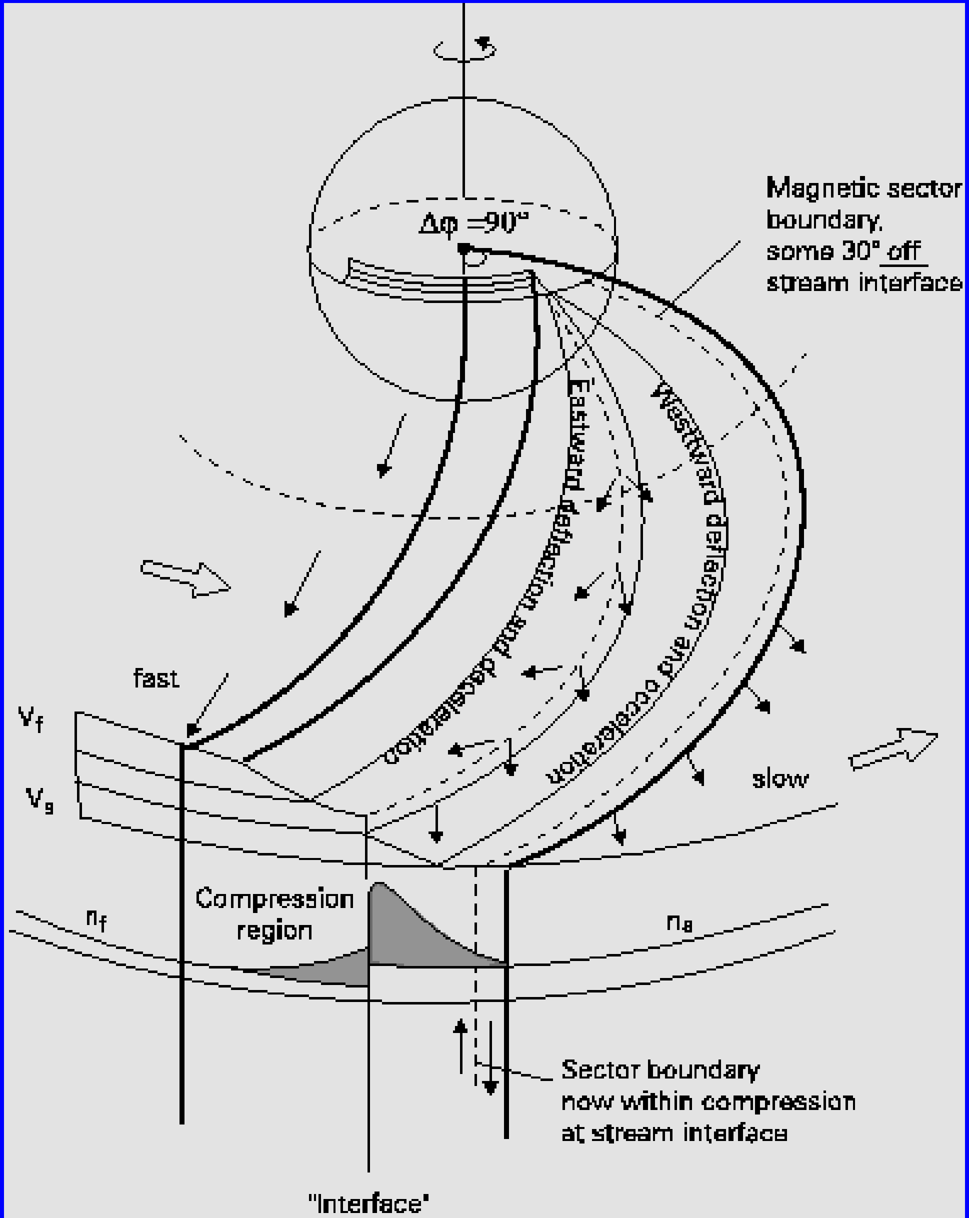


Parker, 1963

Alfven, 1977

Stream interaction region

Dynamic processes in inter-planetary space



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

Schwenn, 1990

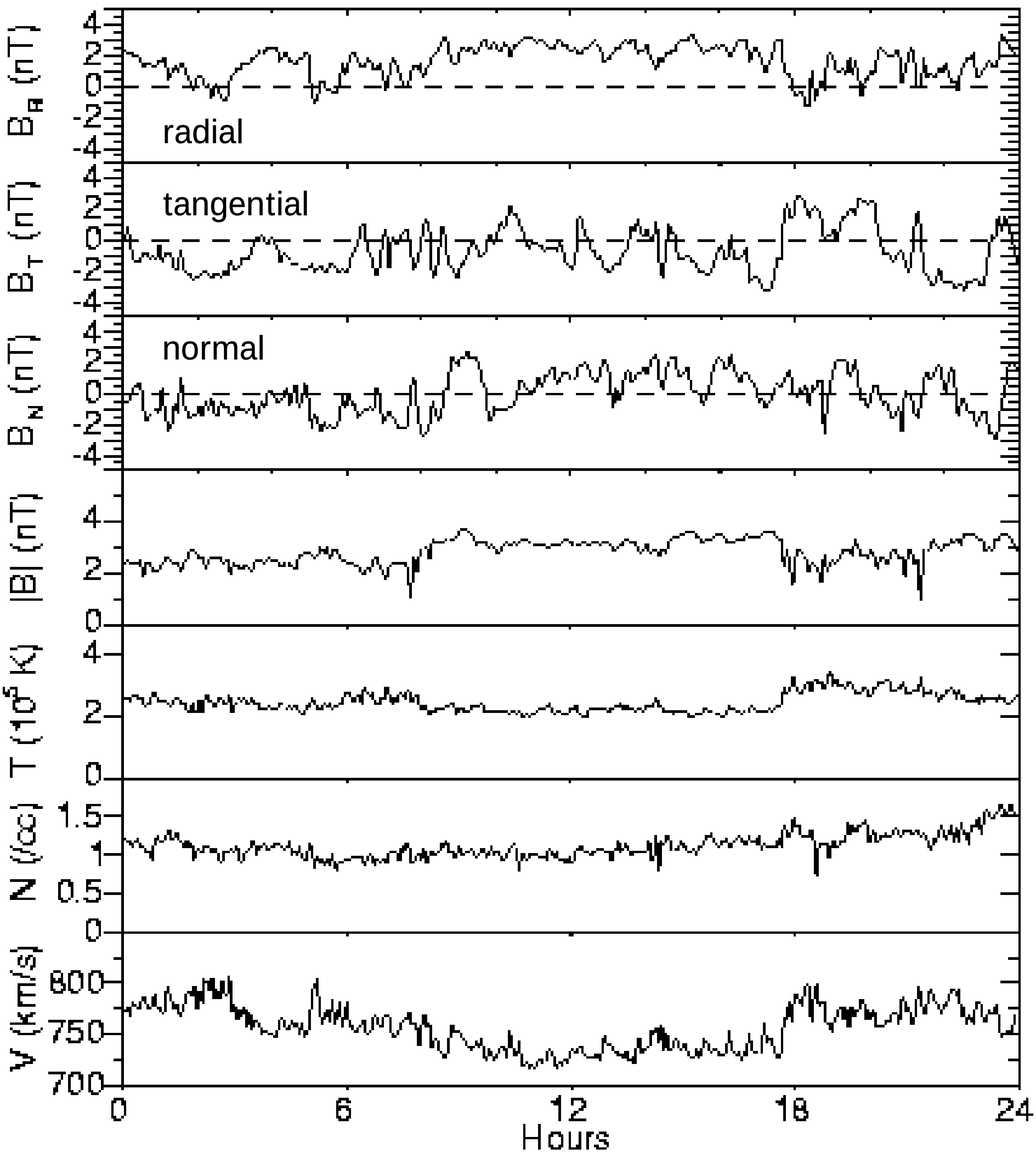
Spatial and temporal scales

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

Fluctuations

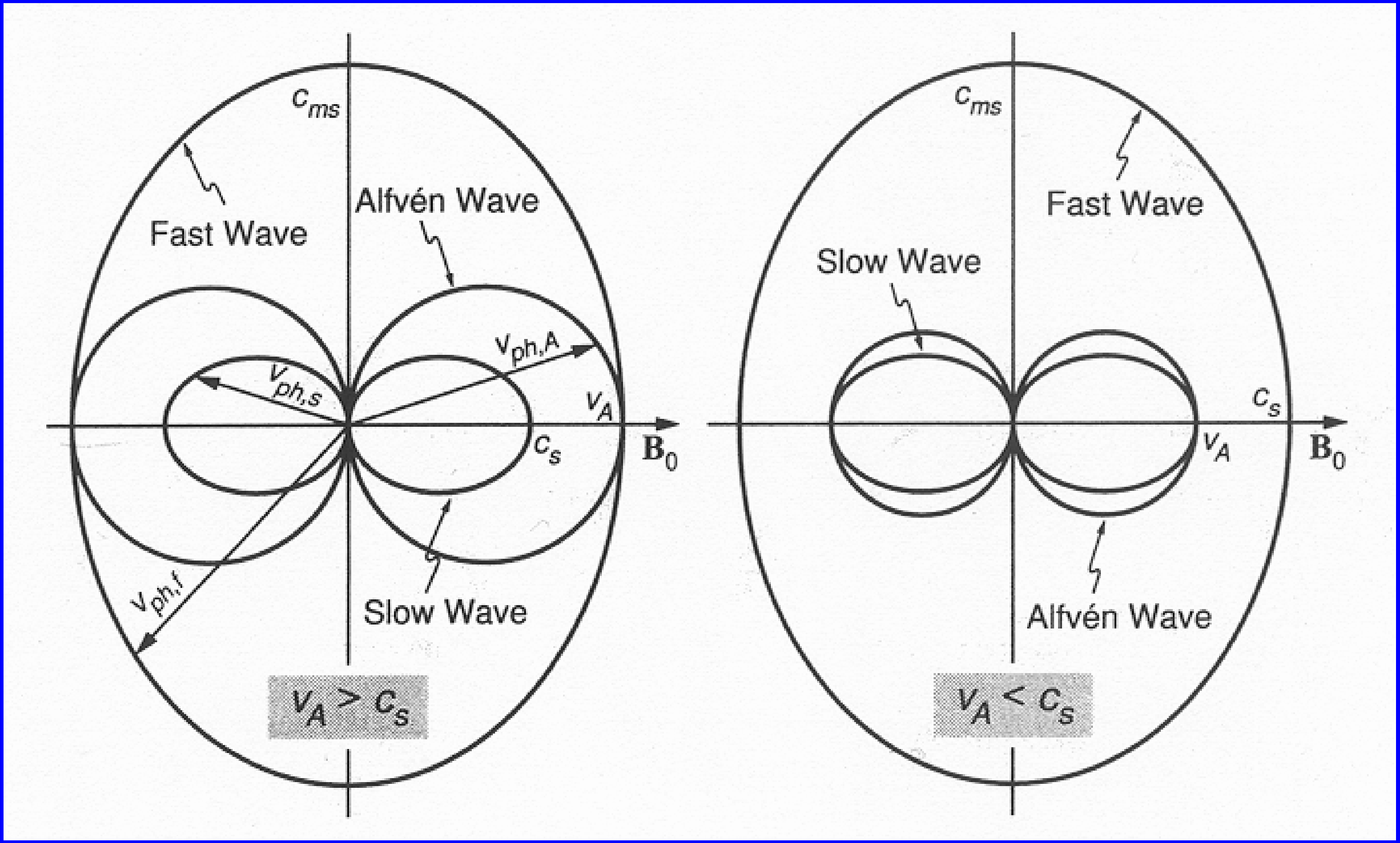


Typical day in April 1995 of Ulysses plasma and field observations in the polar (42^0 north) heliosphere at 1.4 AU

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

Horbury & Tsurutani, 2001

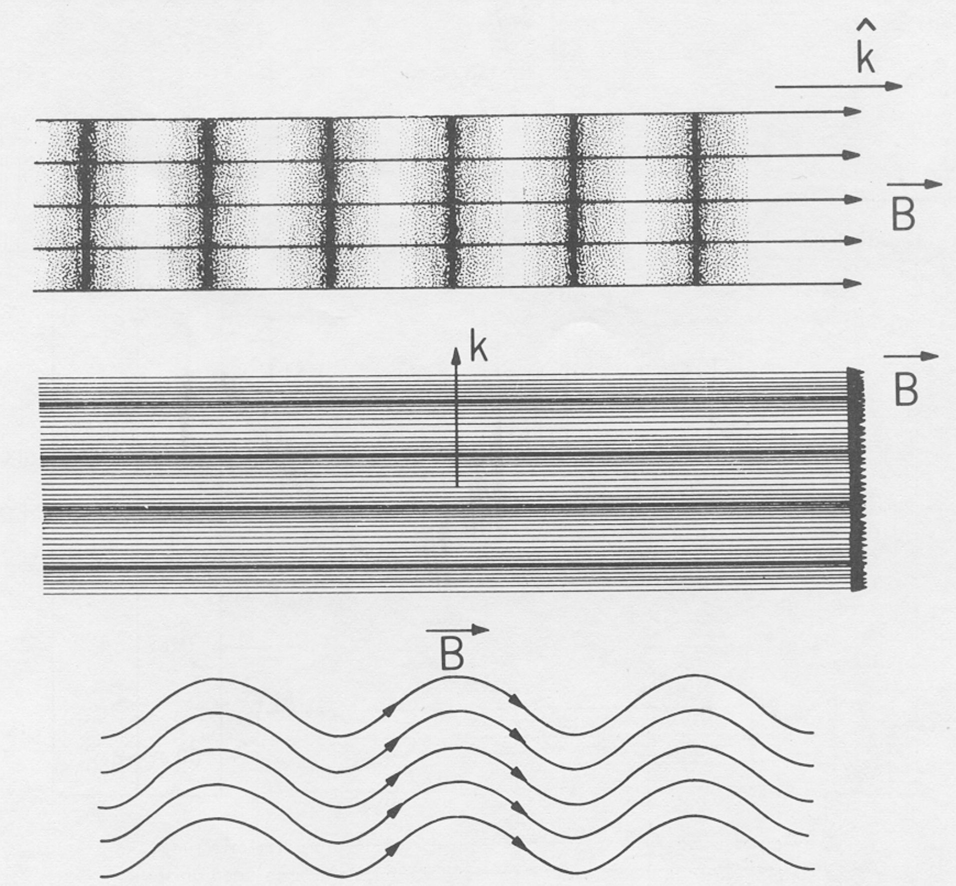
Phase velocities of MHD modes



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

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

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

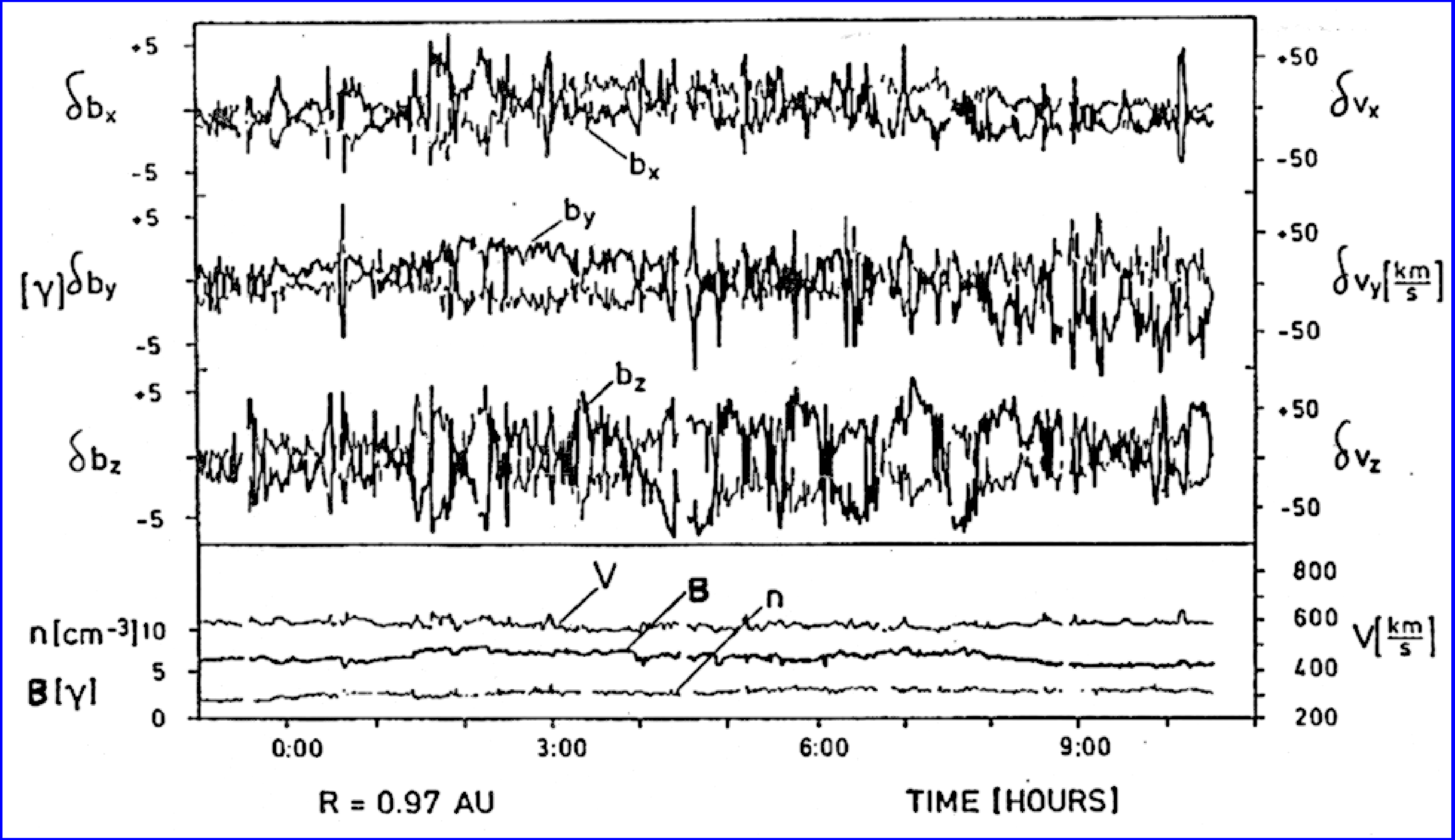
incompressible

parallel and oblique

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

Broad band in **k** and random phases

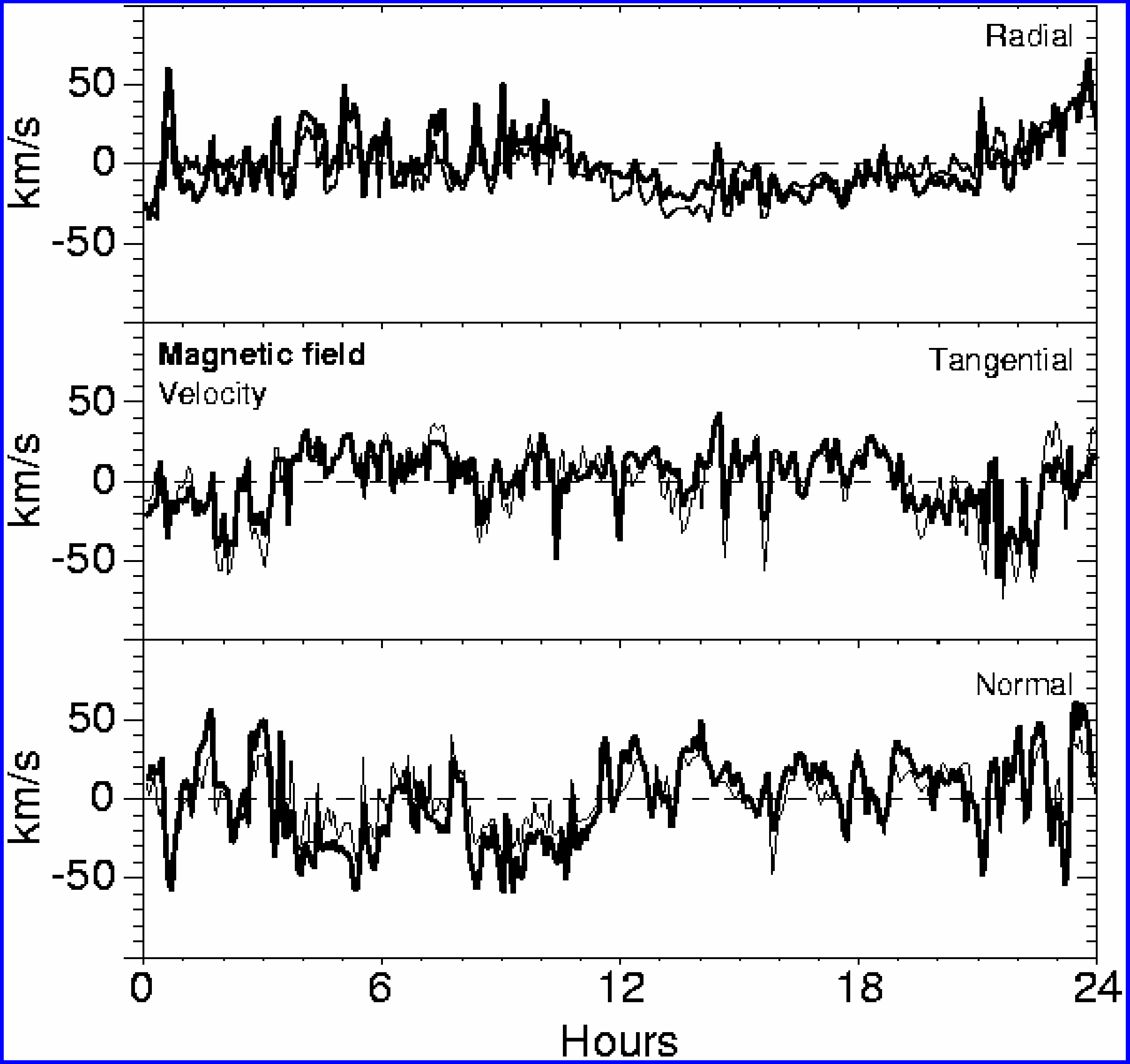
Alfvénic fluctuations (Helios)



Neubauer et al., 1977

$$\boxed{\delta V = \pm\, \delta V_A}$$

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

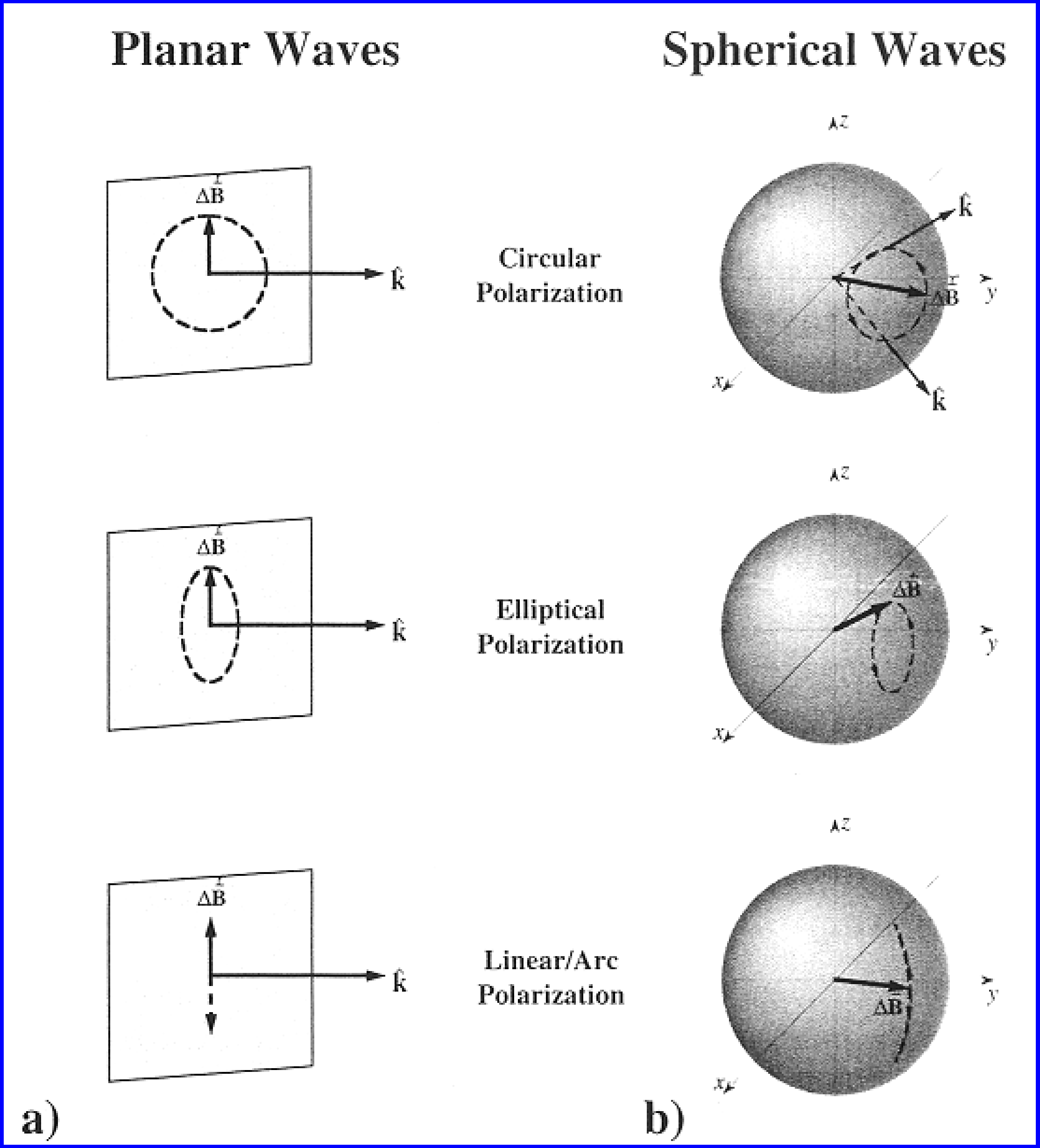
Ulysses observed many such waves (4-5 per hour) in fast wind over the poles:

- Arc-polarized waves
- Phase-steepened

Rotational discontinuity:

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

Finite jumps in velocities over gyrokinetic scales

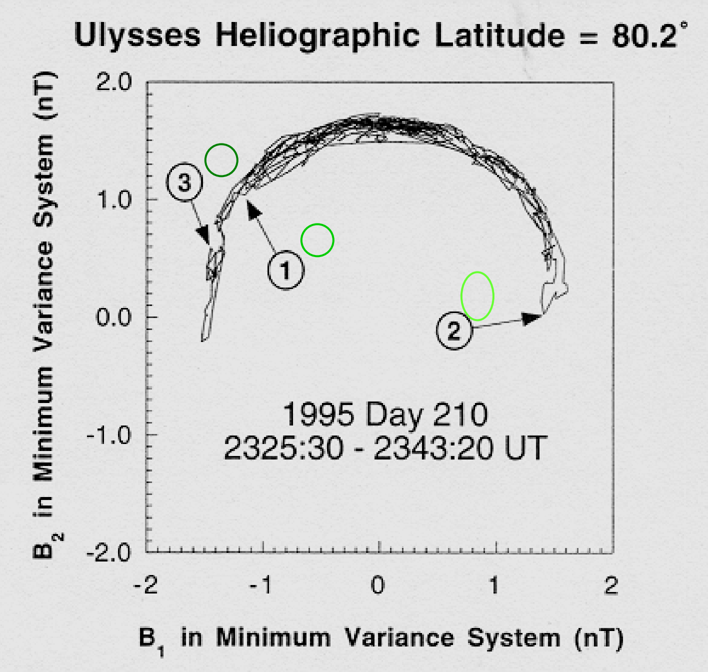


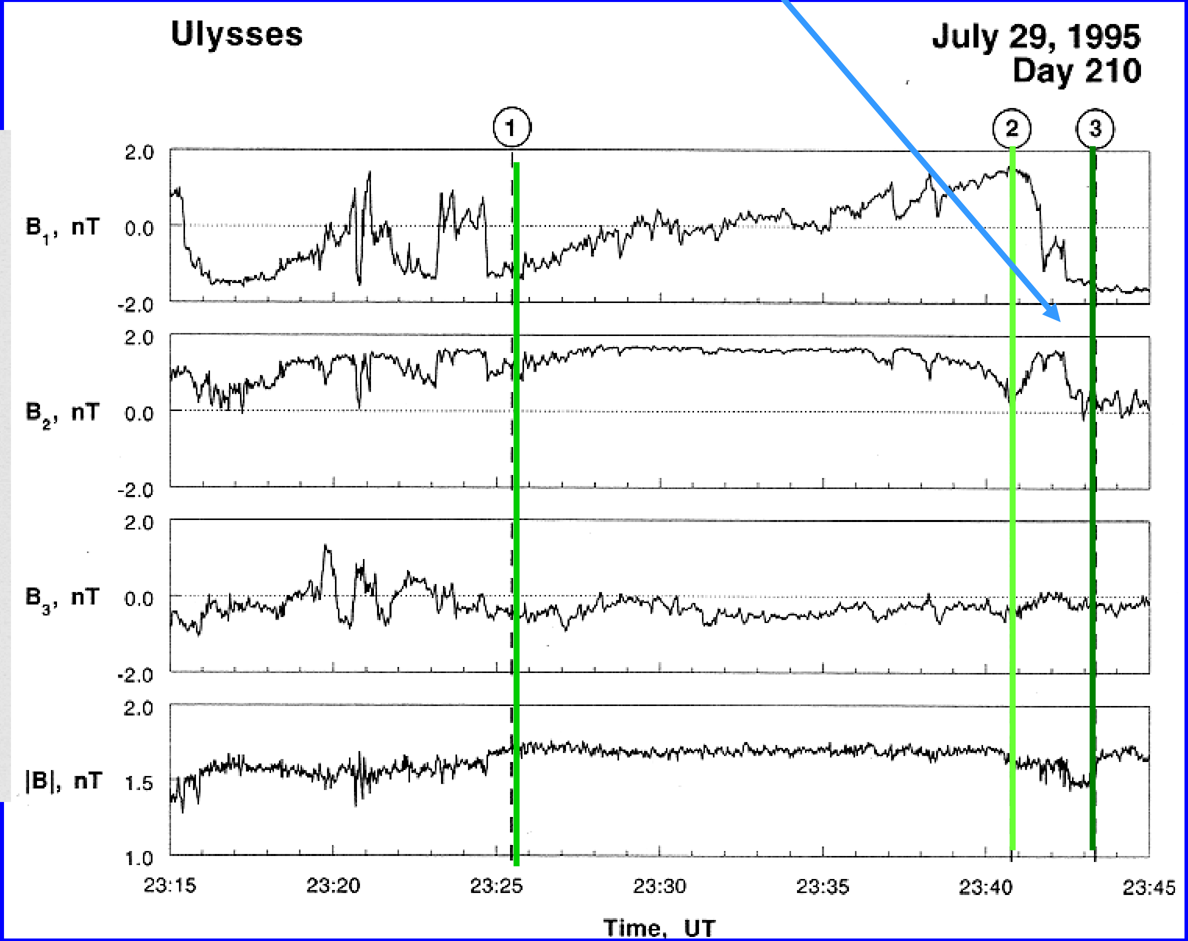
Tsurutani et al., 1997

Arc-polarized Alfvén waves

Slowly rotating Alfvén wave lasts about 15 minutes

Rotational discontinuity RD lasts only 3 minutes

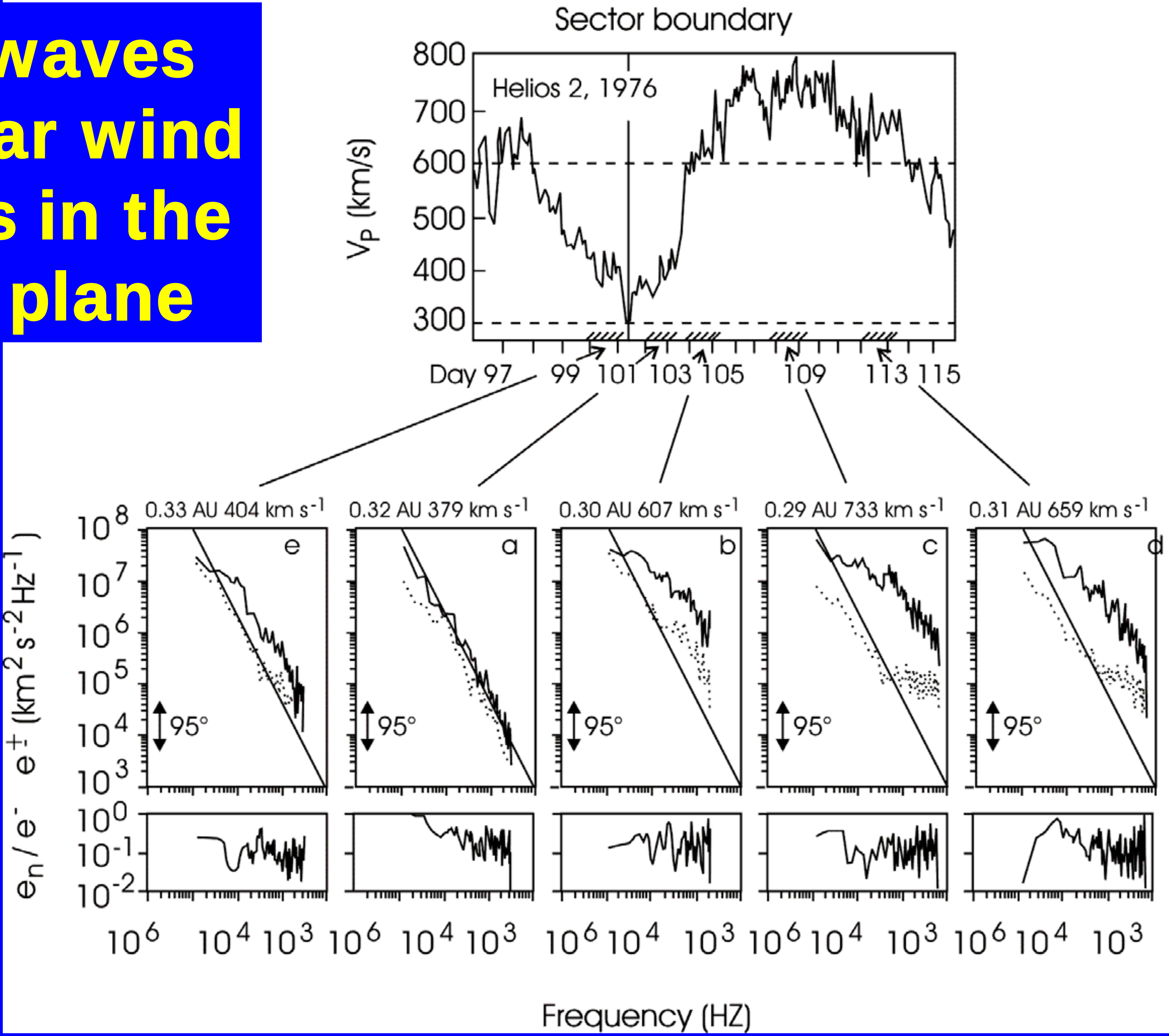




Tsurutani et al., 1997

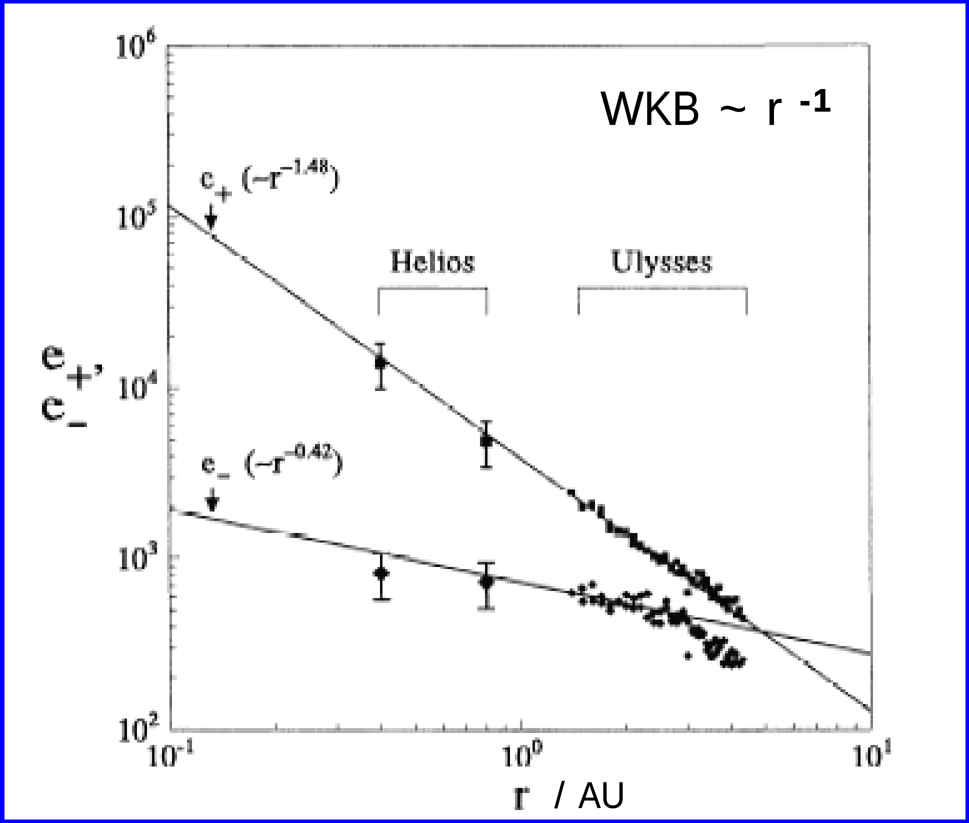
Alfvén waves and solar wind streams in the ecliptic plane

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



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

Alfvén waves in polar solar wind



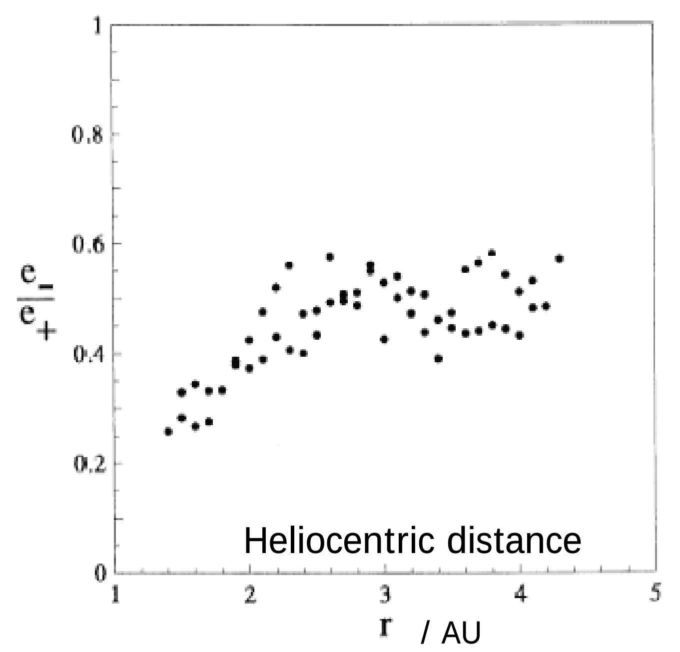
Radial variation of $e^{\pm}(r)$; wave amplitude at 1-h period is not sufficient to drive fast wind!

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

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

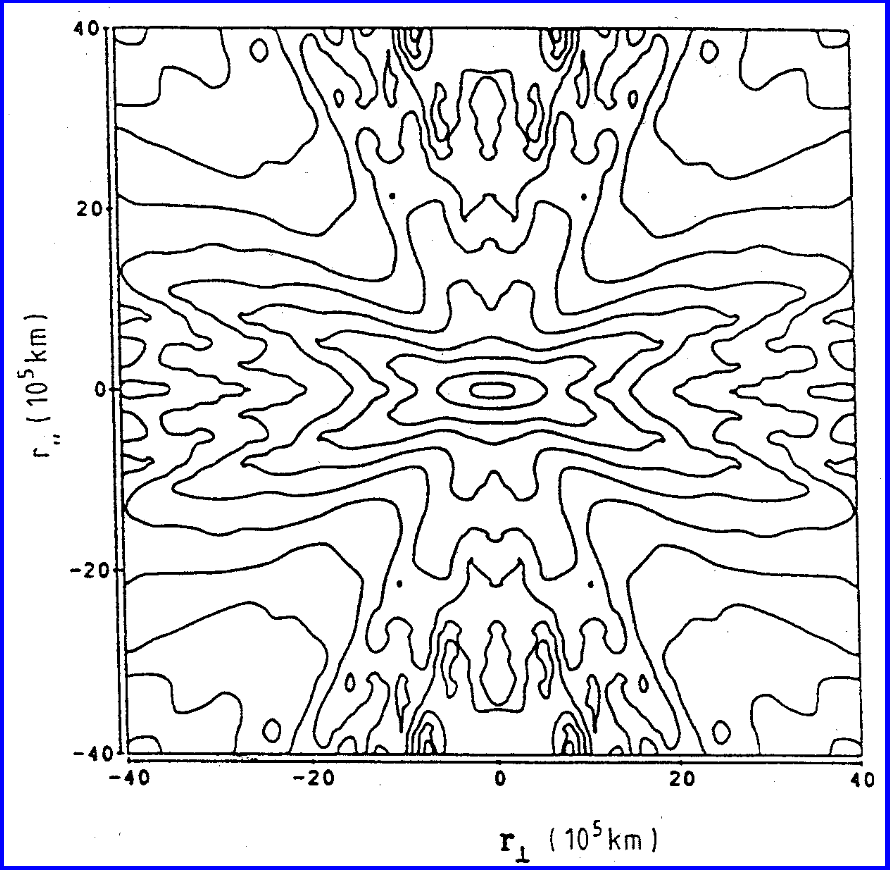
Turbulence energy: $e^{\pm} = 1/2\ (\mathbf{Z}^{\pm})^2$

Elsässer ratio: $r_e = e^-/e^+$



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

Anisotropy and dimension



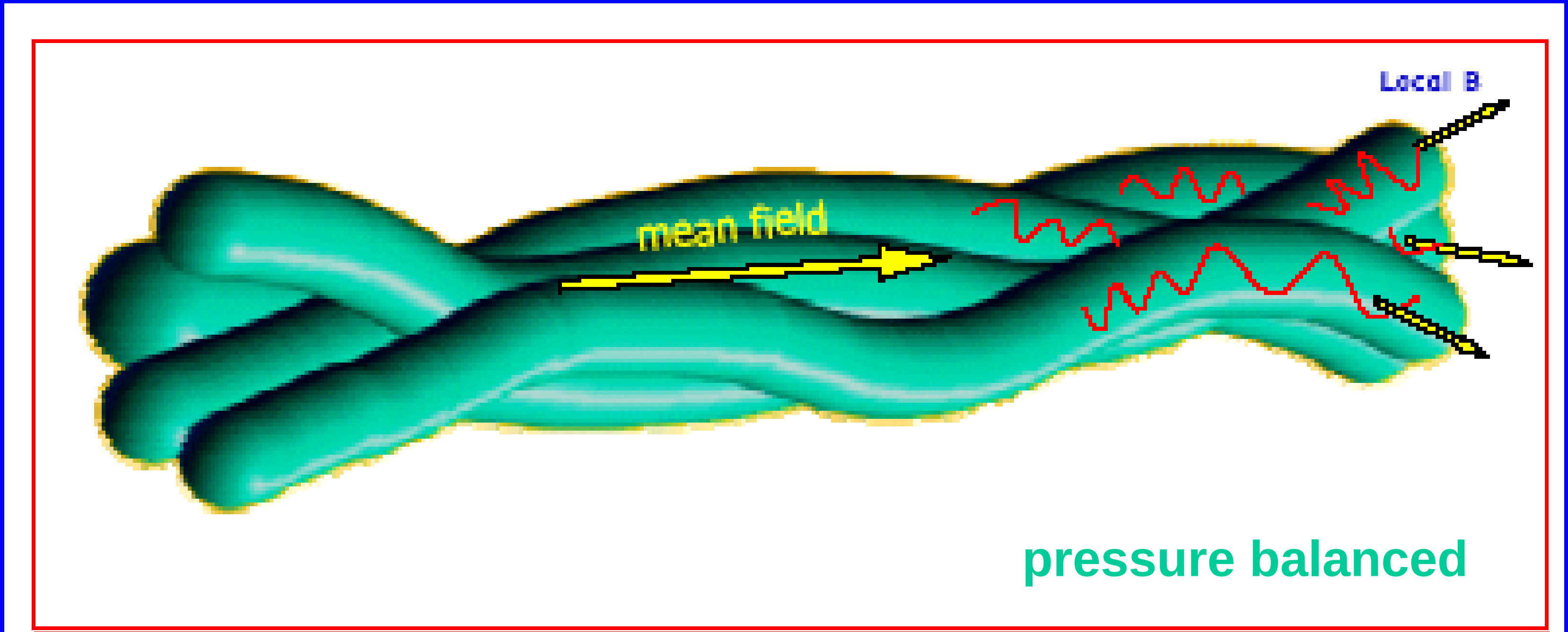
„Maltese cross“

- **Particle pitch-angle scattering is weaker than for isotropic MHD**
- **Compressible fluctuations are described by 2-D MHD**

Correlations: →
Alfvén waves and 2-D turbulence

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

Two-component model

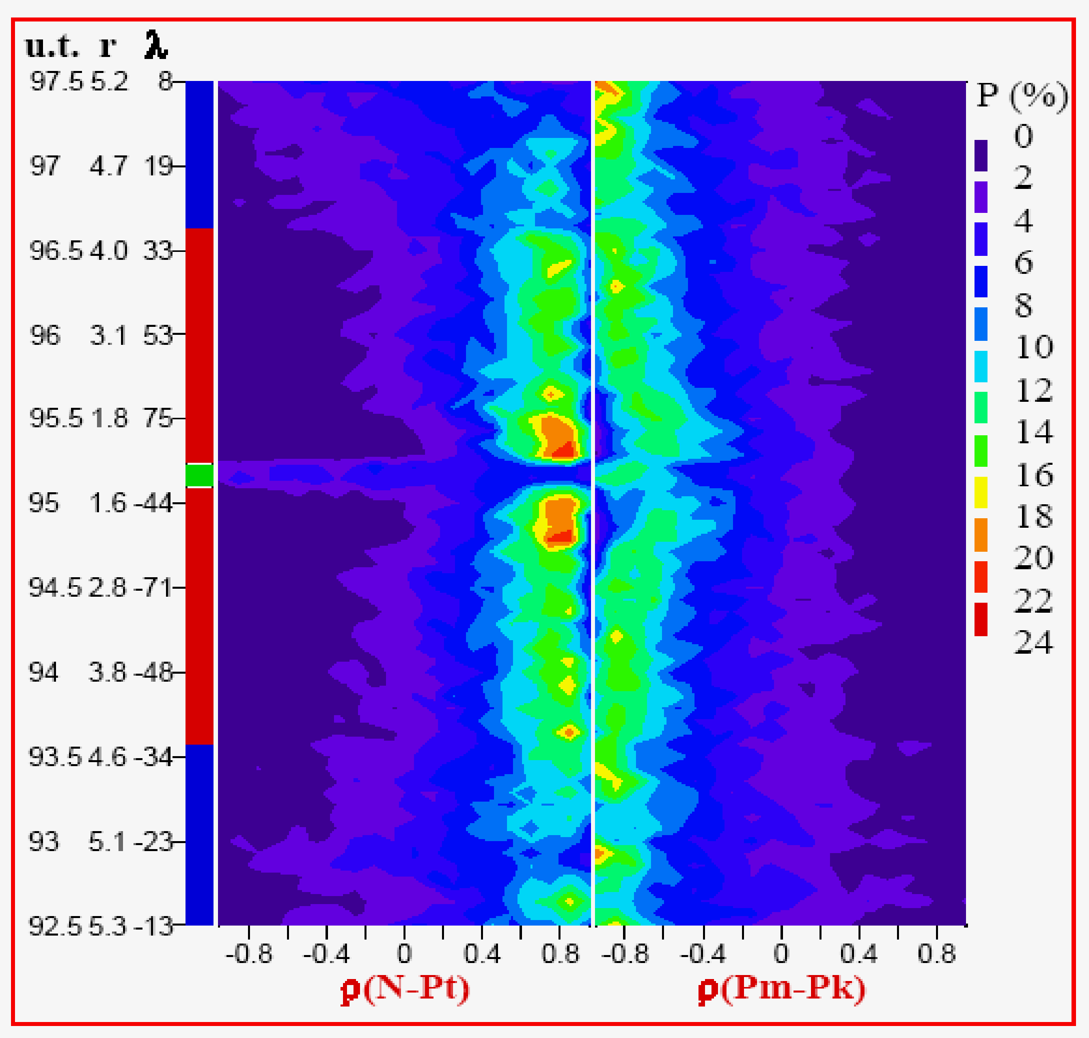


pressure balanced

Flux tube angular scale: 2° - 4°; supergranule: 20-30 Mm

- Alfvén waves parallel to the mean field
- 2-dimensional turbulence perpendicular
- Convected structures (discontinuities) and shocks

Compressive fluctuations



Colour coding:

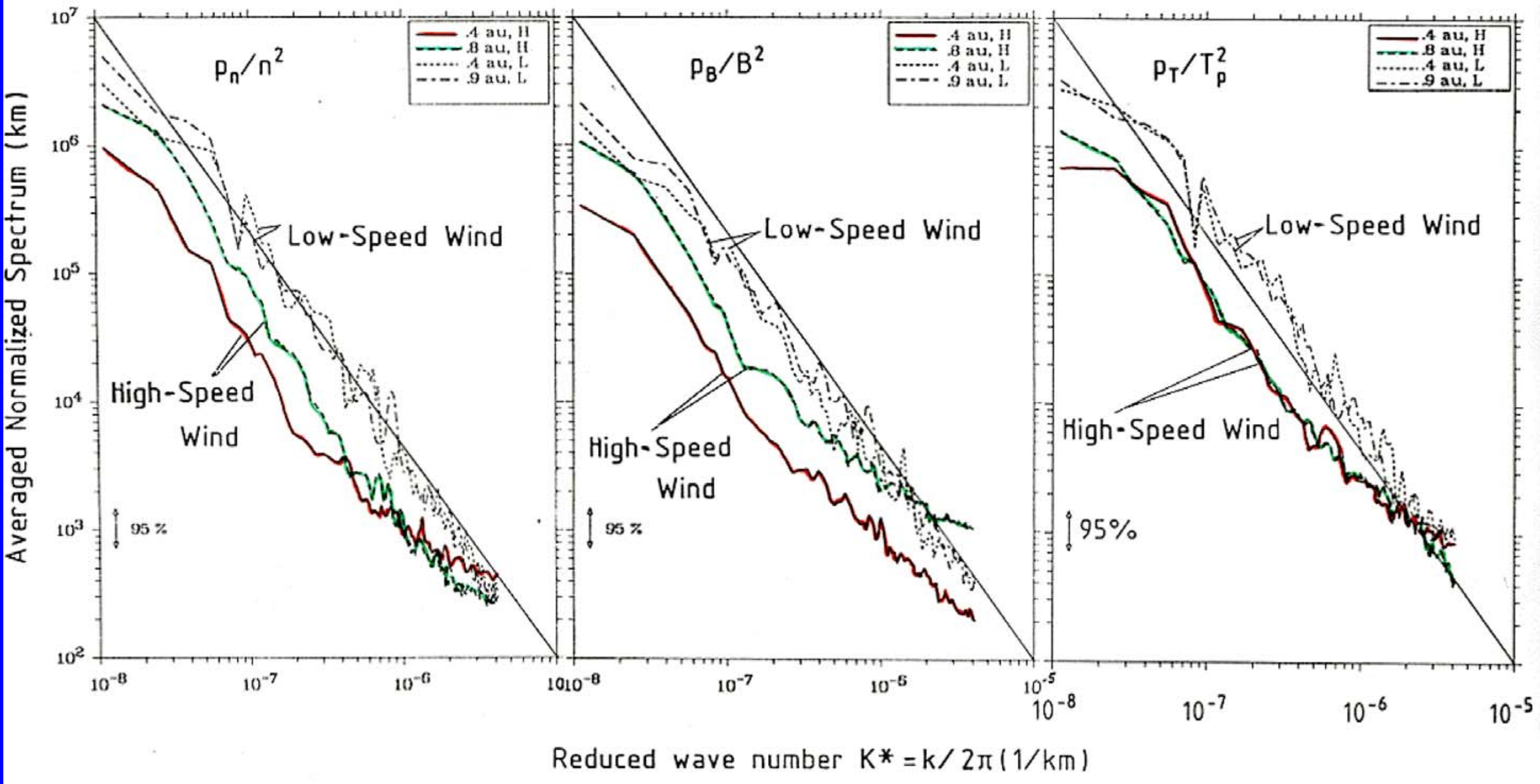
Correlation coefficient (per solar rotation) between total plasma pressure p_t and density n, and kinetic (thermal) p_k and magnetic p_m pressure, indicating magnetoacoustic slow mode type fluctuations.

Left scale:

Time, radial distance, and heliographic latitude of Ulysses.

Bavassano et al., Ann. Geophysicae., 2004

Compressive fluctuations in the solar wind

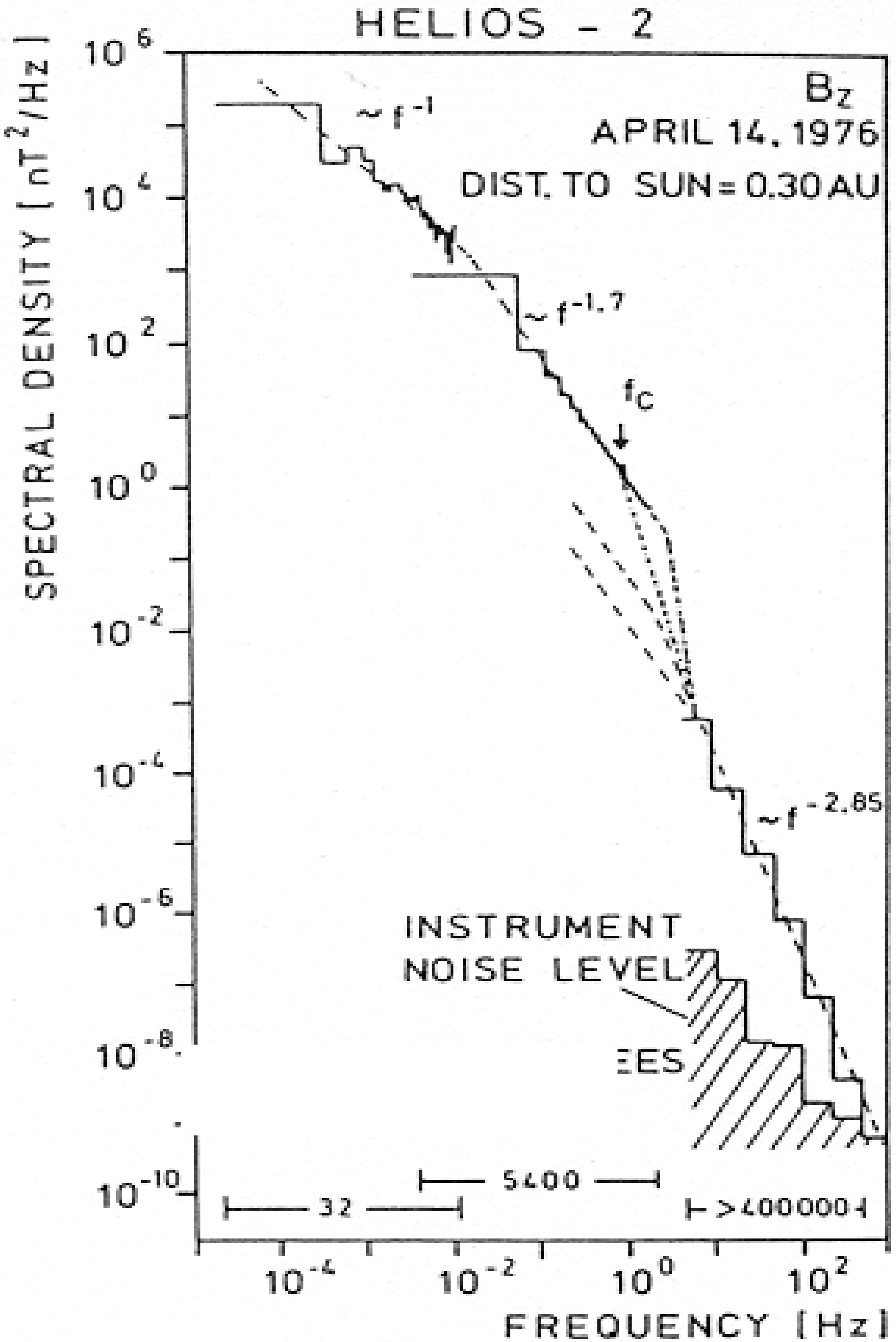


Marsch and Tu, JGR,
95, 8211, 1990

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

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?

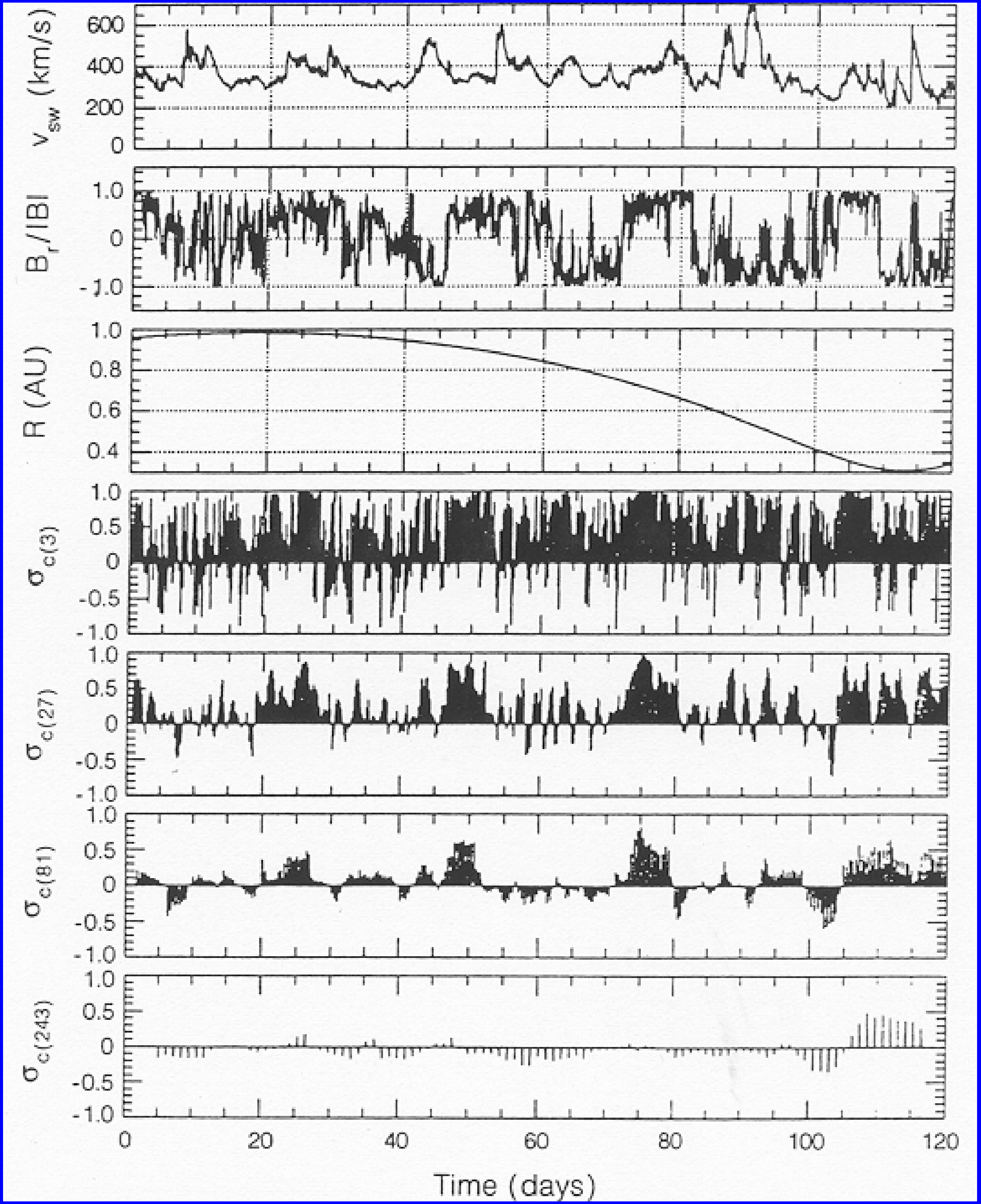
Evolution of cross helicity

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

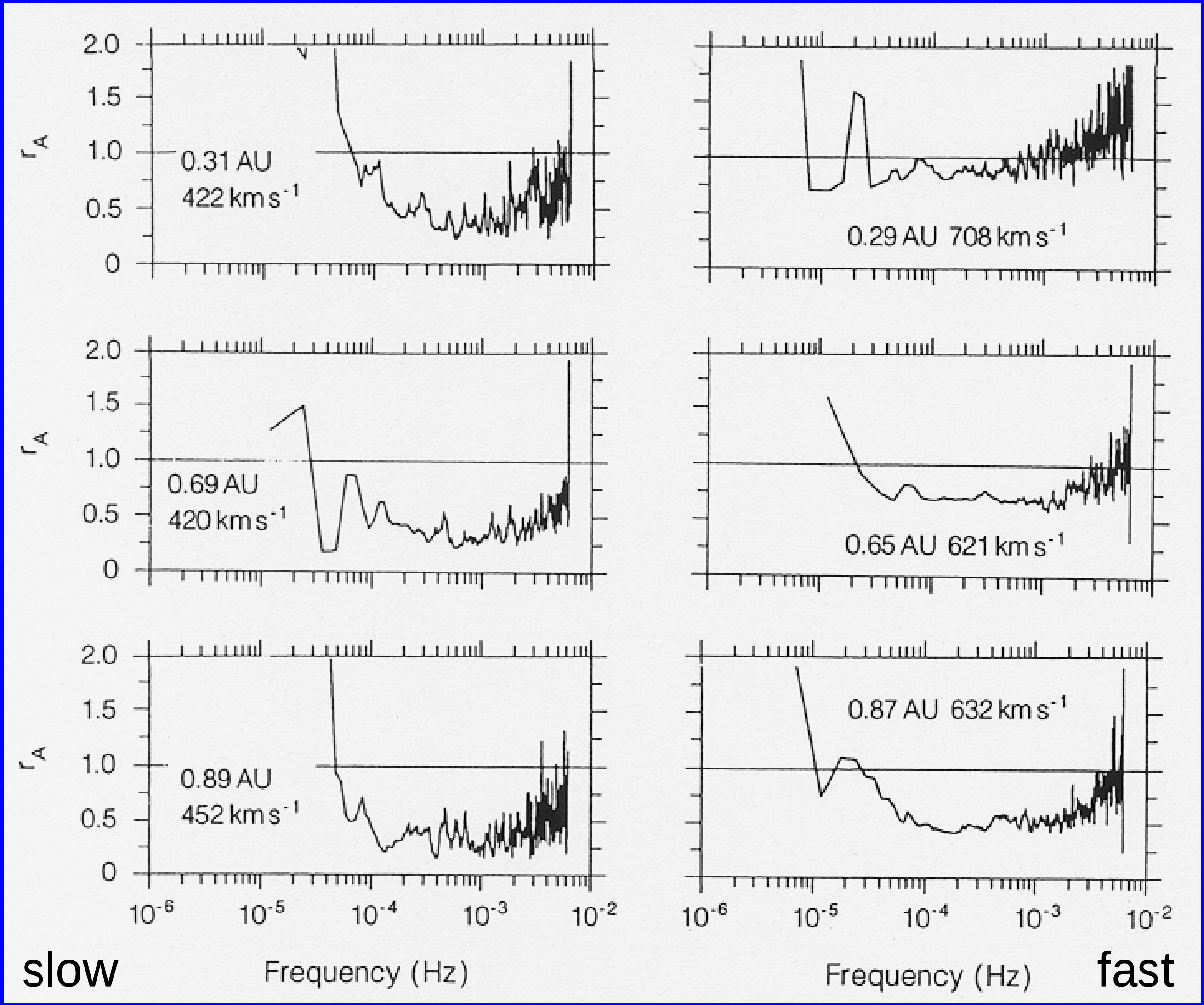
$$= (e^+ - e^-)/(e^+ + e^-)$$

Alfvénic correlations decay radially!

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



Alfvén ratio

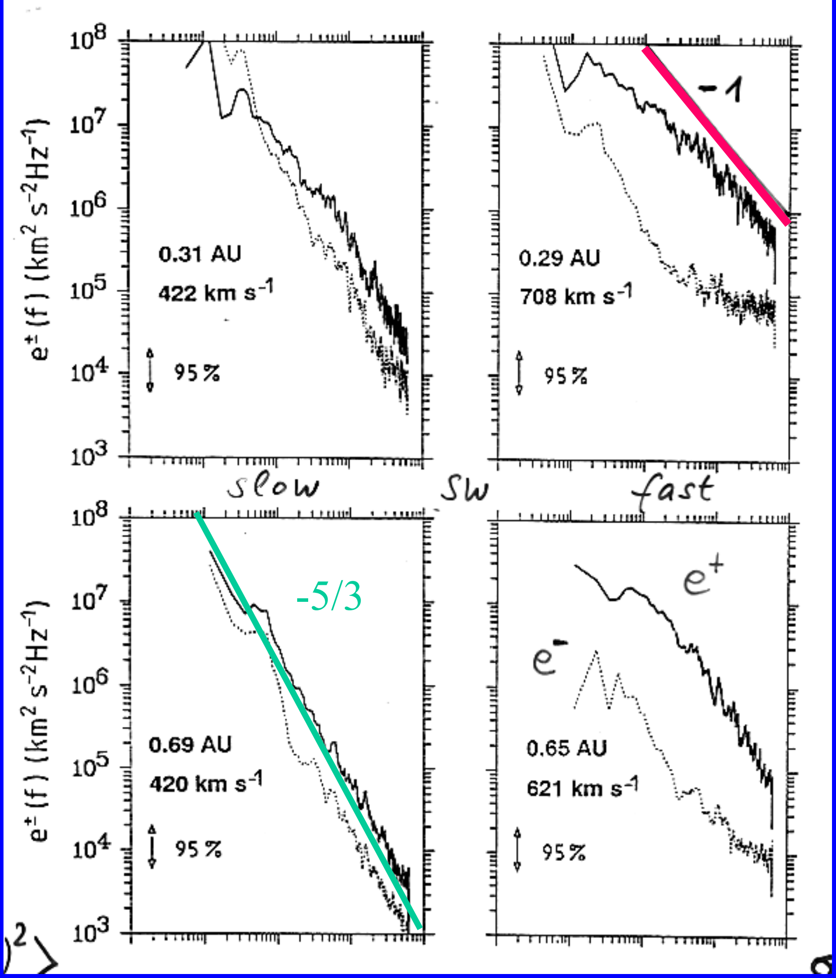


$r_A(\mathbf{k}) = e_V(\mathbf{k})/e_B(\mathbf{k})$

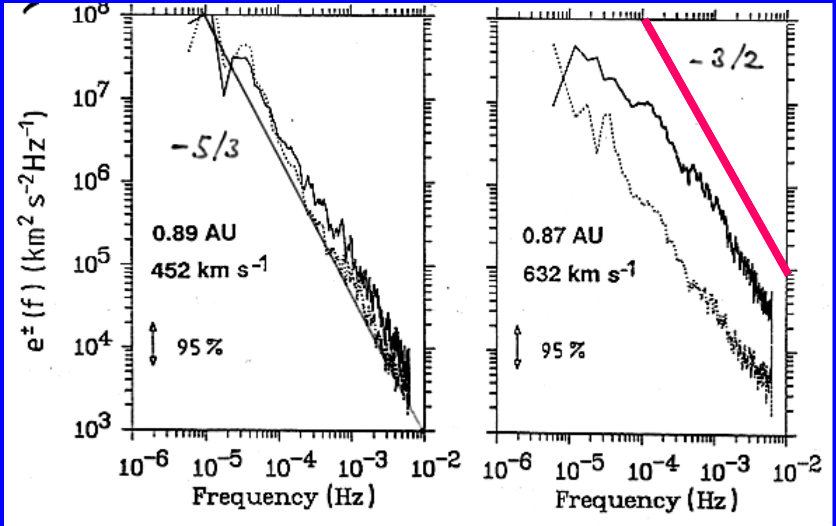
Spectrum

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

Spectral indices and spatial evolution of turbulence



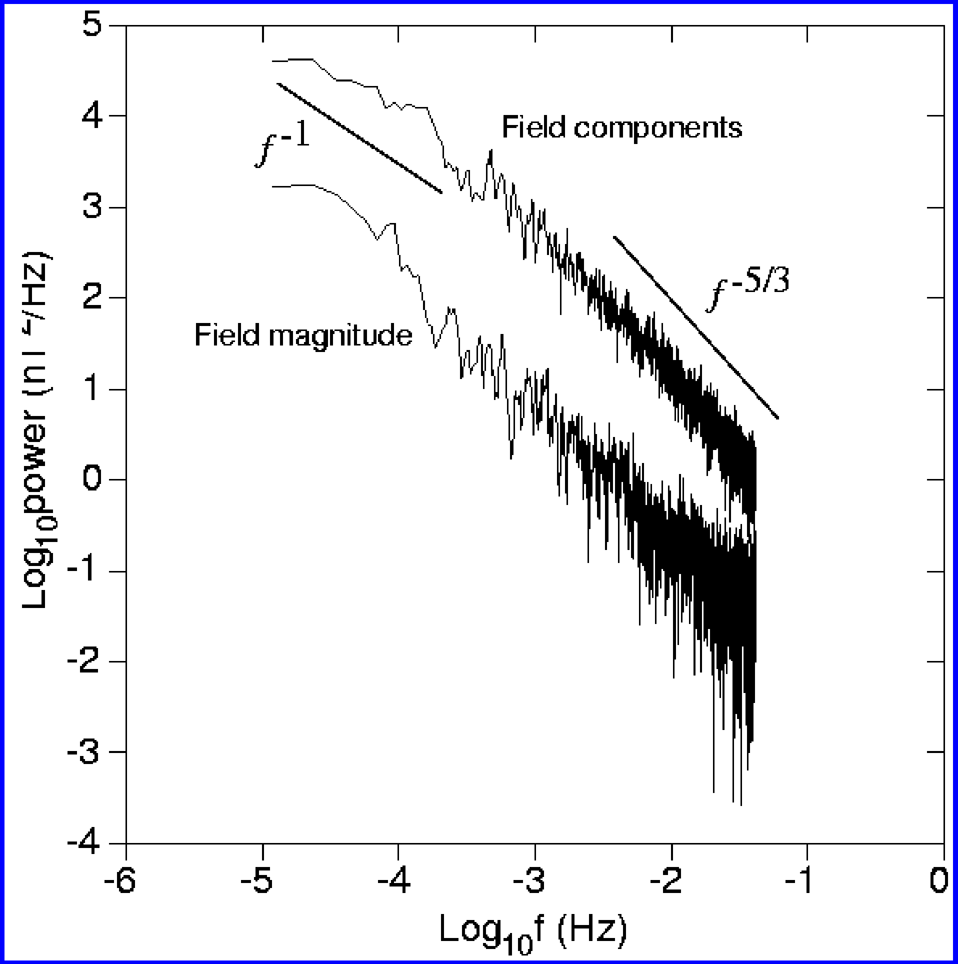
slow <-> fast wind

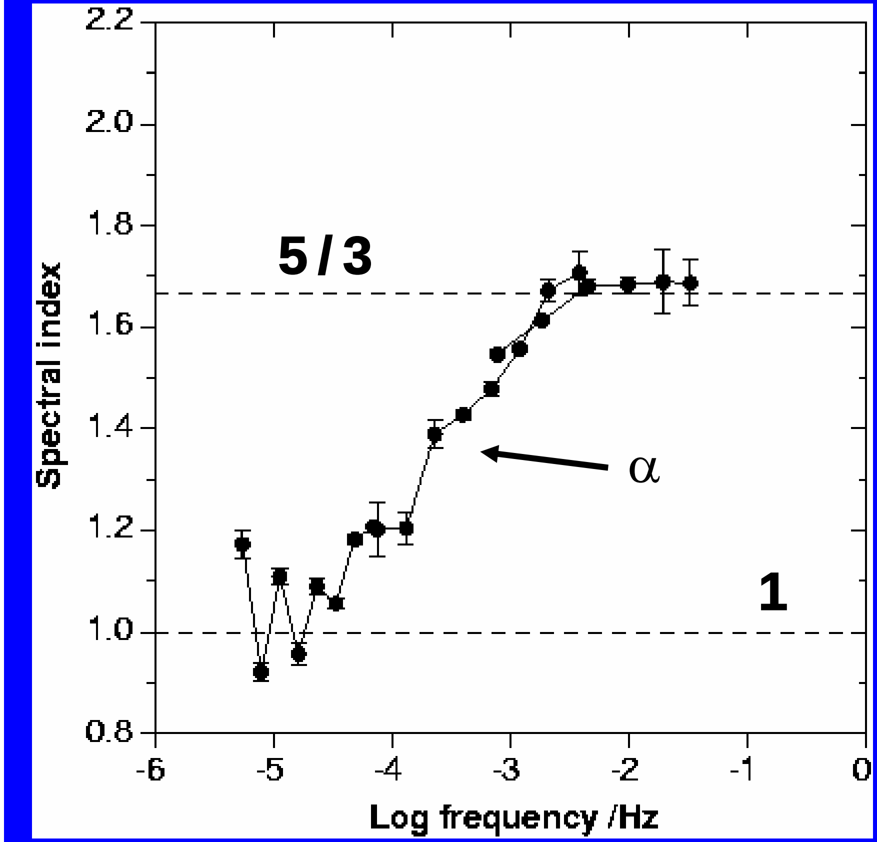


- **Spectra steepen!**
- **e$^+$ >> e$^-$, Alfvén waves dominate!**

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

Power spectrum evolution



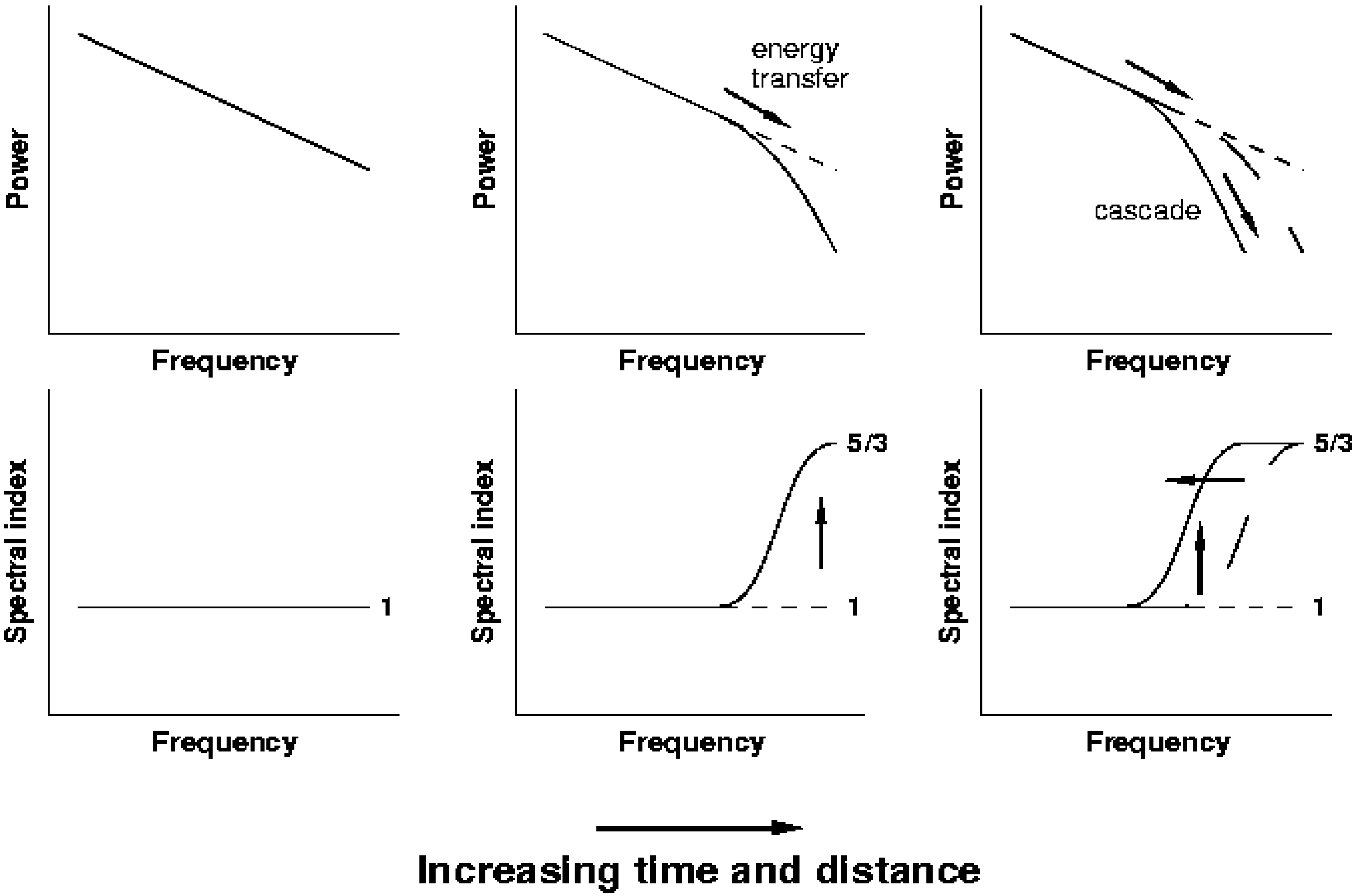


Turbulence spectrum:

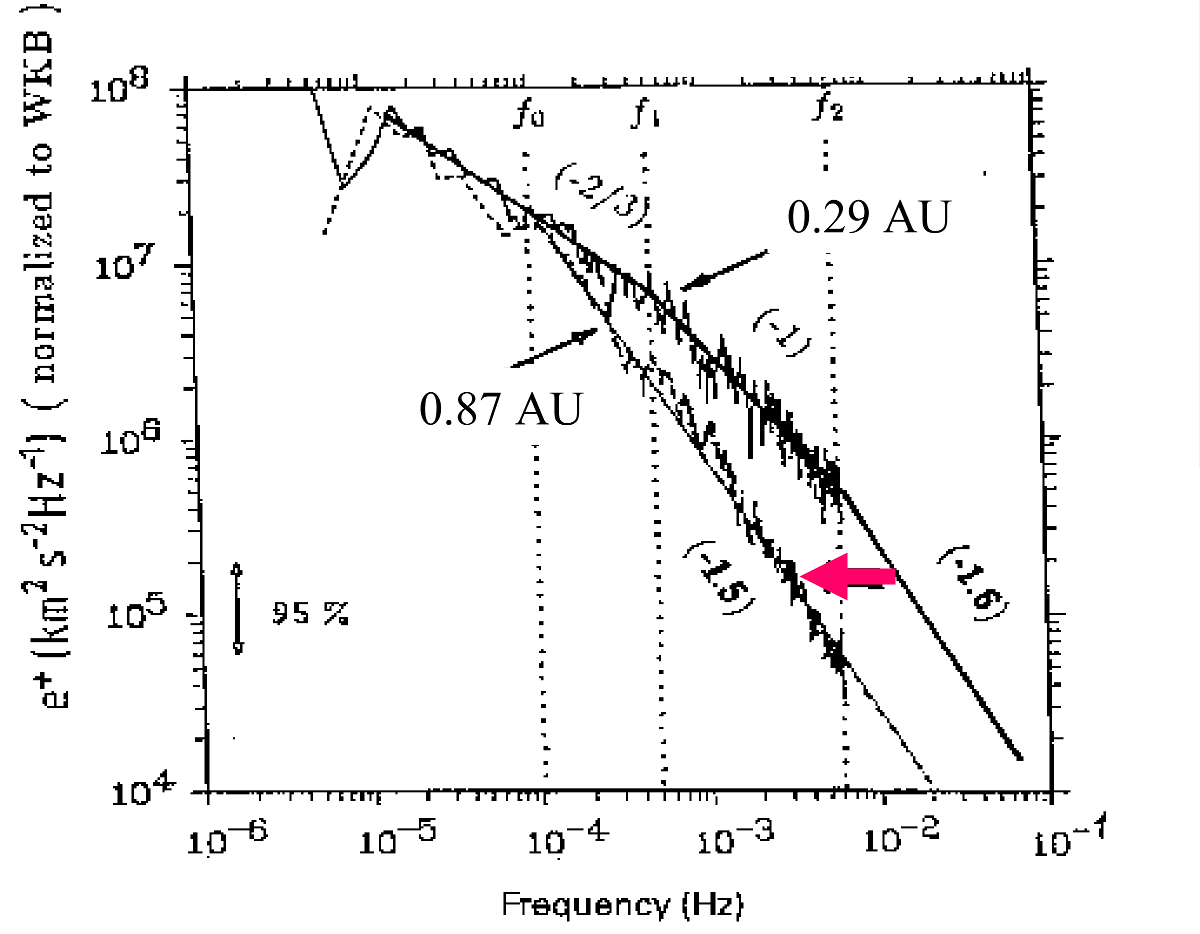
$e^{\pm}(f) = 1/2\ (\delta \mathbf{Z}^{\pm})^2 \sim (f/f_0)^{-\alpha}$

Horbury et al., JGR **101**, 405, 1996

Spectral evolution and turbulent cascade: slope steepening



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

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: $\tau \sim \ell / \delta Z_\ell$

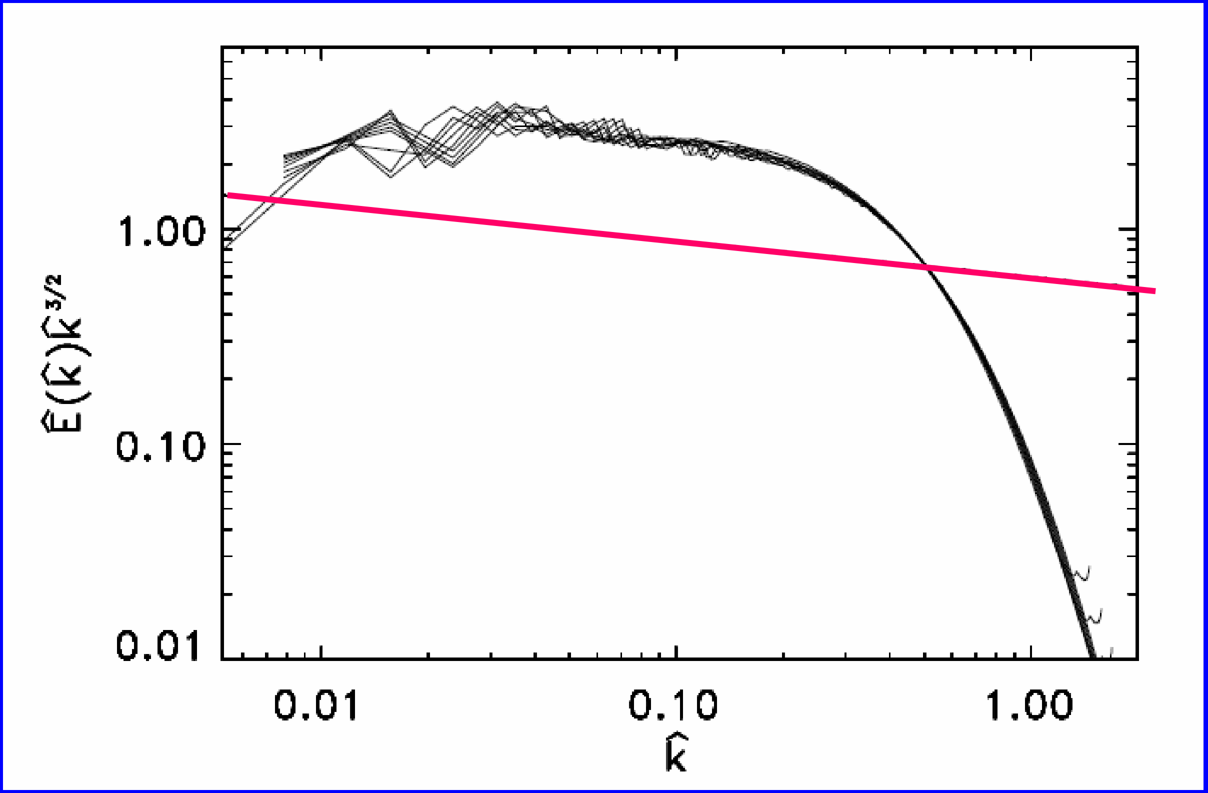
wavenumber: $k \sim 1/\ell$

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

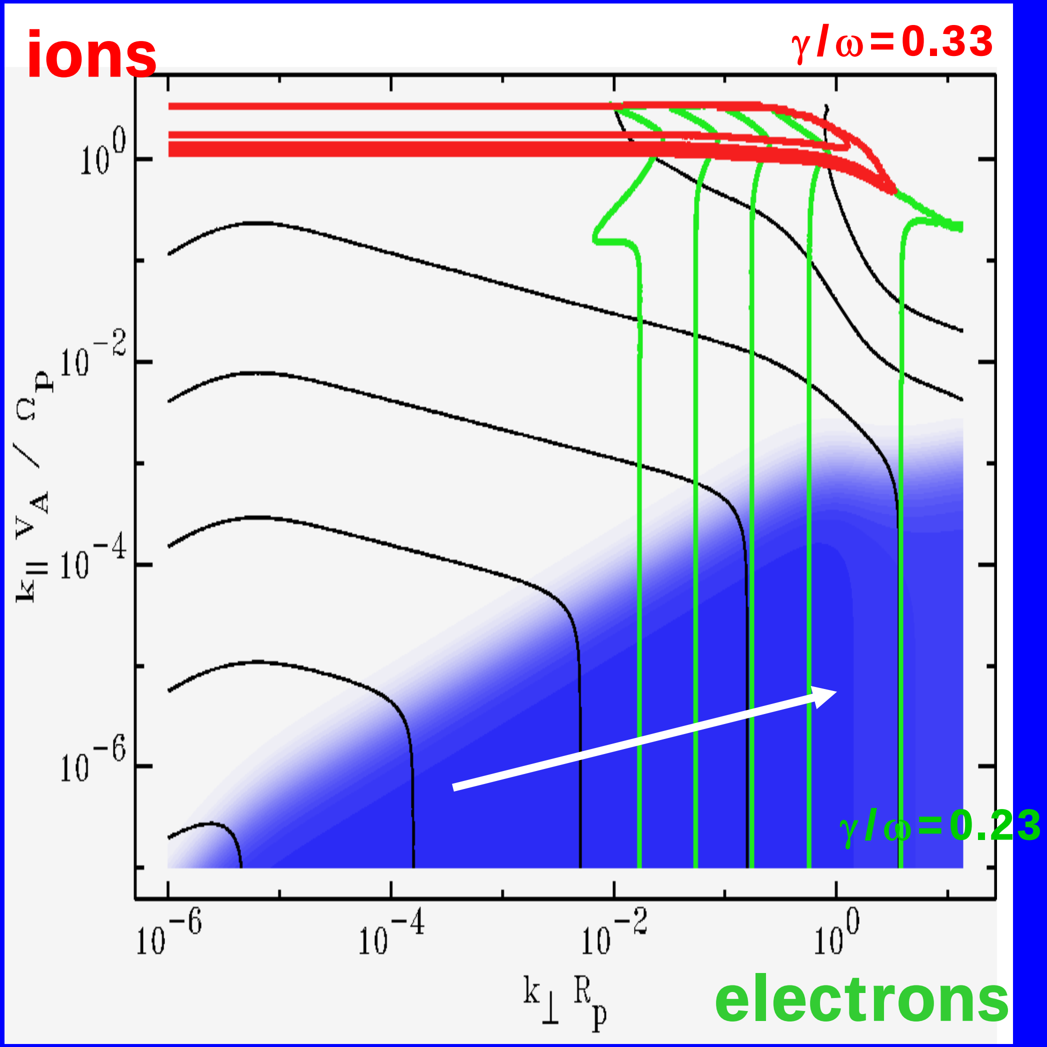
Müller and Biskamp, Phys. Rev. Lett., **84**, 475, 2000

MHD turbulence dissipation through absorption of plasma waves

- Viscous and Ohmic dissipation in collisionless plasma (coronal holes and fast solar wind) is not important
- Waves become dispersive (at high frequencies beyond MHD) in the multi-fluid or kinetic regime.
- Question: KAW or Alfvén-cyclotron dissipation?

- **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!**

Anisotropic MHD cascade



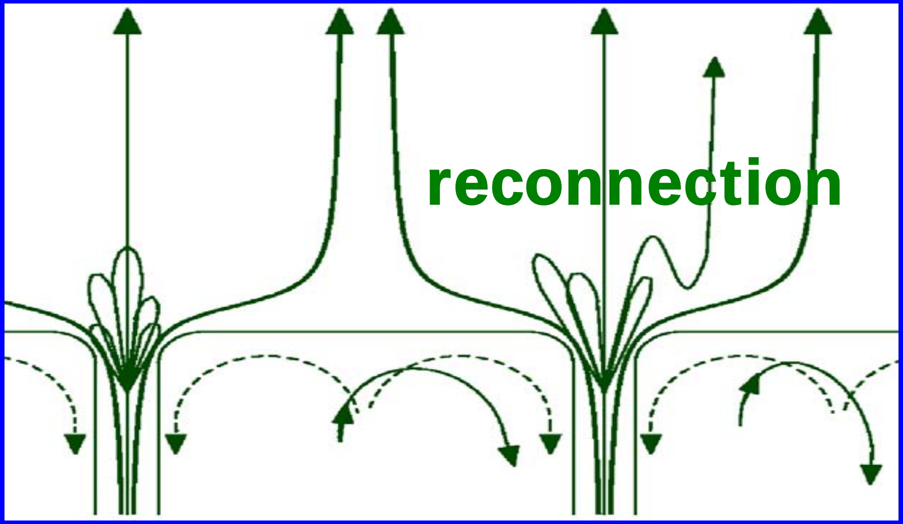
Isocontours of model spectrum E_k

- Simulations and analytic models predict cascade from small to large $k_\perp$, leaving $k_{||}$ unchanged.
- **Critical balance** assumes $\omega_A = k_{||} V_A \cong \omega_{NL} = k_\perp \delta V$ (Goldreich and Sridar, ApJ. 1995, 1997)
- **Kinetic Alfven wave** (KAW) with large $k_\perp$ does not necessarily have a high ω_A.
- In a low-beta plasma, KAWs are Landau-damped, heating **electrons** preferentially!

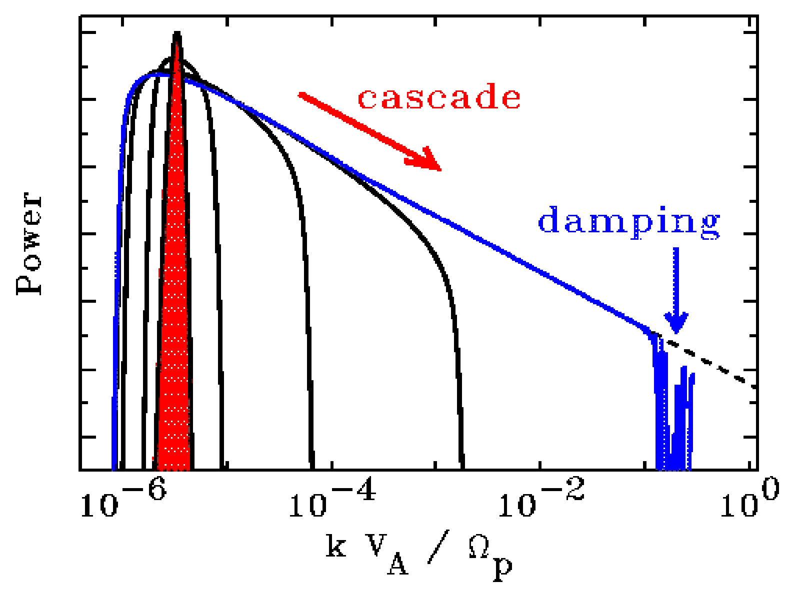
Cranmer, 2010

Cyclotron wave generation

Base generation by, e.g., “microflare” reconnection in the lanes that border convection cells (see Axford and McKenzie, 1997).

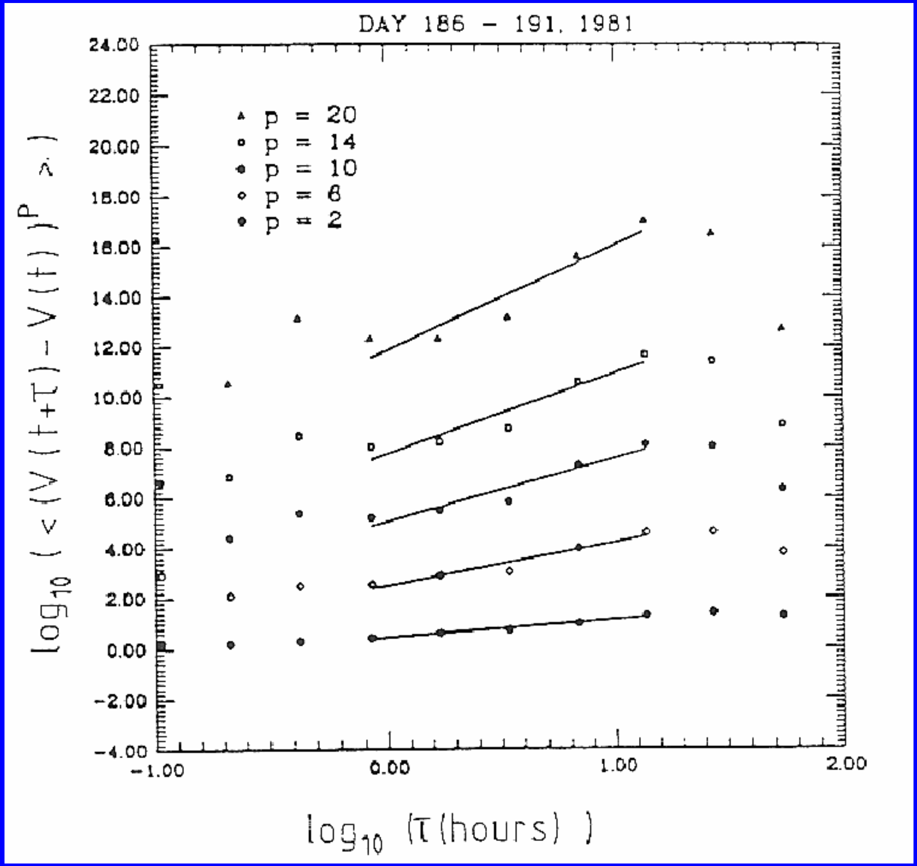


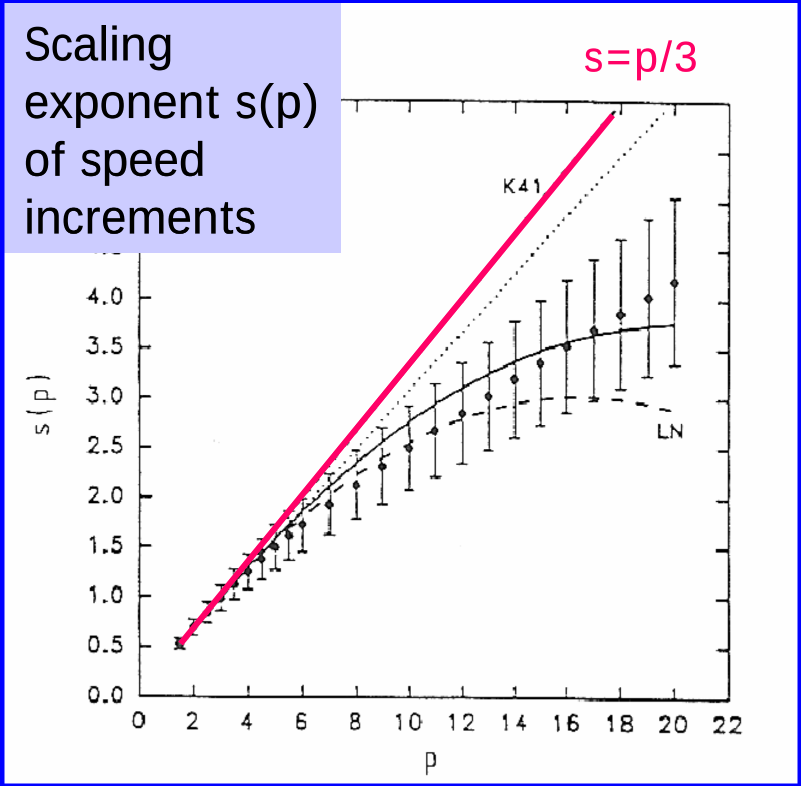
Secondary generation by low-frequency Alfven waves being converted by parallel cascading into cyclotron waves gradually in the corona.



Structure function and scaling

Voyager 2 near 8.5 AU





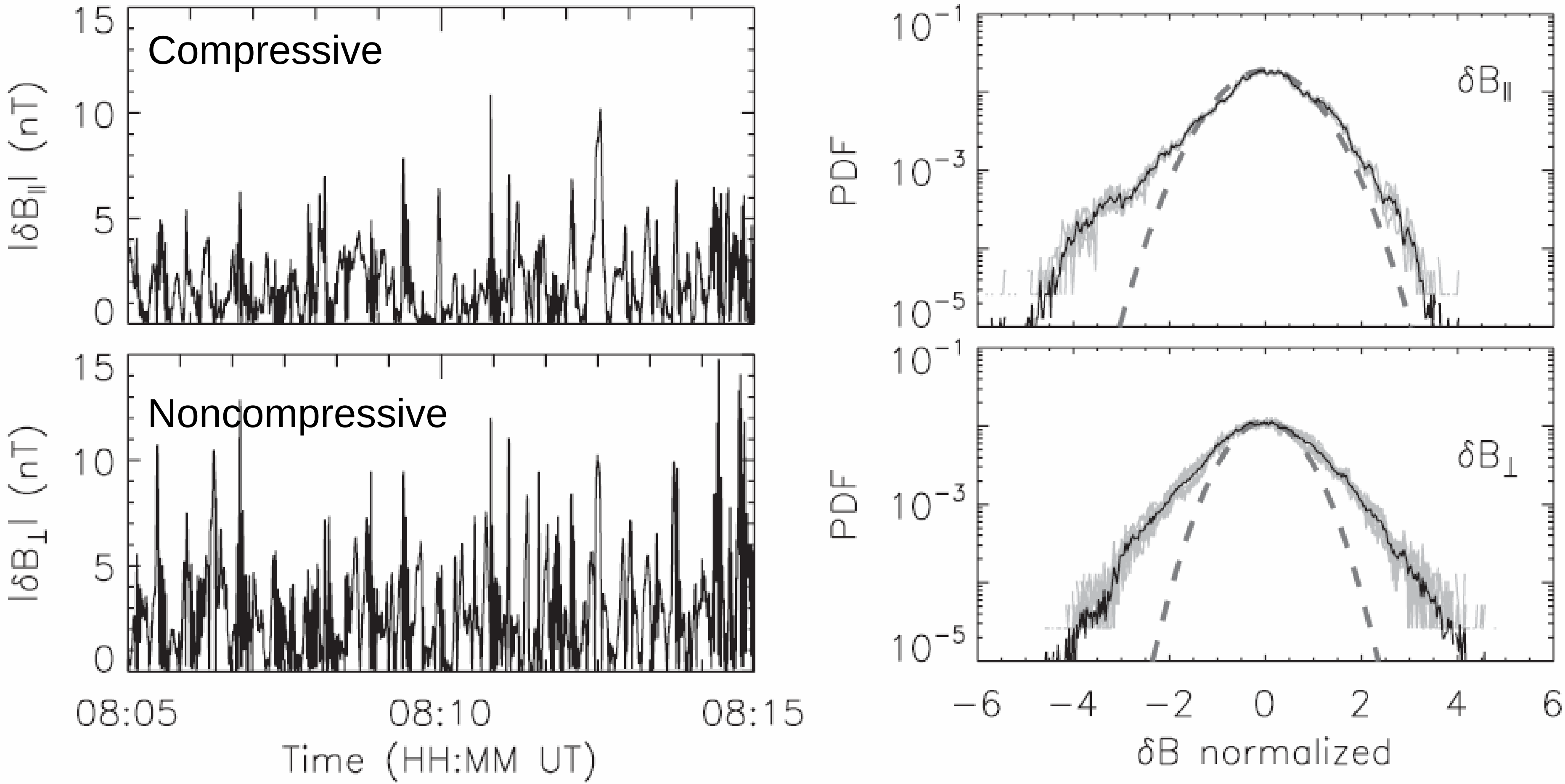
Scaling exponent s(p) of speed increments

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

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

Intermittency at the bowshock

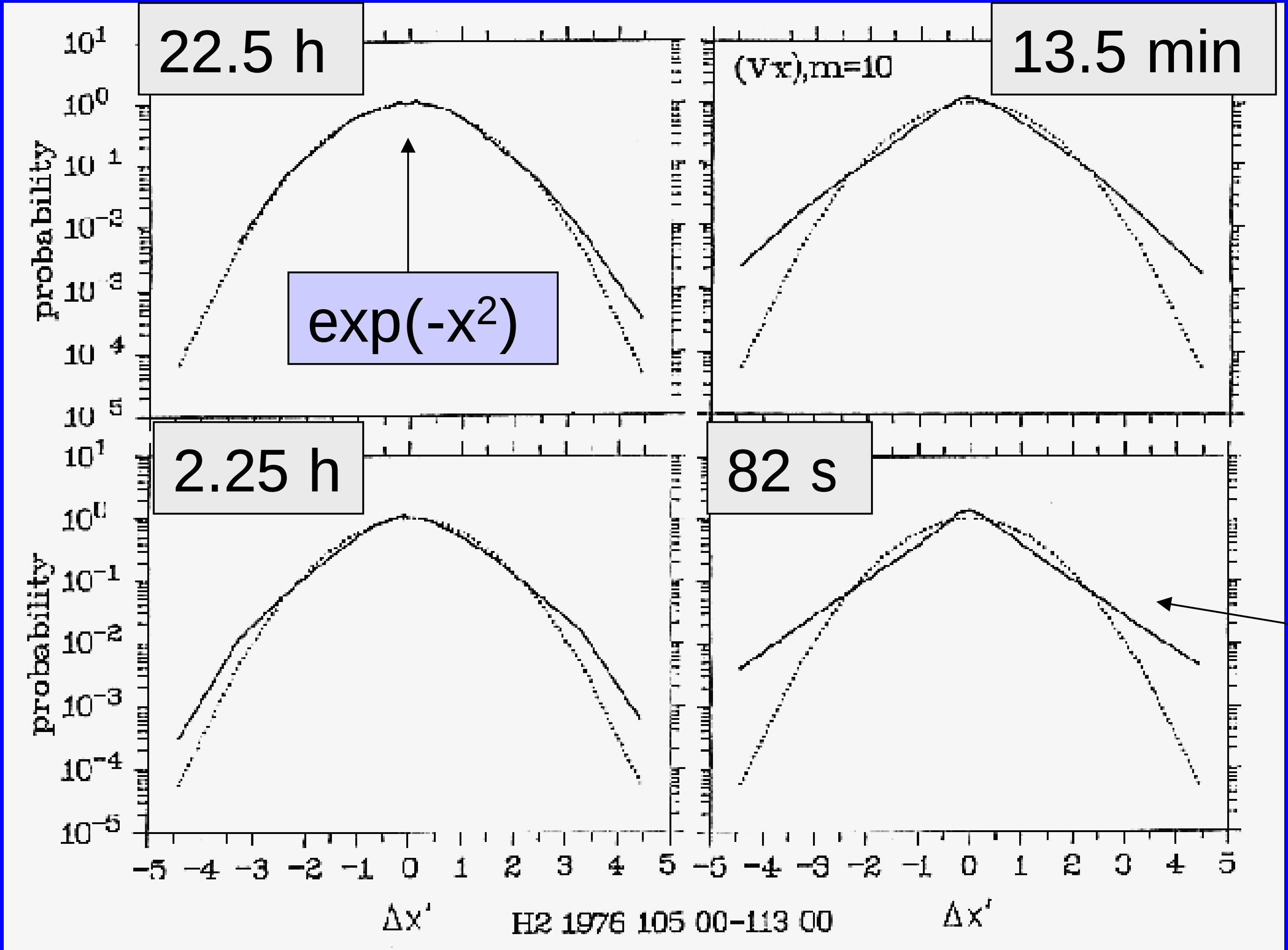


- Kolmogorov -5/3 spectra
- Non-Gaussians tails (F=3.5 – 4.6)

Four-point CLUSTER data

Narita et al., PRL., **97**, 191101, 2006

Probability distribution functions



22.5 h

13.5 min

2.25 h

82 s

$\exp(-x^2)$

$\exp(-x)$

Helios:
fast SW,
V_x radial
component
of flow
velocity

Non-Gaussian statistics at small scales!

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

Summary

- Solar wind is a weakly anisotropic 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