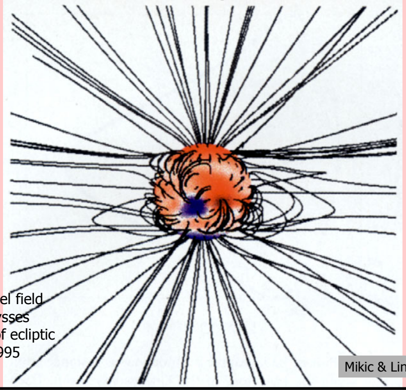
Waves, structures and turbulences

- Fluctuations: scales and parameters
- Magnetohydrodynamic waves
- Structures and Alfvénic fluctuations
- Turbulence spectra and evolution
- Plasma waves and dispersion
- Shocks and discontinuities

The Sun' open magnetic field lines



MHD model field during Ulysses crossing of ecliptic in early 1995

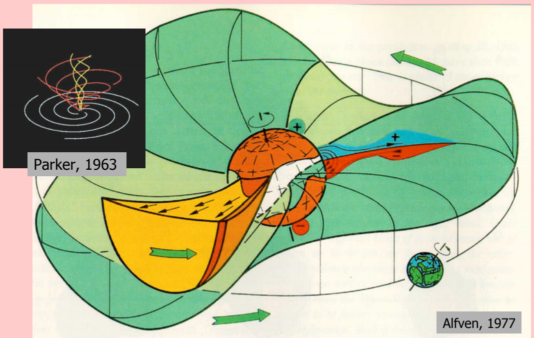
Mikic & Linker, 1999

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

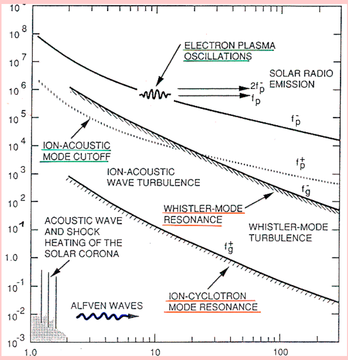
Spatial and temporal scales

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

Plasma waves and frequencies

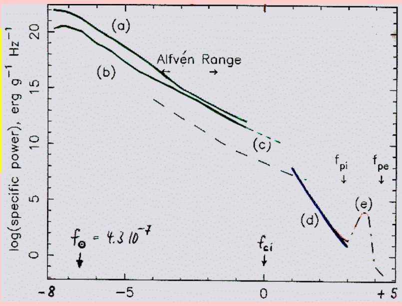


Non-uniformity leads to strong radial variations of the plasma parameters!

Gurnett, 1978

Power spectrum of fluctuations

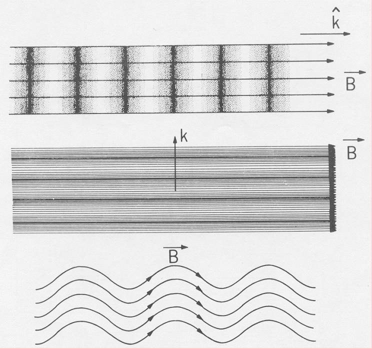
(a) Alfvén waves
(b) Slow and fast magnetosonic
(c) Ion-cyclotron
(d) Whistler mode
(e) Ion acoustic, Langmuir waves



Log(frequency /Hz)

Mangeney et al., 1991

Magnetohydrodynamic waves



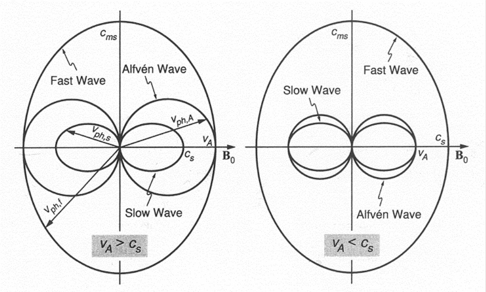
- Magnetosonic waves
compressible
- parallel slow and fast
- perpendicular fast

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

- Alfvén wave
incompressible
parallel and oblique

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

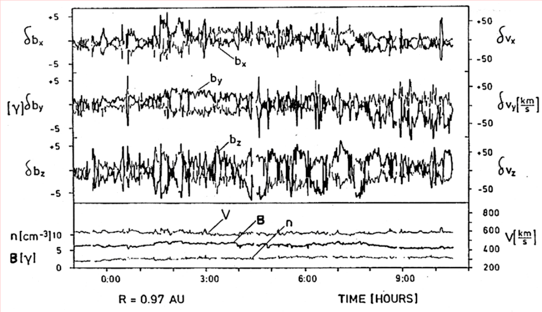
Phase velocities of MHD modes



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

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

Alfvénic fluctuations

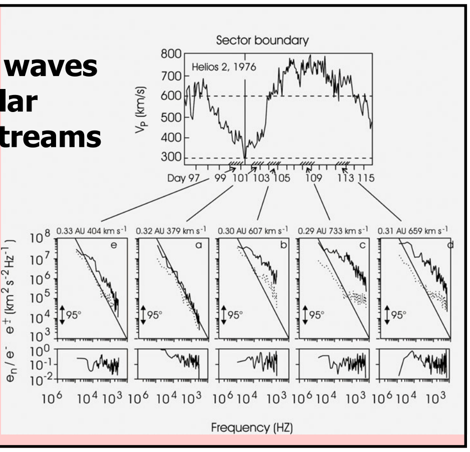


Neubauer et al., 1977

Helios

$\delta V = \pm \delta V_A$

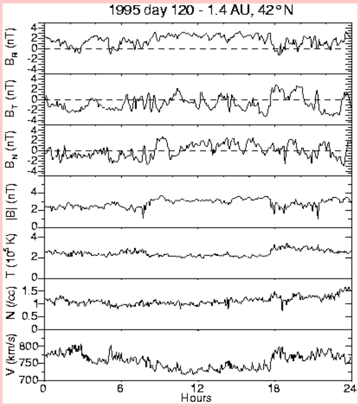
Alfvén waves and solar wind streams



- **High wave flux in fast streams**
- **Developed turbulence in slow streams**

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

Fluctuations

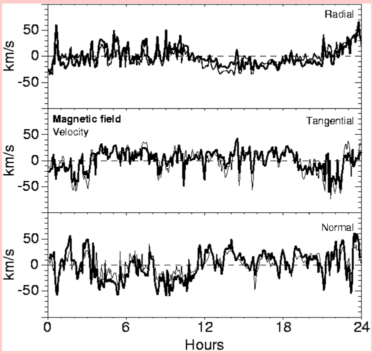


- Sharp changes in field direction
- Large Component variations

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

Horbury & Tsurutani, 2001

Alfvénic fluctuations (Ulysses)



Elsässer variables:

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

Turbulence energy:

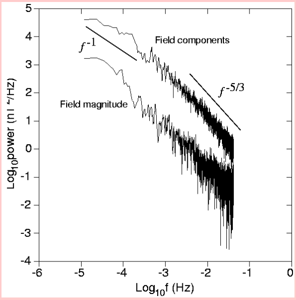
$e^{\pm} = 1/2\,(\mathbf{Z}^{\pm})^2$

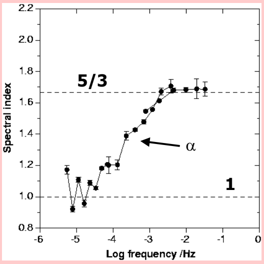
Cross helicity:

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

Horbury & Tsurutani, 2001

Power spectrum



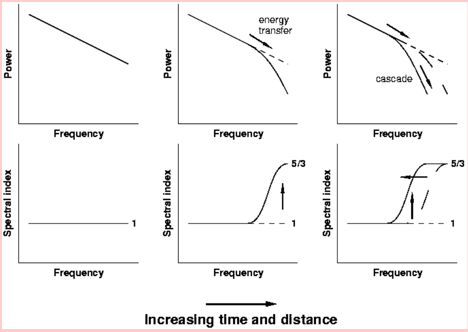


Horbury et al., JGR **101**, 405, 1996

Turbulence spectrum:

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

Spectral evolution and turbulent cascade: slope steepening



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.

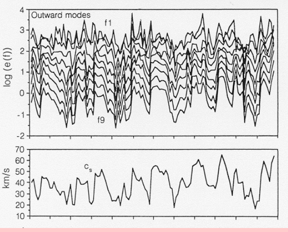
energy transfer rate:	$\varepsilon_\ell \sim (\delta Z_\ell)^2/\tau$
turnover time:	$\tau \sim \ell / \delta Z_\ell$
wavenumber:	$k \sim 1/\ell$
energy spectrum:	$e_k k \sim (\delta Z_\ell)^2$

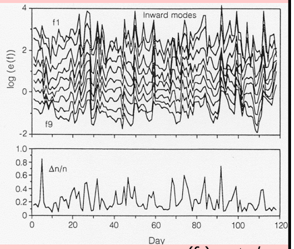
$$\varepsilon_\ell \sim \delta Z/\ell\,(\delta Z)^2 \sim e_k^{3/2}\,k^{5/2}$$

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

Daily fluctuations of energy spectra

Out: $e^+(f)$ (units of 1 km²s⁻²/day) In: $e^-(f)$





$e(f_9) \sim c_s$

$f_n = 1/\mathrm{day}\ 2^n$

$e(f_1) \sim \Delta n/n$

Grappin et al., J. Geophys. Res. **95**, 8197, 1990

Self-similar fluctuations

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*
- *Microphysics of dissipation*

Alfvénic correlations: Alfvénicity (cross helicity)

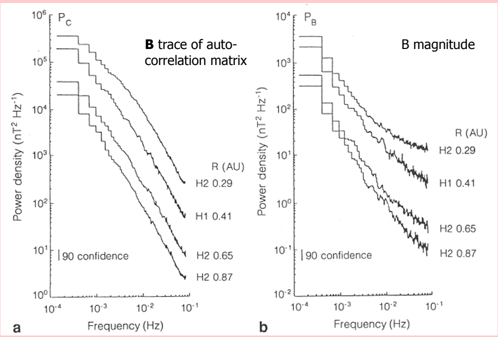
$\sigma_c = (e^+ - e^-)/(e^+ + e^-) = 2\langle \delta\mathbf{V}\bullet\delta\mathbf{V}_A\rangle / \langle (\delta V)^2 + (\delta V_A)^2 \rangle$

Magnetic versus kinetic energy: Alfvén ratio

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

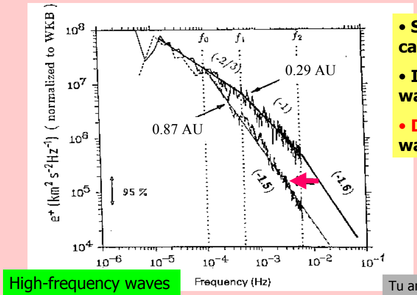
Scaling, non-linear couplings and cascading?

Radial evolution of spectral densities



Bavassano et al., J. Geophys. Res. **87**, 3617, 1982

Spectral evolution of Alfvénic fluctuations

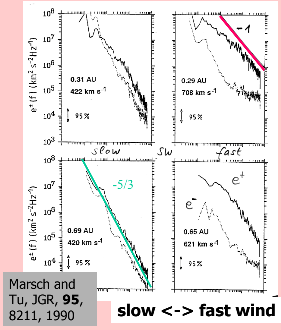


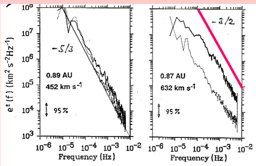
- **Steepening by cascading**
- **Ion heating by wave sweeping**
- **Dissipation by wave absorption**

High-frequency waves in the corona?

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

Spectral indices and spatial evolution of turbulence





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

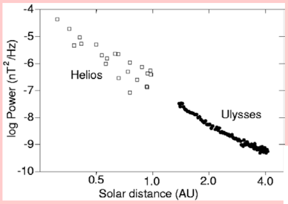
Marsch and Tu, JGR, **95**, 8211, 1990

slow <-> fast wind

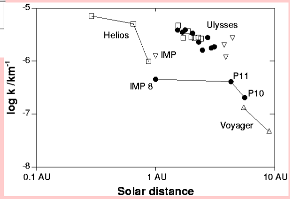
Solar wind turbulence

Parameter	Coronal Hole (open)	Current sheet (closed)
Alfvén waves:	**yes**	**no**
Density fluctuations:	**weak (<3%)**	**intense (>10%)**
Magnetic/kinetic turbulent energy:	**≅ 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**

Radial variation of spectral features



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

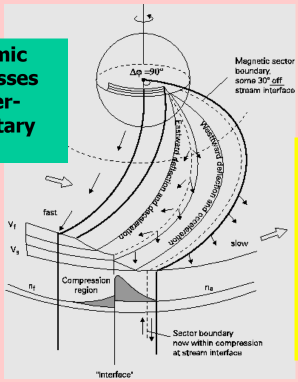


- Turbulence intensity declines with solar distance
- Wave amplitudes is consistent between Helios and Ulysses in fast streams from coronal holes

Horbury & Tsurutani, 2001

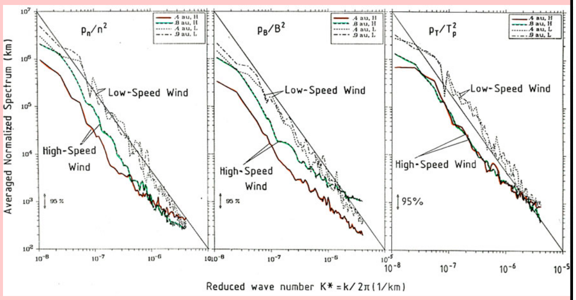
Stream interaction region

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)**

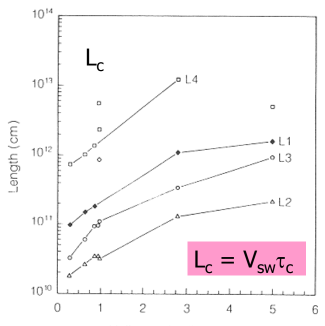
Compressive fluctuations in the solar wind



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

Kolmogorov-type turbulence

Correlation length of turbulence



$L_c = V_{sw}\tau_c$

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

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

Helios, Voyager

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

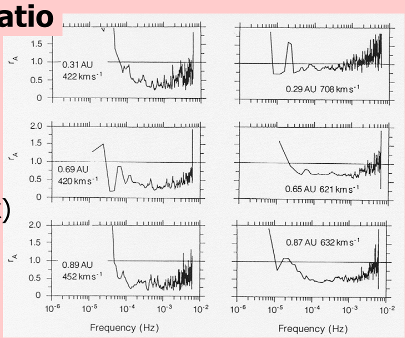
$H_m = \int d^3x\, (\mathbf{A} \cdot \mathbf{B})$ Magnetic helicity

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

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

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

Alfvén ratio



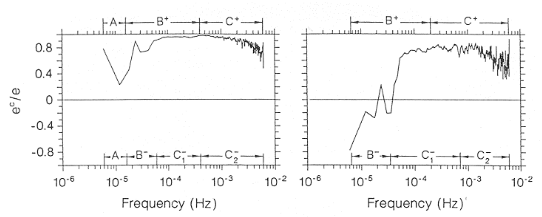
$r_A(\mathbf{k}) = e_V(\mathbf{k})/e_B(\mathbf{k})$

Spectrum:

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

Cross helicity

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



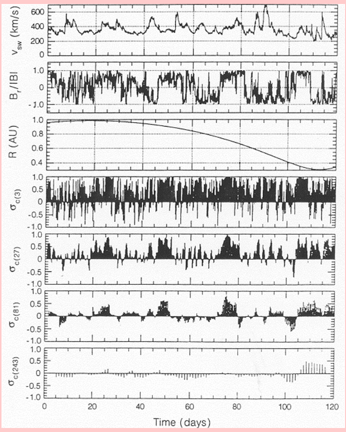
Tu et al., J. Geophys. Res. **95**, 1739 , 1989

High Alfvénic correlations

Evolution of cross helicity

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

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



Alfvénic correlations

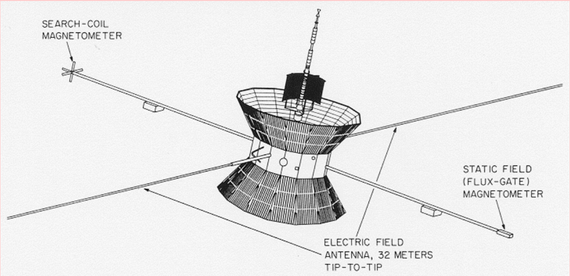
Roberts et al., J. Geophys. Res. **92**, 12023 , 1987

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**

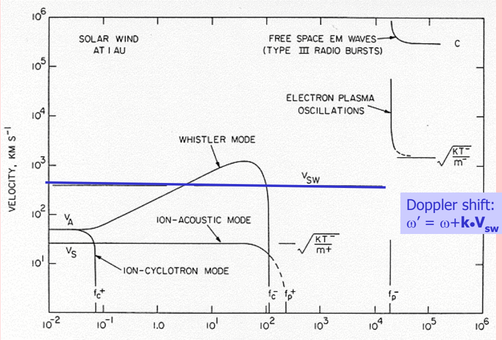
- **Turbulence dissipation involves absorption (or emission by instability) of kinetic plasma waves!**
- **Cascading and spectral transfer of wave and turbulence energy is not well understood in the dispersive dissipation domain!**

The Helios spacecraft



Twin spacecraft for heliospheric physics in highly eccentric orbits with perihelion at 0.3 AU during the years 1974-1986

Phase velocities of wave modes



Doppler shift:
$\omega' = \omega + \mathbf{k} \cdot \mathbf{V}_{sw}$

Gurnett, 1978

Electrostatic waves

Plasma frequency

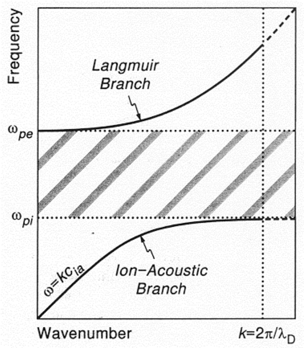
$\omega_{pe}^2 = 4\pi e^2 n_e / m_e$

Ion acoustic speed

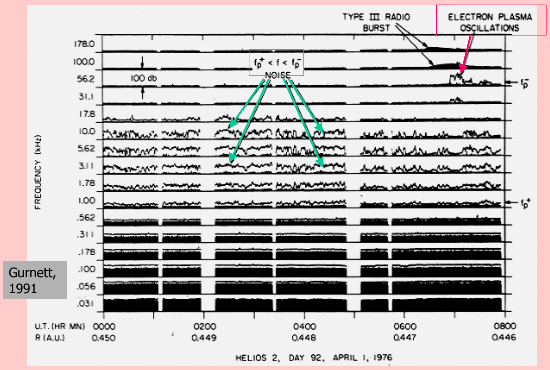
$c_{ia}^2 = \gamma_e k_B T_e / m_i$

Debye length

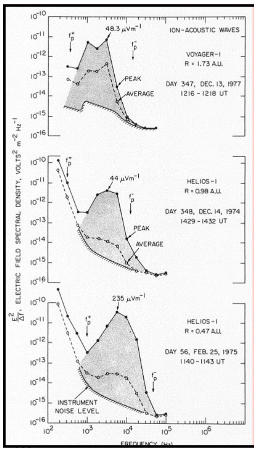
$\lambda_D^2 = k_B T_e / (4\pi e^2 n_e)$



Ion acoustic and Langmuir waves



Gurnett, 1991

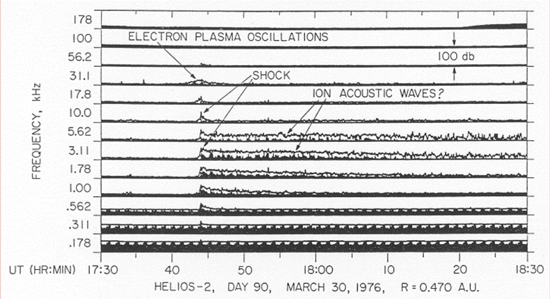


Electric field power spectrum

- No power law but hump
- Abrupt decline at f_p^- indicates electron Landau damping (absorption)
- Spectrum at frequencies between 10^3 Hz and 5×10^4 Hz is mainly due to Doppler-shifted ion acoustic waves

Gurnett & Anderson, JGR **82**, 632, 1977

Ion acoustic waves at a shock

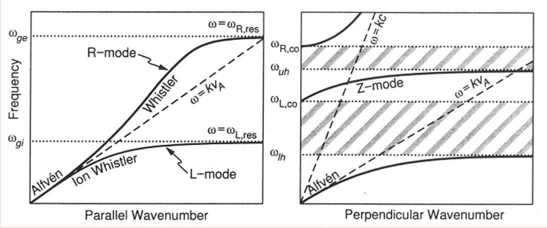


Gurnett et al., JGR **84**, 541, 1979

$\omega = \omega_s + \mathbf{k} \cdot \mathbf{V}$

$\omega_s = c_s k/(1+k^2\lambda_D^2)^{1/2}$

Electromagnetic waves



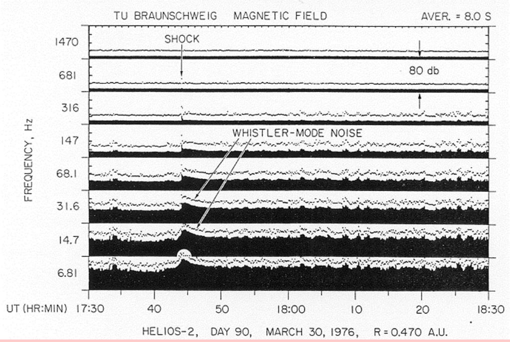
Ion gyrofrequency

$\omega_{gi} = q_i B/(m_i c)$

Upper/lower hybrid frequency

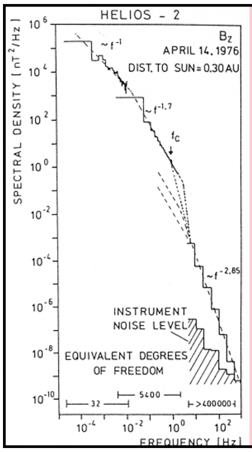
$\omega_{uh}^2 = \omega_{pe}^2 + \omega_{ge}^2$; $\omega_{lh}^2 = \omega_{ge}\omega_{gi}$

Whistler mode waves at a shock



Gurnett et al., JGR **84**, 541, 1979

$\omega_w = \omega_{pe}(kc/\omega_{ge})^2$



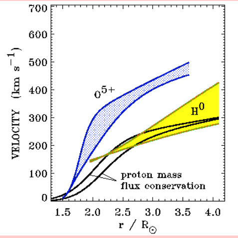
Magnetic field power spectrum

- 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

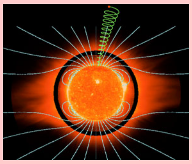
Denskat et al., JGR **54**, 60, 1983

Oxygen and hydrogen velocities in coronal holes

Outflow velocities



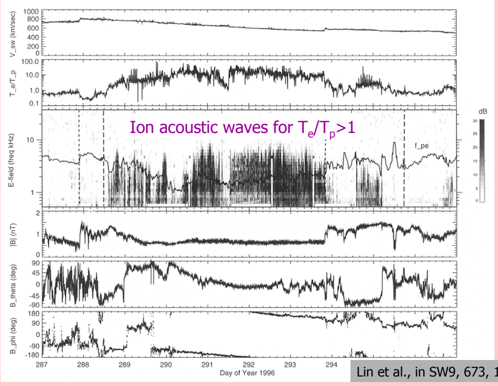
Preferential acceleration of oxygen!



Cranmer et al., Ap. J., **511**, 481, 1998

- **Magnetic mirror in polar coronal hole**
- **Cyclotron resonance ⇒ increase of μ_O**

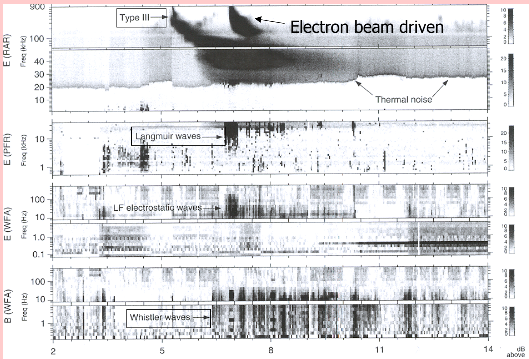
Solar wind data in a magnetic cloud



Ion acoustic waves for $T_e/T_p>1$

Lin et al., in SW9, 673, 1999

Ulysses wave data - day 73 in 1995



McDowell and Kellog, 2001

Power in grey scale in dB above noise

Discontinuities and shocks

Continuity of the mass flux and magnetic flux:

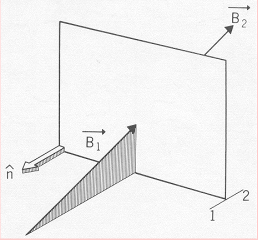
$B_n = B_{1n} = B_{2n}$

$G_n = \rho_1(V_{1n}-U) = \rho_2(V_{2n}-U)$

U is the speed of surface in normal direction; **B** magnetic field vector; **V** flow velocity. Mach number: M = V/C; C is the wave phase speed.

Shock: $G \neq 0$

Discontinuity: $G = 0$



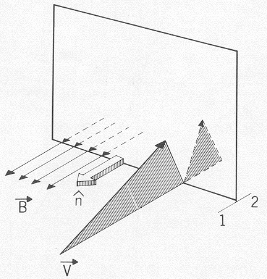
Contact discontinuity (CD)

Index 1 upstream and 2 downstream;

B does not change across the surface of the CD, but $\rho_1 \neq \rho_2$ and $T_1 \neq T_2$.

Shocks (with mass flow)

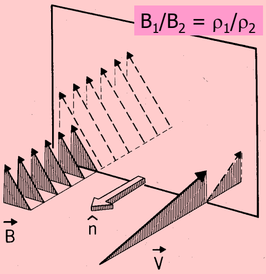
Parallel shock



B is parallel to the normal **n** of the shock surface.

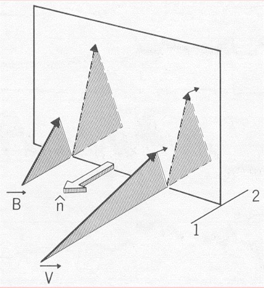
Perpendicular shock

$B_1/B_2 = \rho_1/\rho_2$



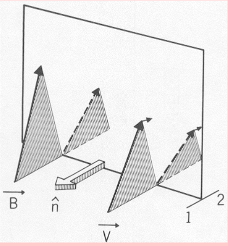
B is perpendicular to the normal **n** of the shock surface.

Fast and slow shocks



Fast shock

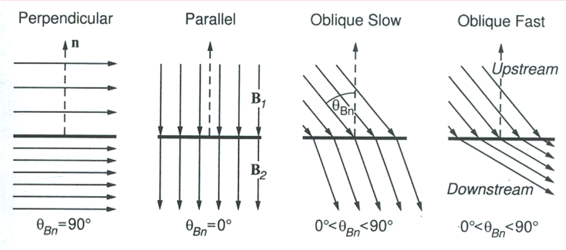
B and **V** refract away from normal



Slow shock

B and **V** refract towards the normal

Possible geometries of shock normal and magnetic field

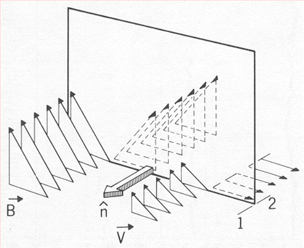


Laminar

Turbulent

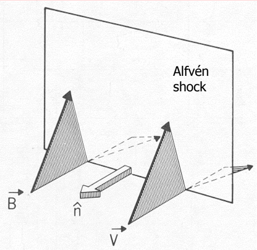
$\cos(\theta_{Bn}) = \mathbf{B \cdot n}/B$

Discontinuities (no mass flow)



Tangential discontinuity (TD)

B is parallel to the surface of the TD, but its direction may change across it.



Rotational discontinuity (RD)

B is oblique to the surface of the RD and its direction changes across it.

Alfvénic fluctuations

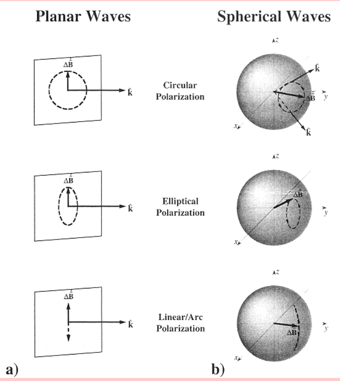
Ulysses observed many such waves (4-5 per hour) in fast wind over the poles:

- Arc polarized waves
- Phase-steepened

Rotational discontinuity:

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

Finite jumps in velocities over gyrokinetic scales

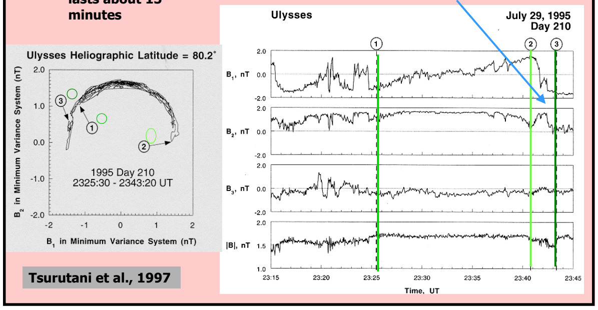


Tsurutani et al., 1997

Arc-polarized Alfvén waves

Slowly rotating Alfvén wave lasts about 15 minutes

Rotational discontinuity RD lasts only 3 minutes



Tsurutani et al., 1997