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AUTUMN COLLEGE ON PLASMA PHYSICS

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Kinetic Physics of the Solar Corona and Solar Wind - III

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These are preliminary lecture notes, intended only for distribution to participants.

Kinetic Physics of the Solar Corona and Solar Wind

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- The Sun's corona and wind – structure, evolution and dynamics
- Ions and electrons – velocity distributions and kinetics
- Waves and turbulence – excitation, transport and dissipation

Waves and turbulence – excitation, transport and dissipation

- Structures and fluctuations in the solar wind
- Alfven waves from the corona
- Magnetosonic waves and density fluctuations
- Coronal and interplanetary origin of fluctuations
- Radial and latitudinal evolution of MHD turbulence
- Spectral indices and cascading
- Transport of waves and turbulence
- Dissipation through wave-particle interactions
- Kinetic wave-heating of the corona

Spatial and temporal scales

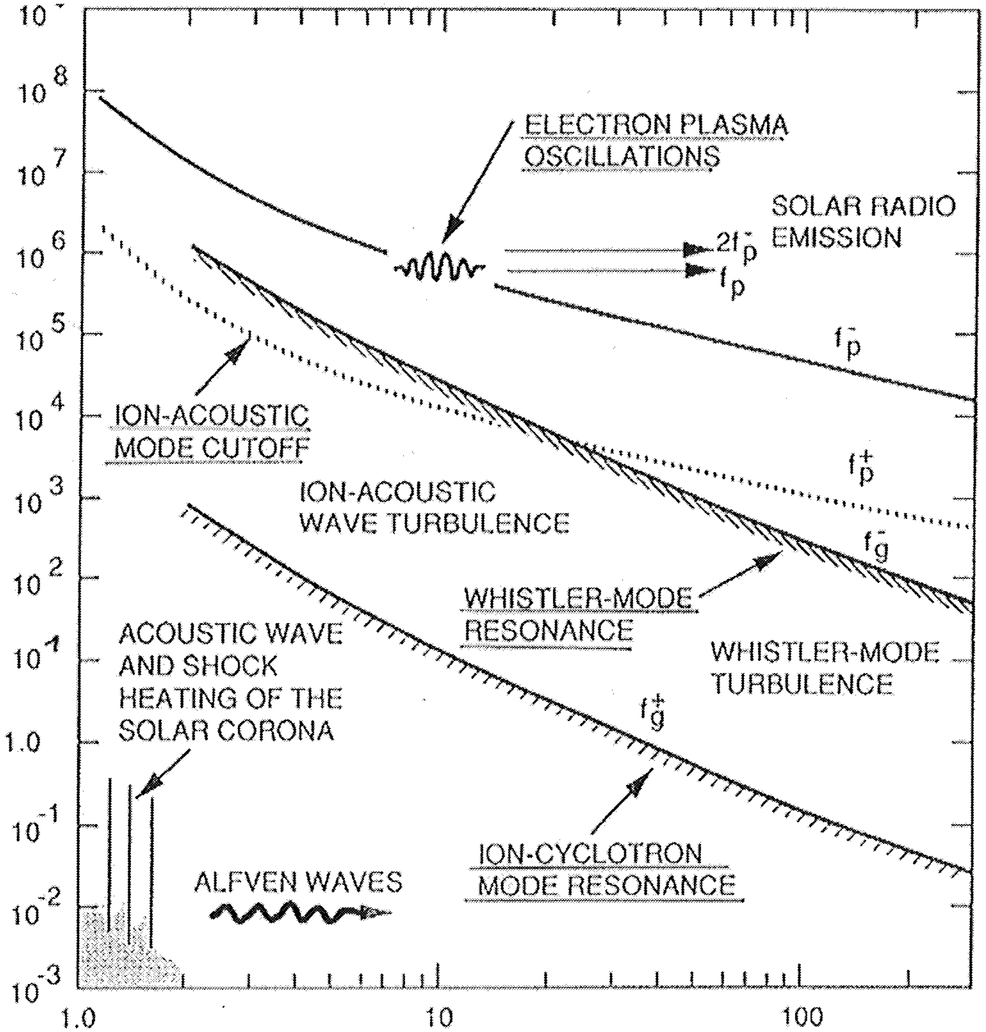
Phenomenon	Frequency (s^{-1})	Period (day)	Speed (km/s)
Solar rotation:	4.6 10^{-7}	25	2
Solar wind expansion:	5 – 2 10^{-6}	2 – 6	800 – 250
Alfvén waves:	3 10^{-4}	1/24	50 (1AU)
Ion–cyclotron waves:	1 – 0.1	1 (s)	(V_A) 50

Turbulent cascade: generation + transport

→ inertial range → kinetic range + dissipation

Plasma waves and frequencies

Frequency/Hz



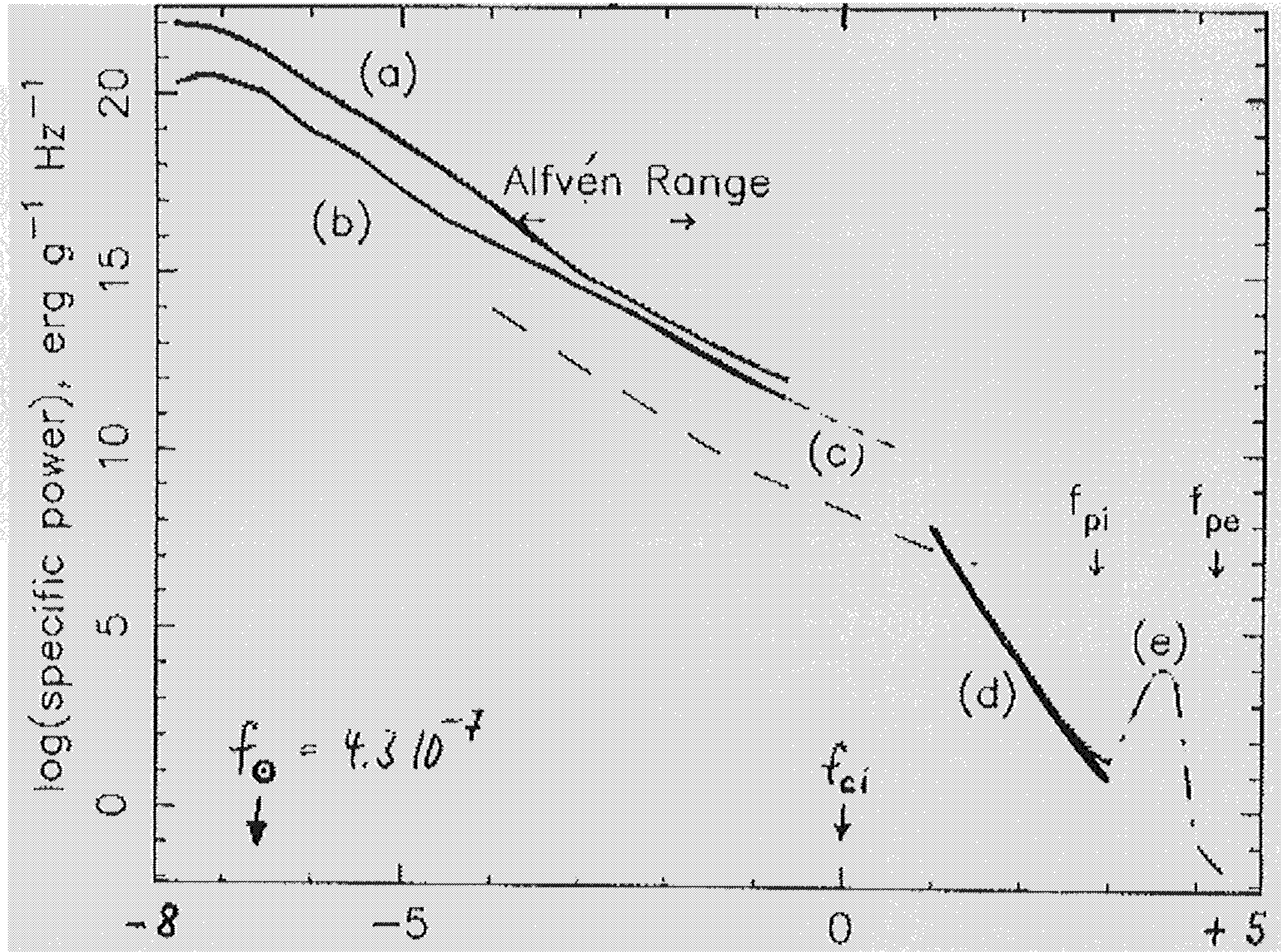
Solar distance $/R_S$

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

Gurnett, 1978

Power spectrum of fluctuations

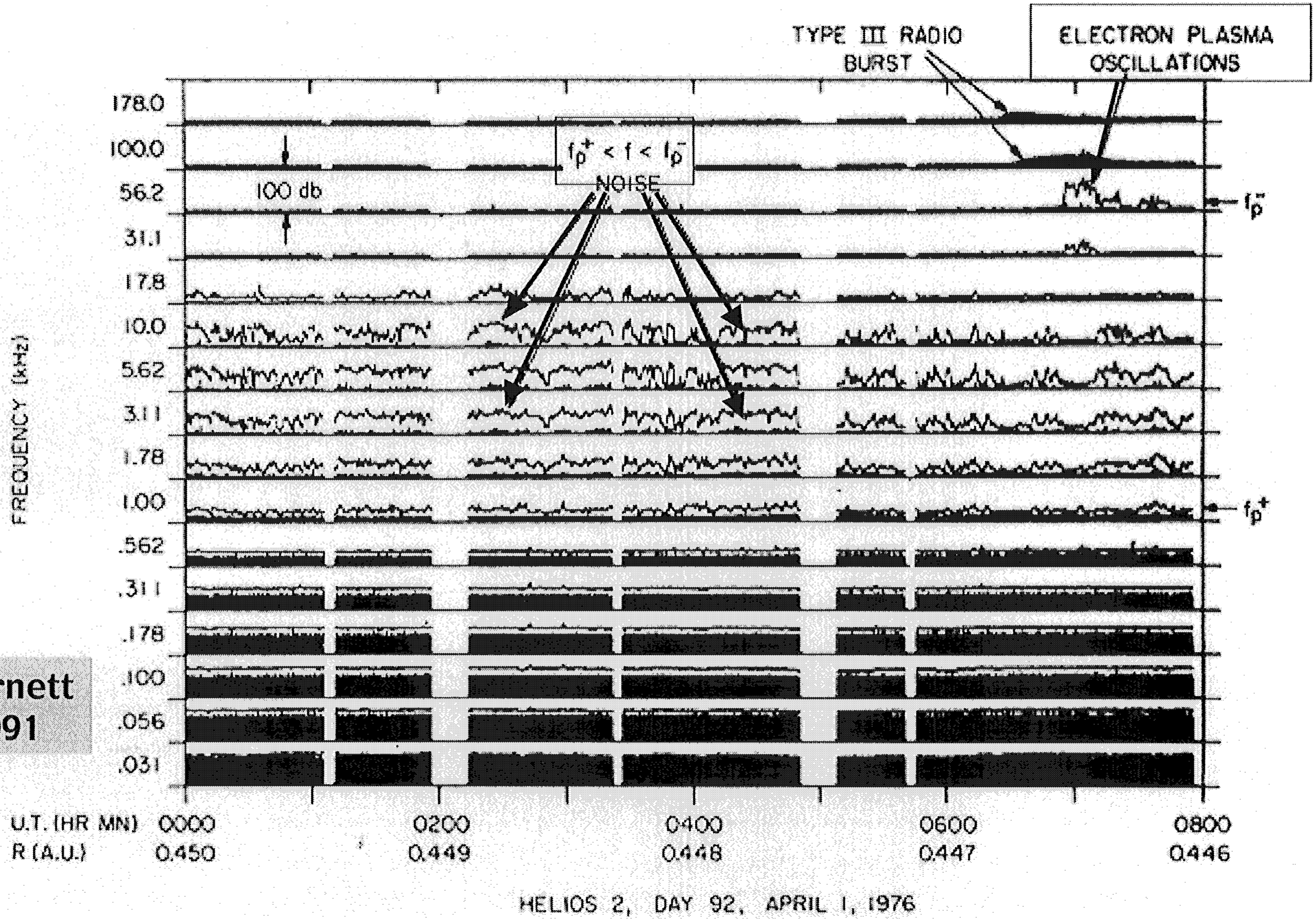
(a) Alfvén waves
(b) Slow and fast magnetosonic
(c) Ion-cyclotron
(d) Whistler mode
(e) Ion acoustic, Langmuir waves



Log(frequency /Hz)

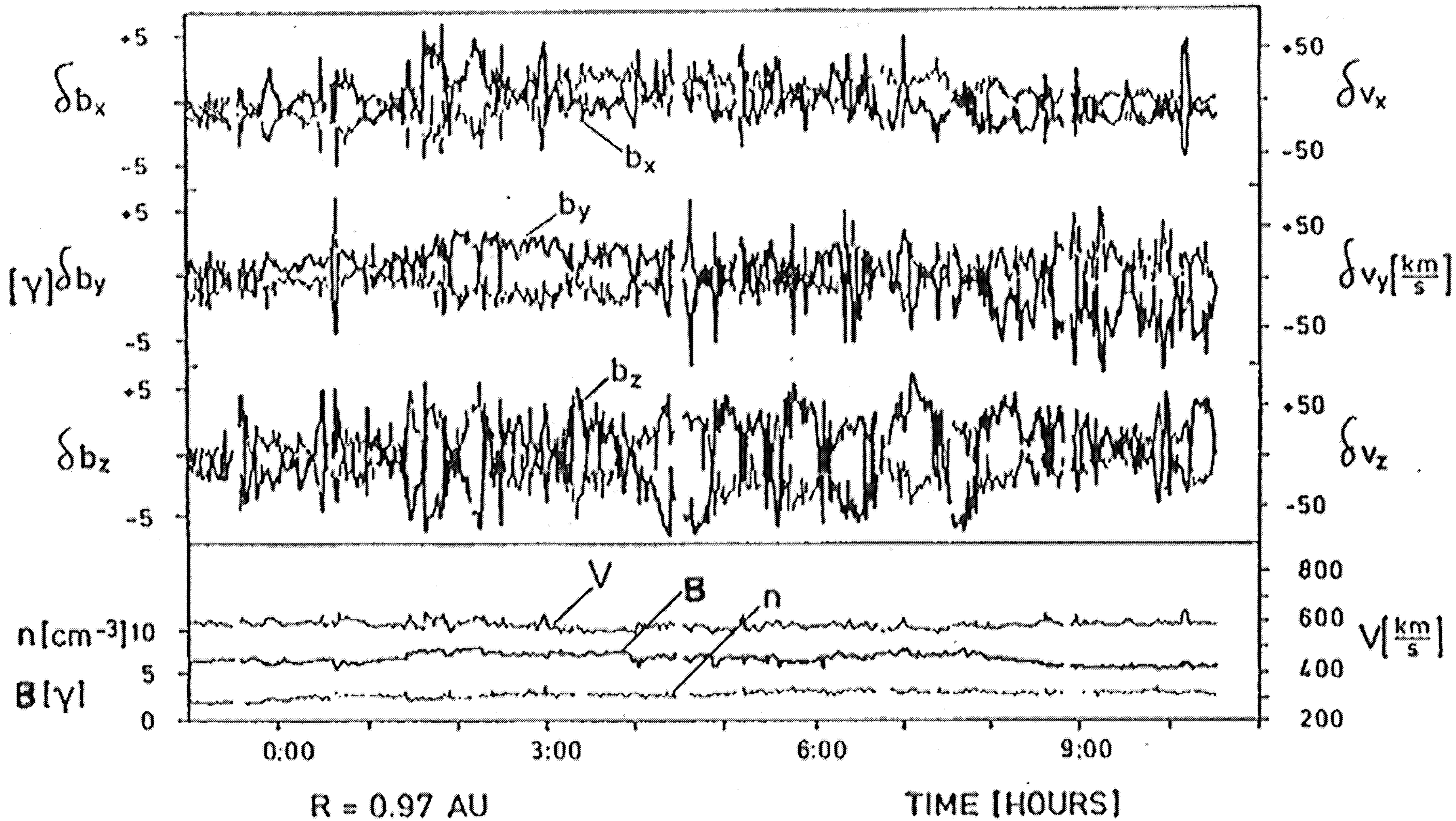
Mangeney et al., 1991

Ion acoustic and Langmuir waves



Gurnett, 1991

Alfvénic fluctuations

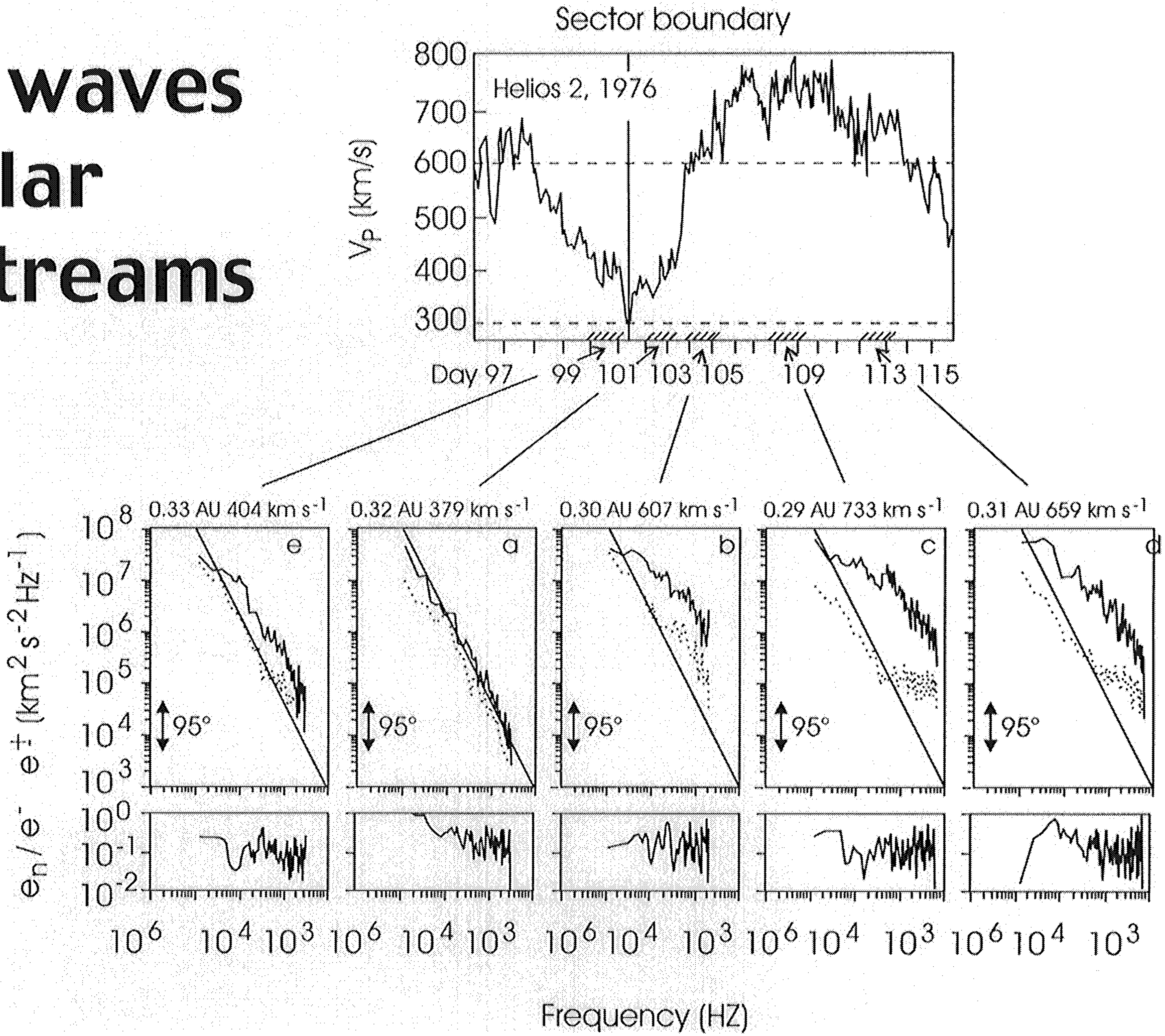


Neubauer et al., 1977

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

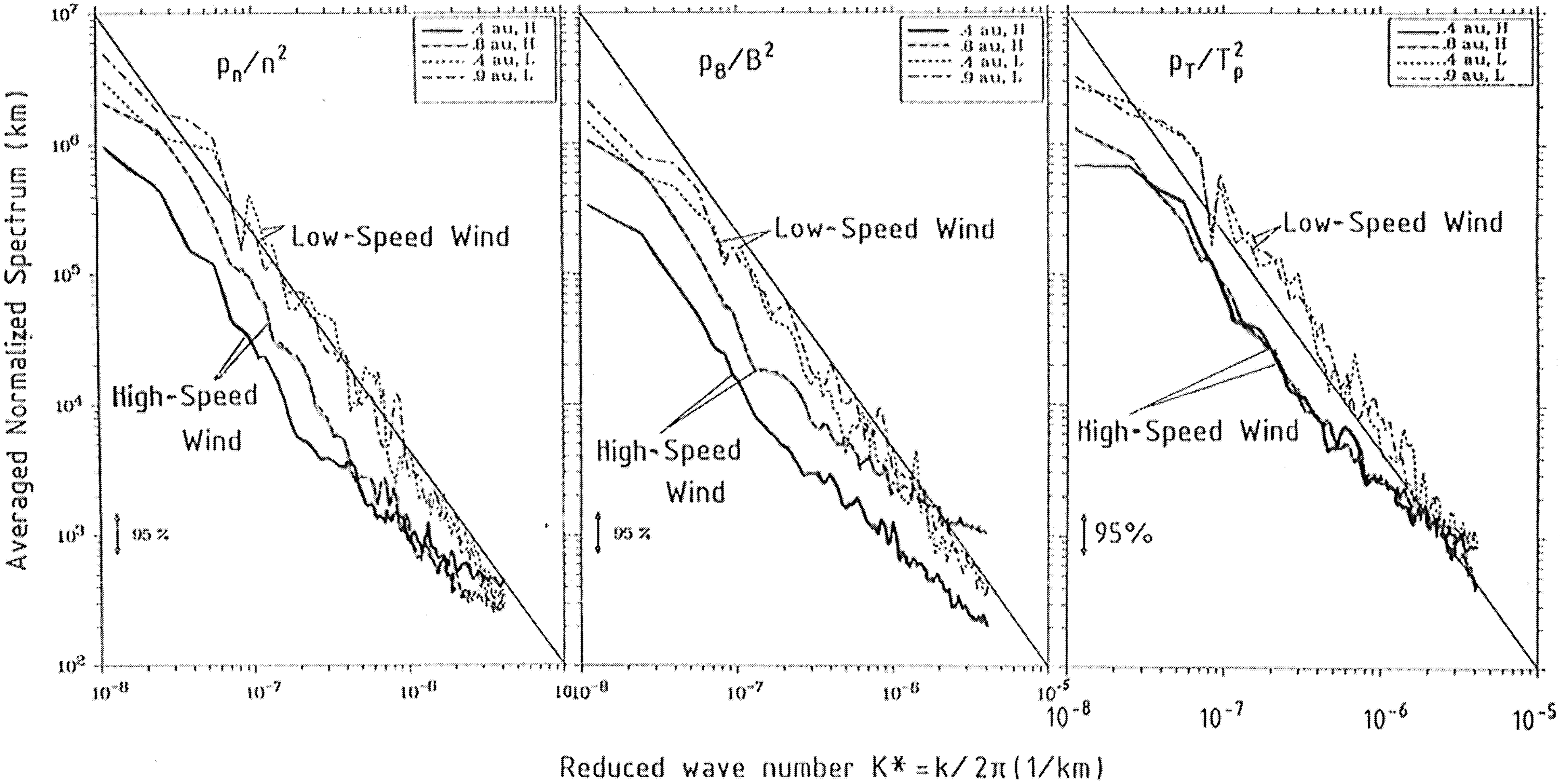
Alfvén waves and solar wind streams

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



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

Compressive fluctuations in the solar wind



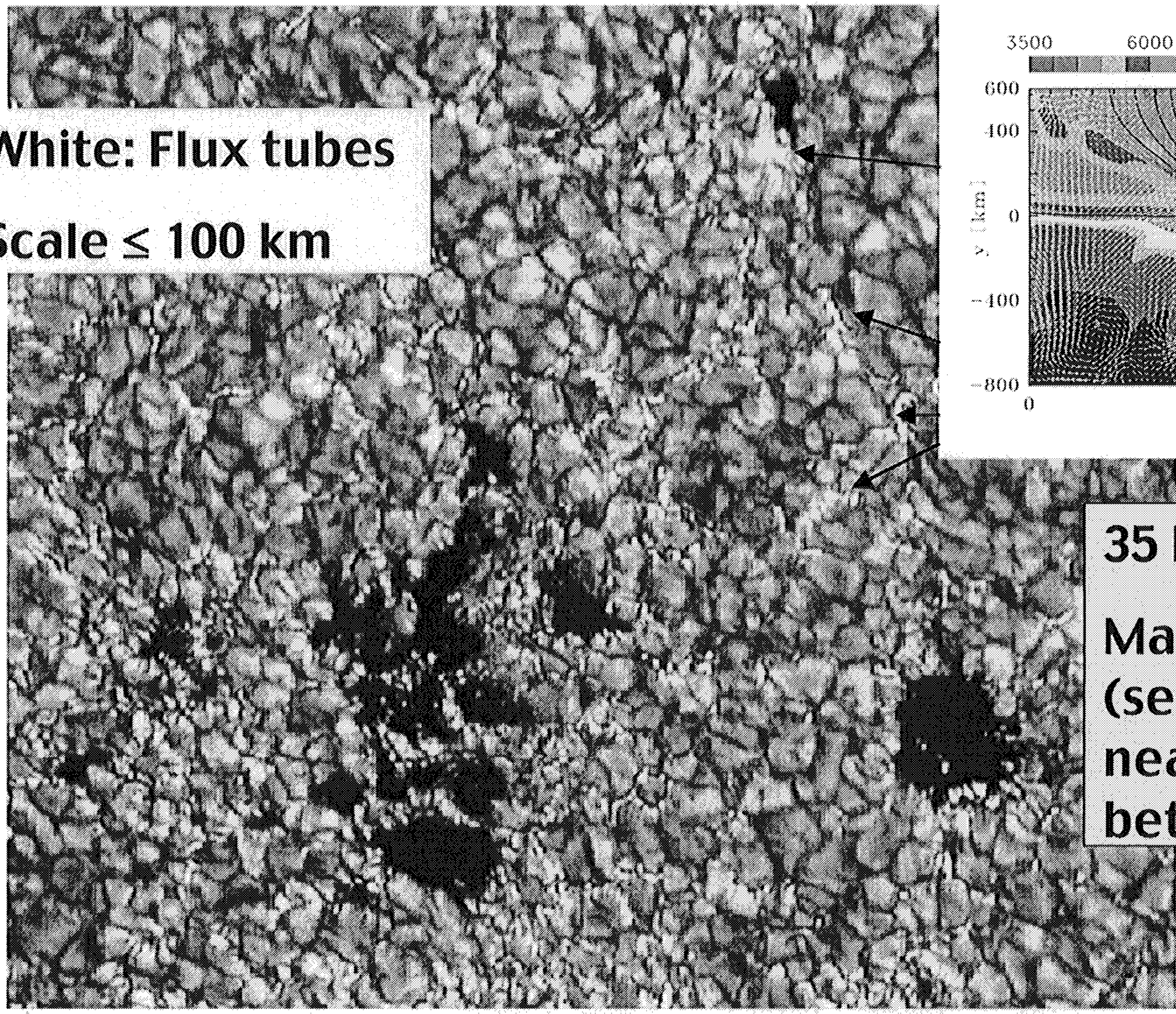
Marsch and Tu, JGR, 95, 8211, 1990

Kolmogorov-type turbulence

Solar wind turbulence

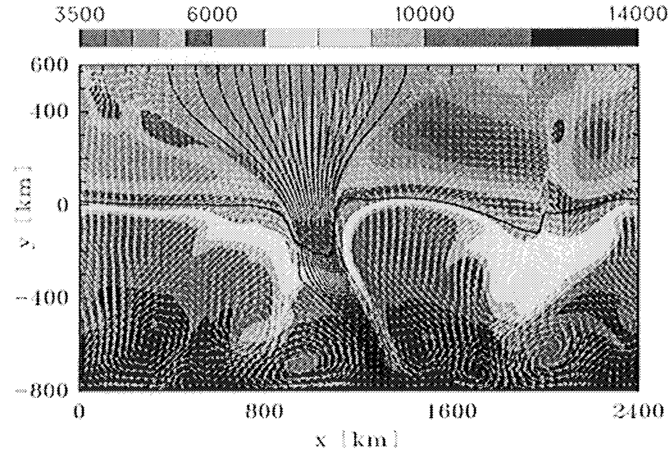
Parameter	Coronal Hole (open)	Current sheet (closed)
Alfvén waves:	yes	no
Density fluctuations:	weak (<3%)	intense (>10%)
Magnetic/kinetic turbulent energy:	$\cong$ 1	> 1
Spectral slope:	flat (−1)	steep (−5/3)
Wind speed:	high	low
T_p (T_e):	high (low)	low (high)
Wave heating:	strong	weak

Small magnetic flux tubes and photospheric granulation



White: Flux tubes

Scale ≤ 100 km



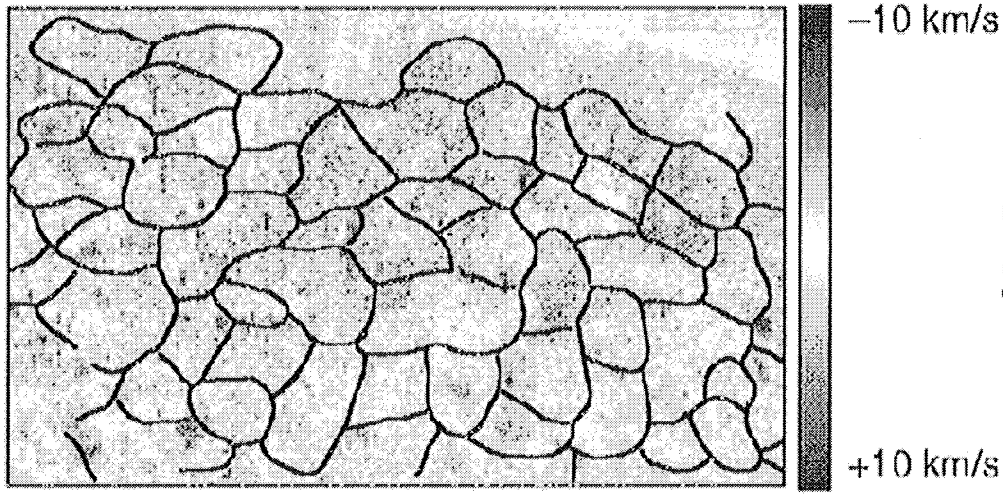
35 Mm x 40 Mm

Magnetic regions (seen in G-band near 430 nm) between granules

Scharmer, 1993

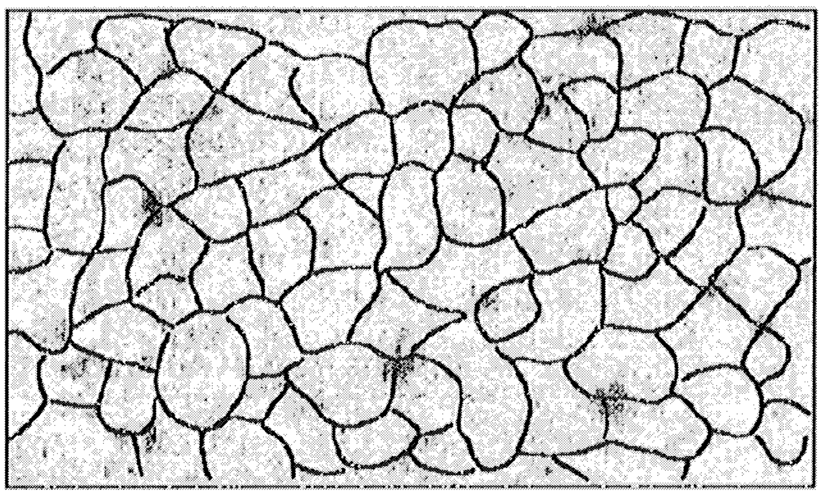
Solar wind outflow from magnetic network lanes and junctions

Line-of-sight Doppler velocity images



Ne VIII 770 Å (630 000 K) September, 1996

North and midlatitude polar region

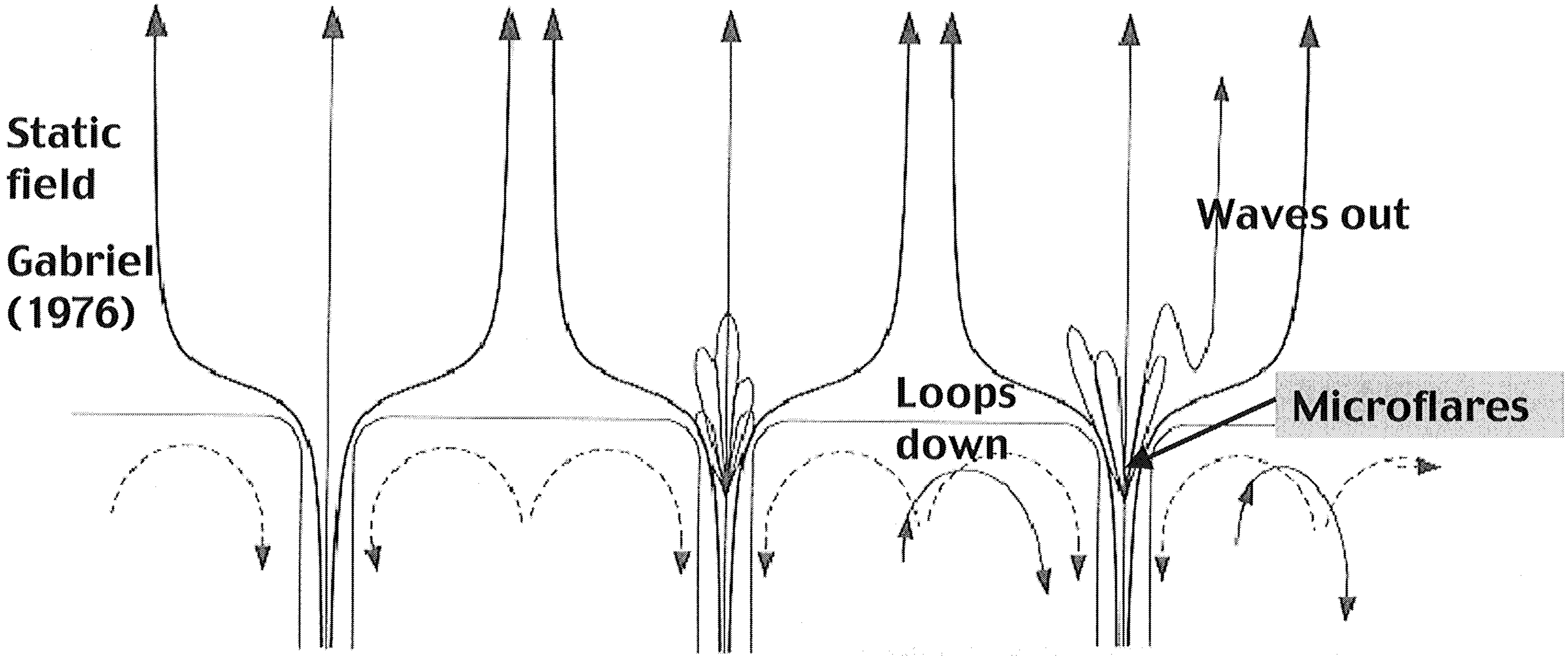


Raster scan: 540" × 300"

Network in Si II 1553 Å (10 000 K)

Hassler et al., Science, 283, 810, 1999

Dynamic network and magnetic furnace by reconnection



New flux fed in at sides by convection (t ~ 20 minutes)

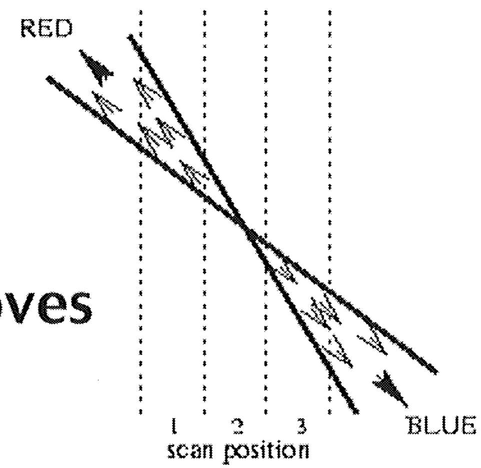
$F_E = 10^7$ erg cm^{-2} s^{-1}

Axford and McKenzie, 1992, and Space Science Reviews, 87, 25, 1999

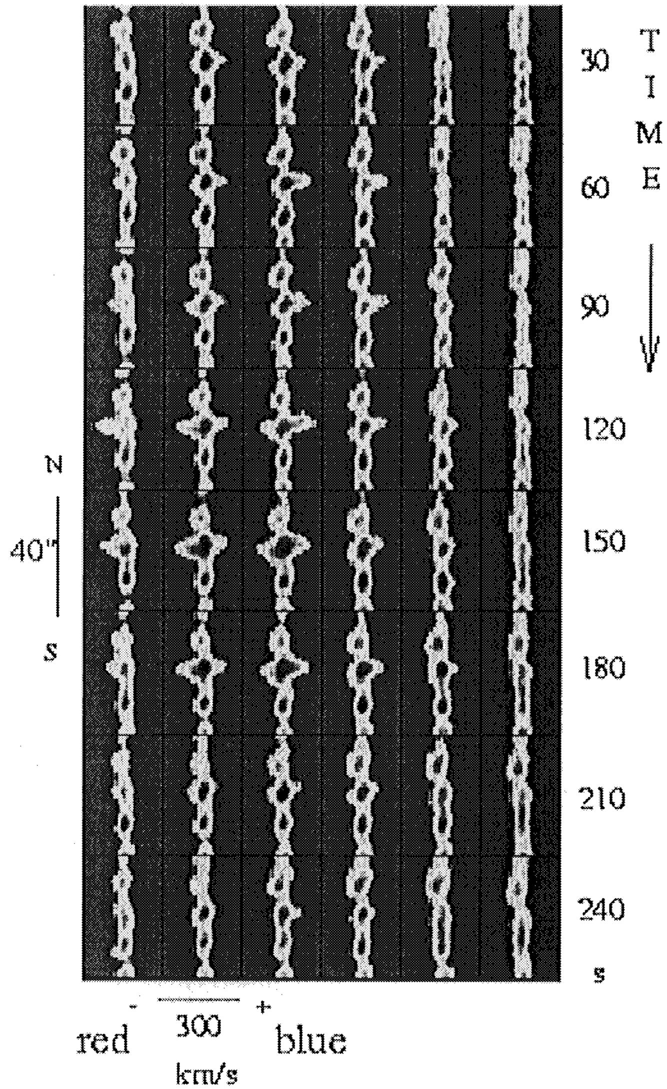
EUV jets and reconnection in the magnetic network

Evolution of a jet in Si IV 1393 Å visible as blue and red shifts in SUMER spectra

- E–W step size 1" , Δt = 5 s



Jet head moves 1" in 60 s



Innes at el., Nature, 386, 811, 1997

Height profile of wave amplitude

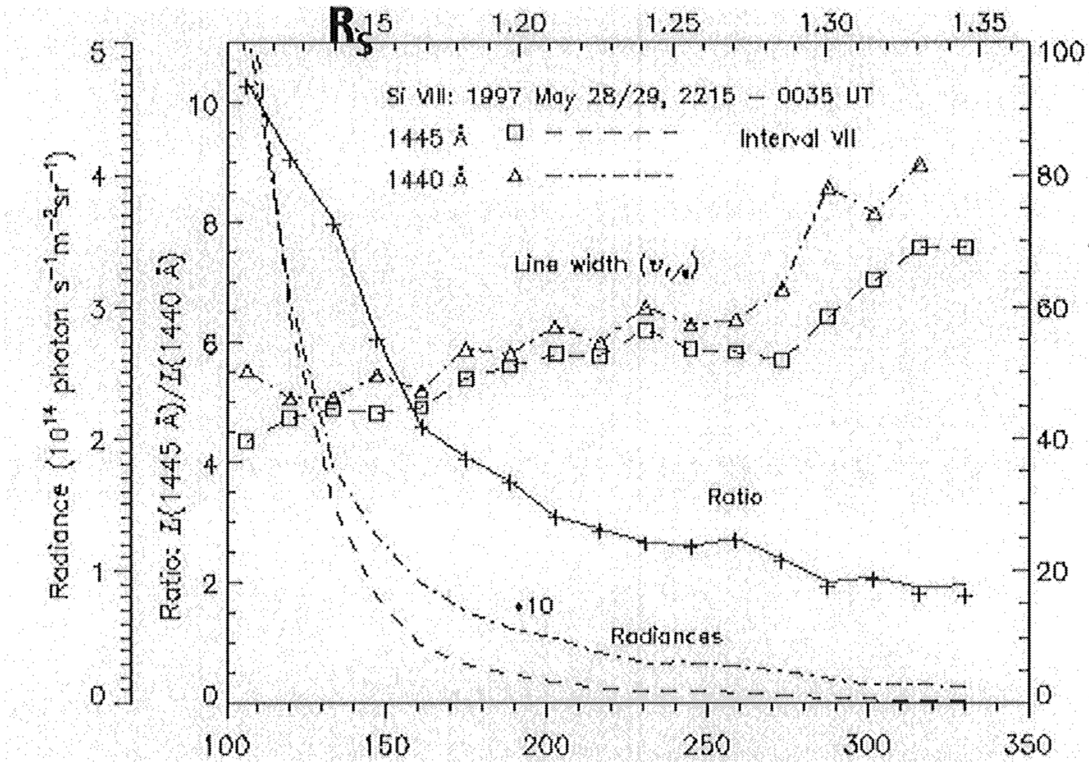
SUMER

Silicon VIII

λλ1440,1445

North polar coronal hole

Heliocentric distance / R_S



Height above limb / arcsec

Doppler velocity

$V_{1/e}$ / km s^{-1}

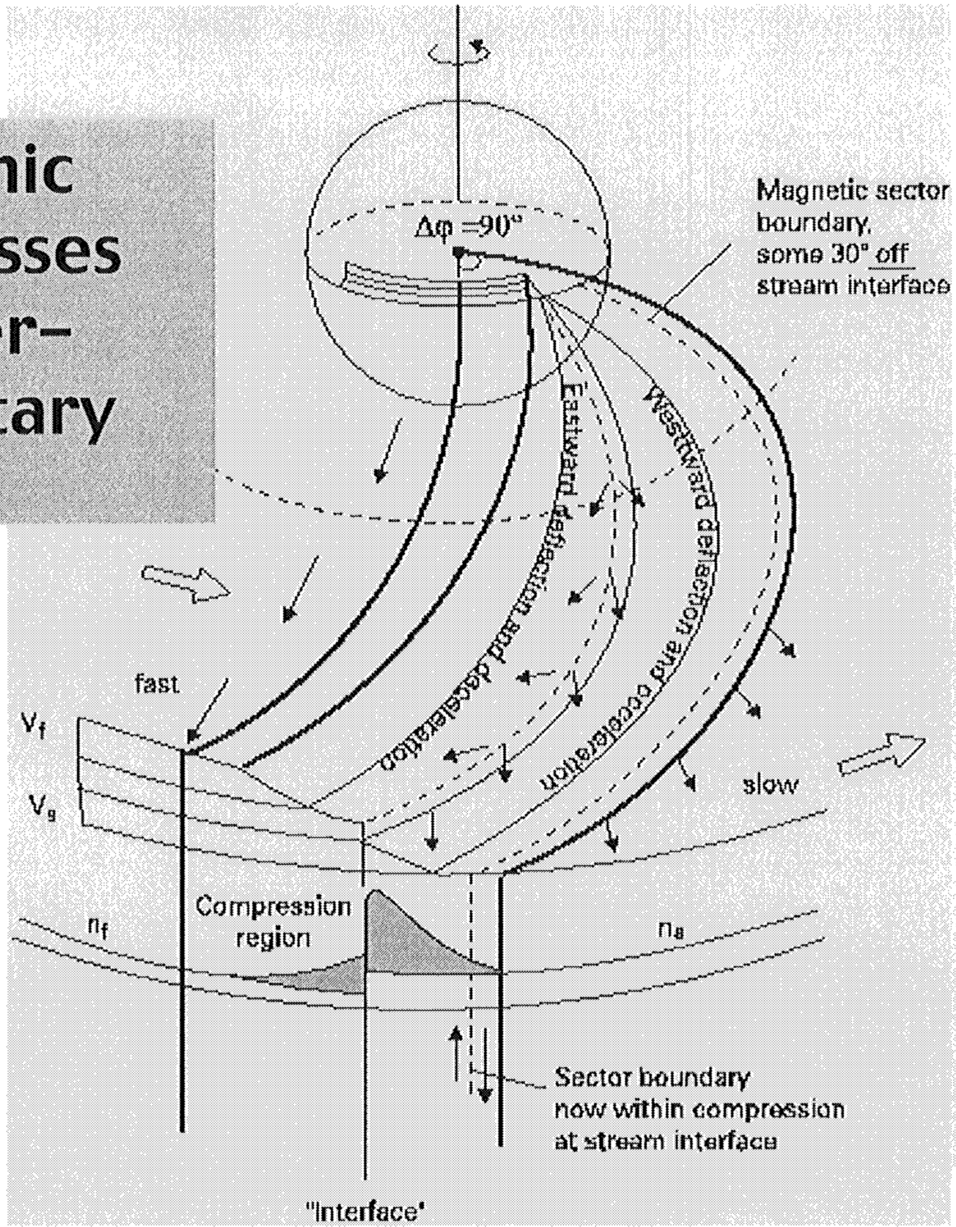
At 1.33 R_S:

$T_{Si} \approx 10^7$ K
$\xi \approx 70$ km s^{-1}
$n_e \approx 10^6$ cm^{-3}

Wilhelm et al., Ap.J., 500, 1023, 1998

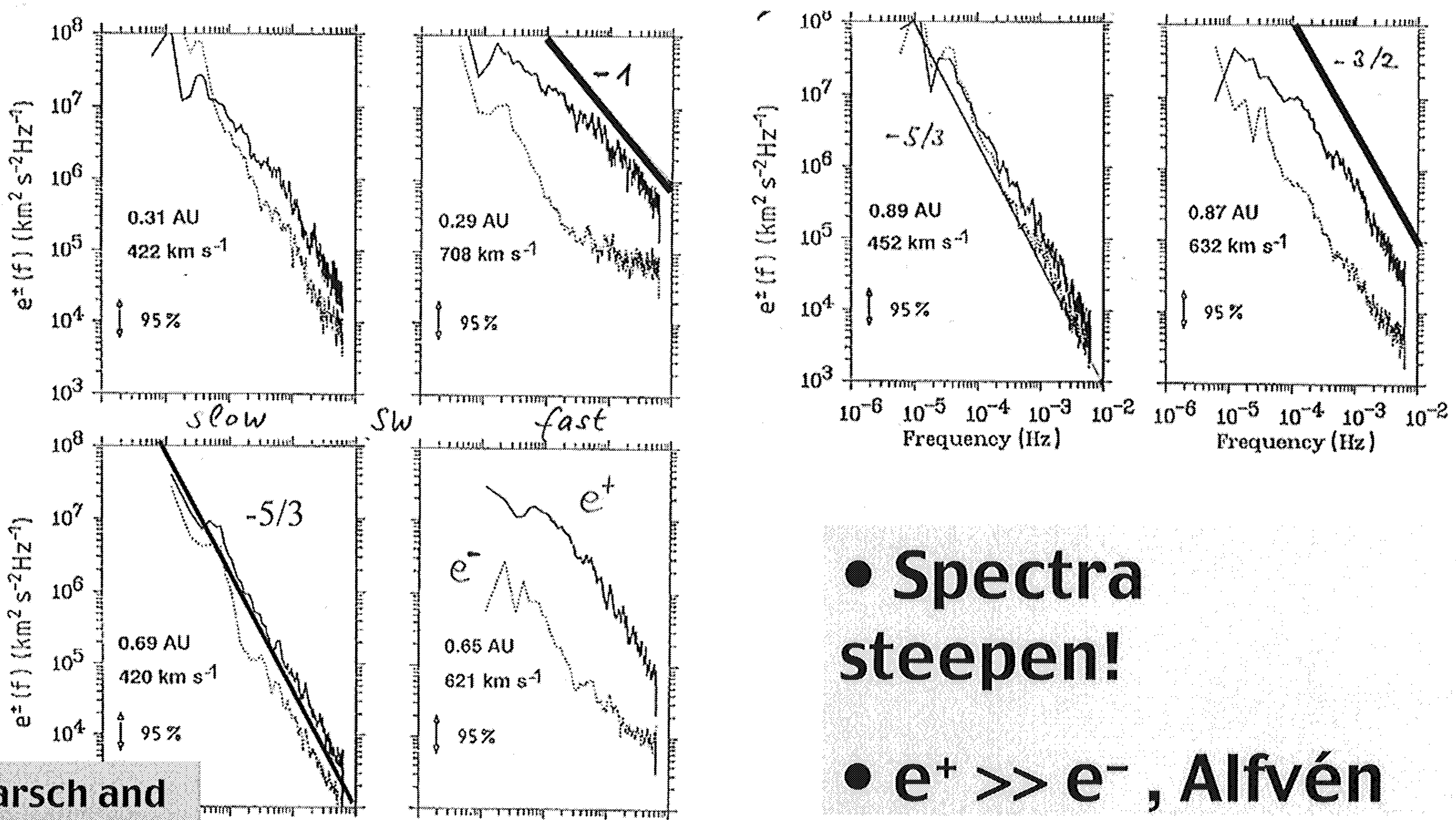
Stream interaction region

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)**

Spectral indices and spatial evolution of turbulence

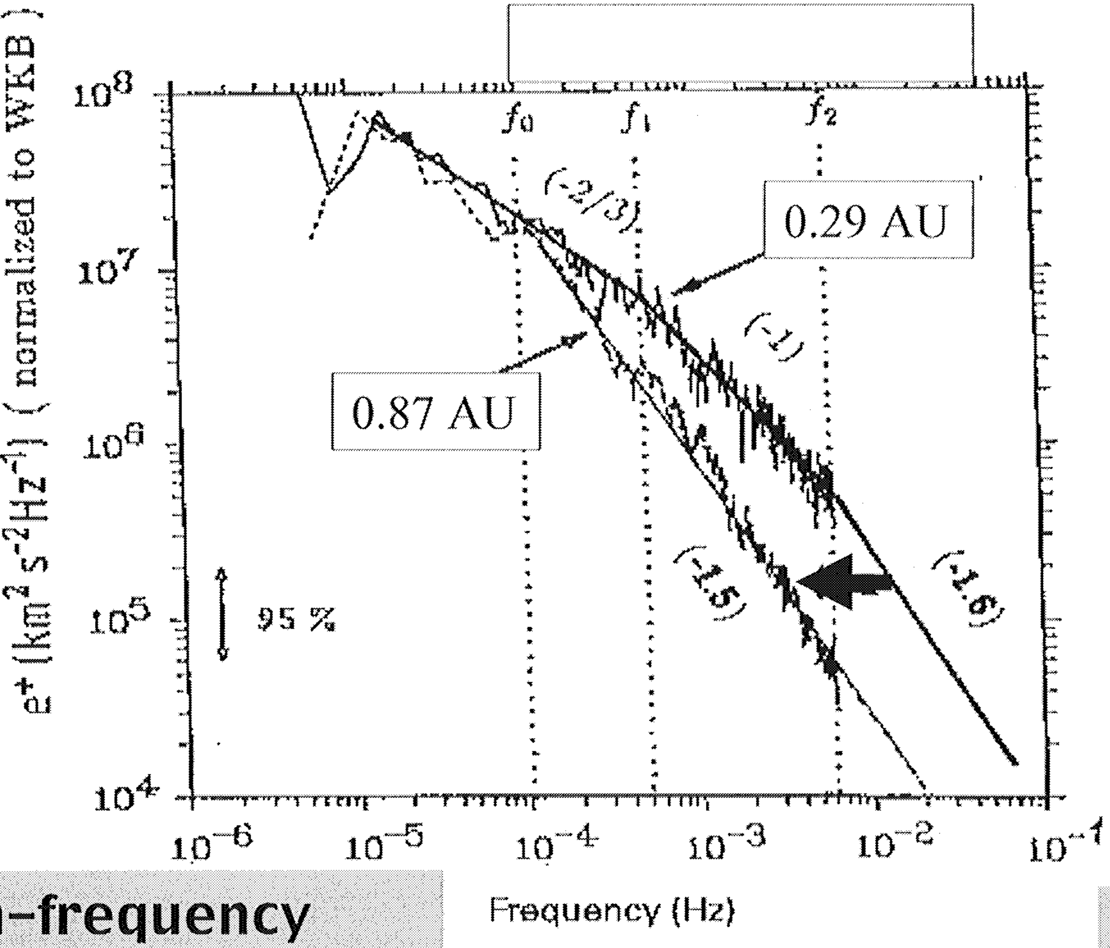


Marsch and Tu, JGR, 95, 8211, 1990

slow <-> fast wind

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

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

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!

Quasi-linear pitch-angle diffusion

Diffusion equation

$$\frac{\partial}{\partial t} f_j(V_\perp, V_\parallel, t) = \sum_M \sum_{s=-\infty}^{+\infty} \frac{1}{(2\pi)^3} \int_{-\infty}^{+\infty} d^3k \, \mathcal{B}_M(\mathbf{k}) \times \frac{1}{V_\perp} \frac{\partial}{\partial \alpha} \left(V_\perp \, \nu_j(\mathbf{k}, s; V_\parallel, V_\perp) \frac{\partial}{\partial \alpha} f_j(V_\perp, V_\parallel, t) \right)$$

Pitch-angle gradient in wave frame

$$\frac{\partial}{\partial \alpha} = V_\perp \frac{\partial}{\partial V_\parallel} - \left(V_\parallel - \frac{\omega_M(\mathbf{k})}{k_\parallel} \right) \frac{\partial}{\partial V_\perp}$$

Kennel and Engelmann, 1966

Ingredients in the quasi-linear diffusion equation

Normalised wave amplitude (Fourier)

$$\hat{\mathcal{B}}_M(\mathbf{k}) = \left(\frac{\delta B_M(\mathbf{k})}{B_0}\right)^2 \left(\frac{k_\parallel}{k}\right)^2 \frac{1}{1 - |\,\hat{\mathbf{k}} \cdot \mathbf{e}_M(\mathbf{k})\,|^2}$$

Wave-particle relaxation rate

$$\nu_j(\mathbf{k}, s; V_\parallel, V_\perp) = \pi \Omega_j^2 \, \delta(\omega_M(\mathbf{k}) - s\Omega_j - k_\parallel V_\parallel)$$
$$\times \, |\, \frac{1}{2}(J_{s-1} e_M^+ + J_{s+1} e_M^-) + \frac{V_j(\mathbf{k}, s)}{V_\perp} J_s e_{Mz} \,|^2$$

Resonant speed; Bessel function

$$V_j(\mathbf{k}, s) = \frac{\omega_M(\mathbf{k}) - s\Omega_j}{k_\parallel}; \quad J_s = J_s\left(\frac{k_\perp V_\perp}{\Omega_j}\right)$$

Marsch, Nonl. Proc. Geophys., in press, 2001

Plateau formation by wave-particle diffusion

Wave-frame coordinates

$$V_{ph} = \omega_M(\mathbf{k})/k_\parallel; \quad V_{ph} = V_A; \quad f_j(V_\perp, V_\parallel)$$

$$U_\parallel = V_\parallel - V_{ph}; \quad U_\perp = V_\perp; \quad U = \sqrt{U_\parallel^2 + U_\perp^2}$$

Transformed velocity distribution function

$$U_\parallel = U \cos\alpha; \quad U_\perp = U \sin\alpha; \quad f_j = f_j(U, \alpha)$$

$$U_j(\mathbf{k}) = -\Omega_j/k_\parallel; \quad \alpha_j(k_\parallel) = \arccos(-\Omega_j/k_\parallel U)$$

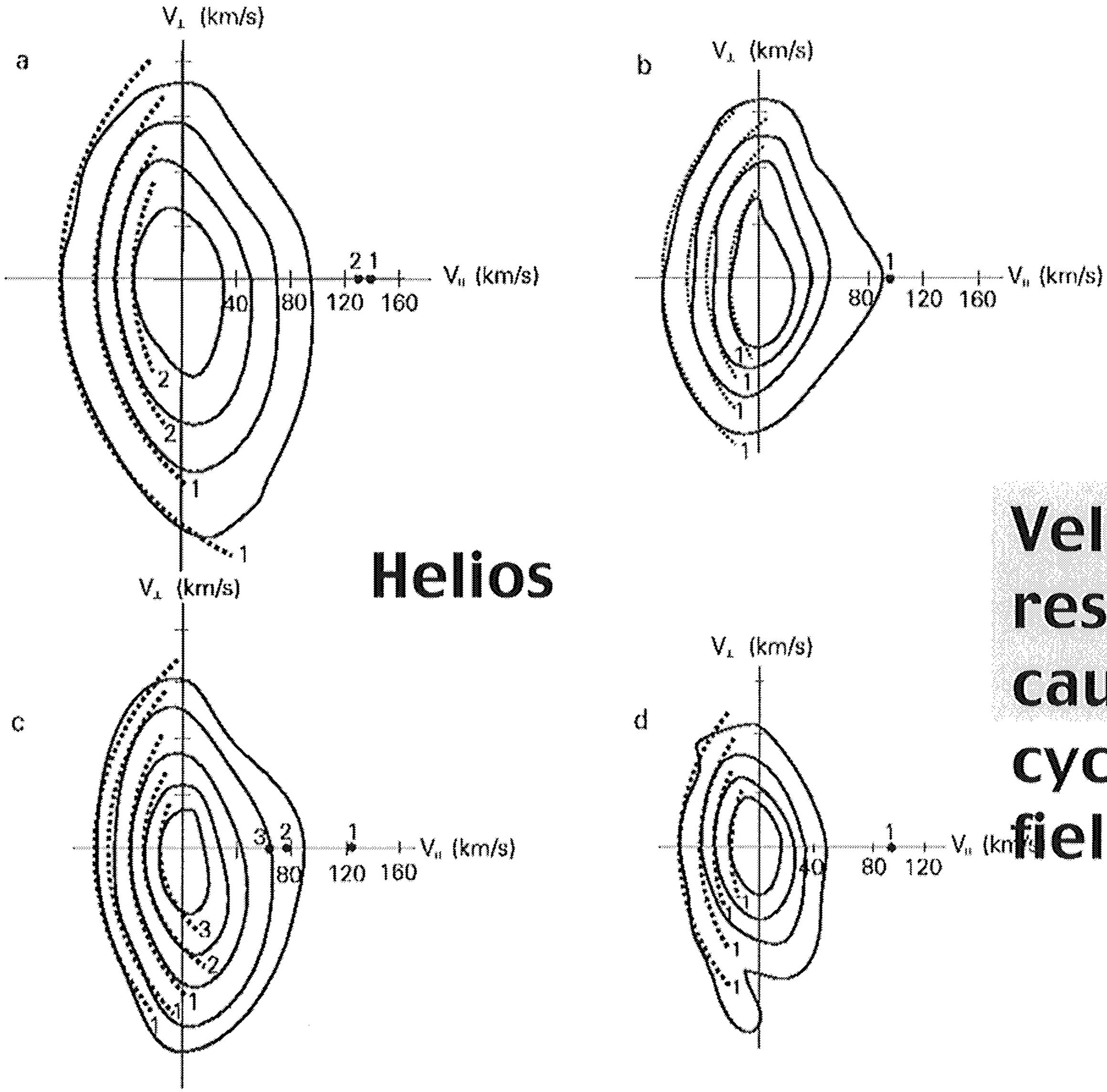
Marsch and Tu, JGR, in press,

nt s

Plateau in pitch-angle gradient

$$\frac{\partial f_j}{\partial \alpha}\Big|_{\alpha=\alpha_j(k_\parallel)} = 0$$

Pitch-angle diffusion of protons



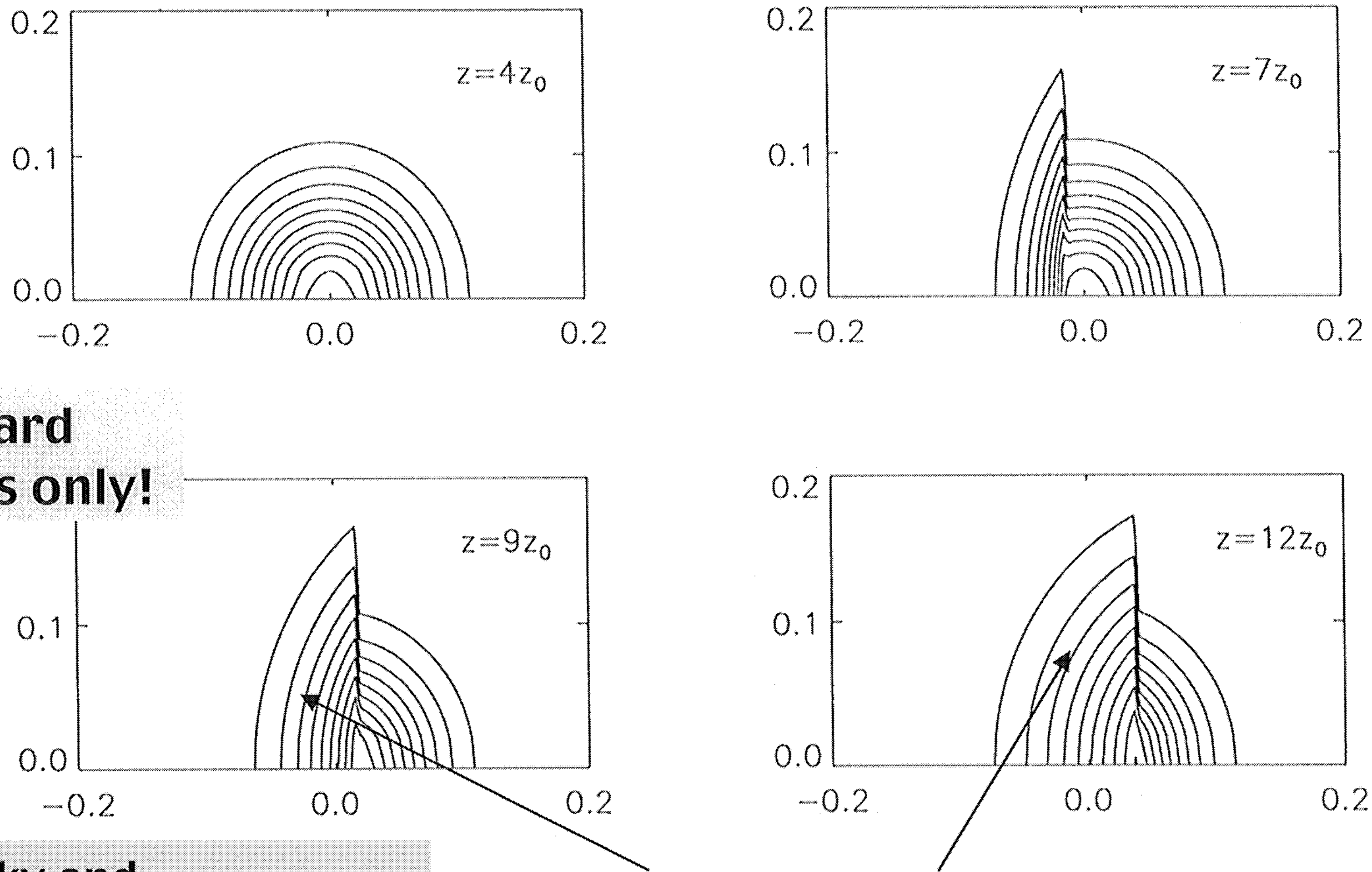
Helios

VDF contours are segments of circles centered in the wave frame (< V_A)

Velocity-space resonant diffusion caused by the cyclotron-wave field!

Marsch and Tu, JGR, in press, 2001

Quasilinear diffusion model of solar wind protons



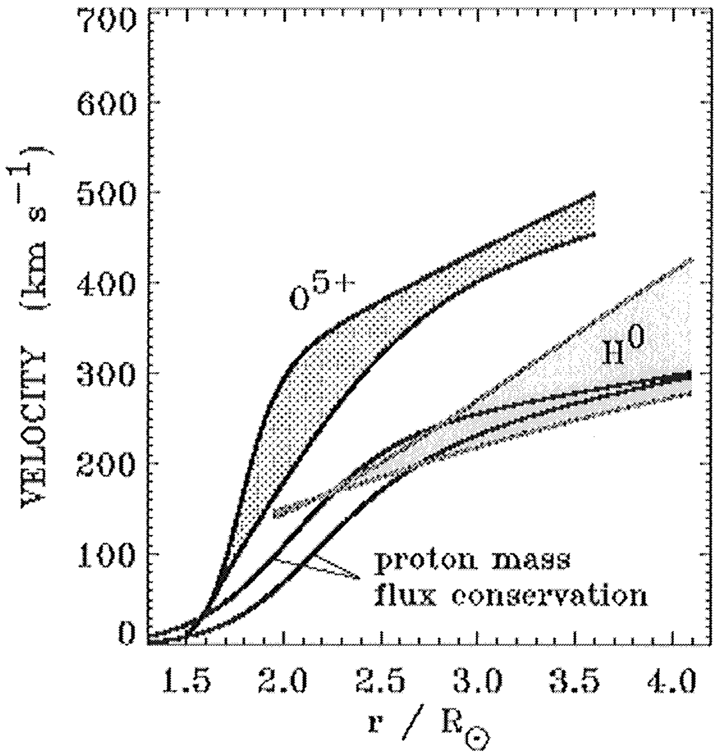
Outward waves only!

Pitch angle diffusion!

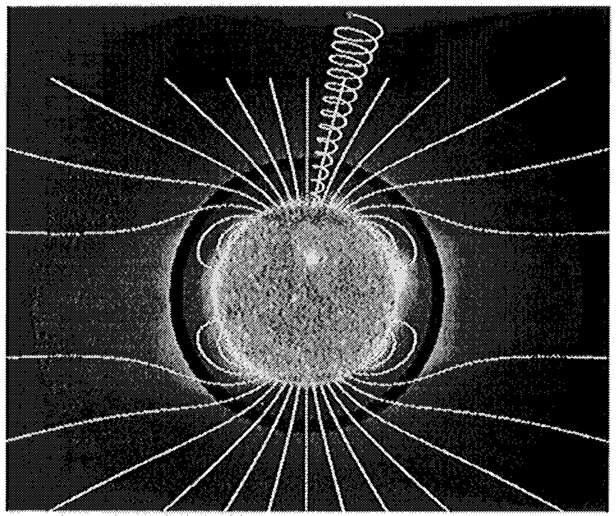
Galinsky and Shevchenko, Phys. Rev. L., 85, 90, 2000

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 ...

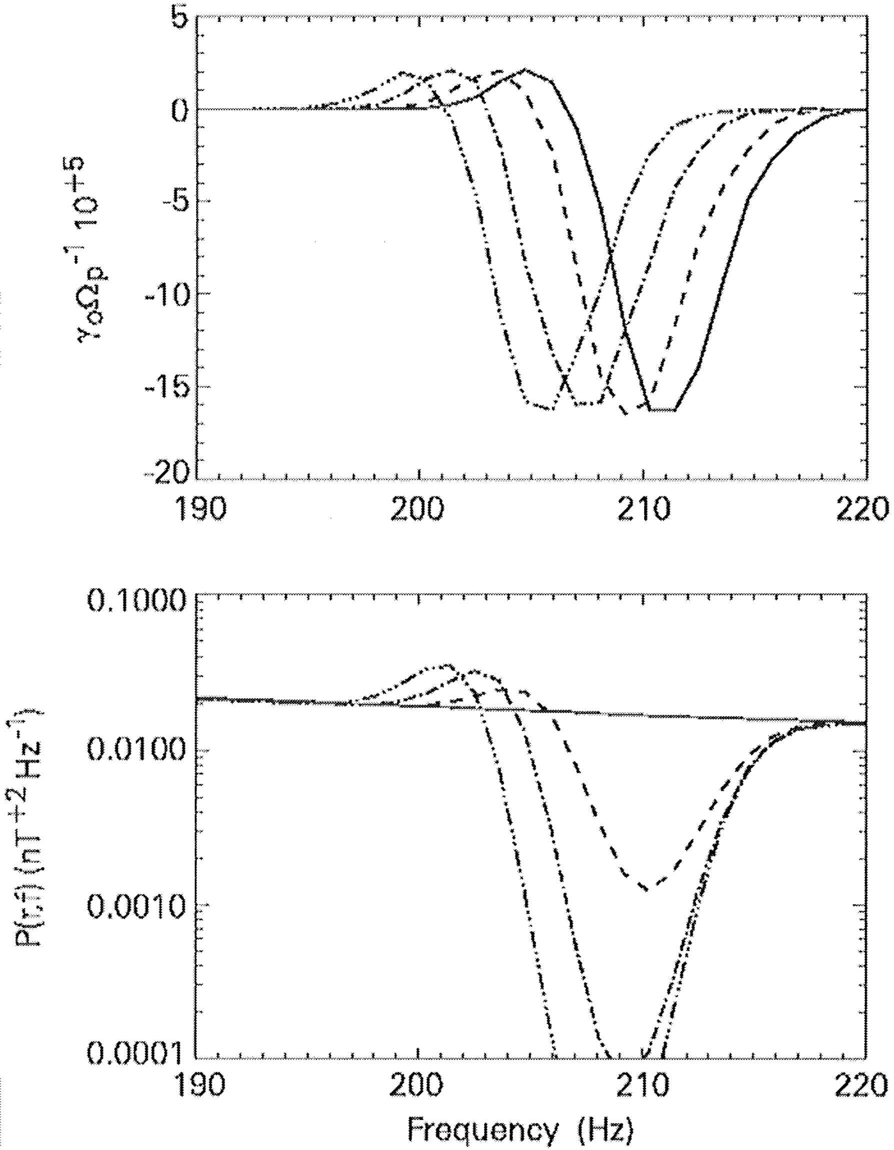
Absorption of cyclotron waves

Oxygen ion damping rate

Frequency sweeping!

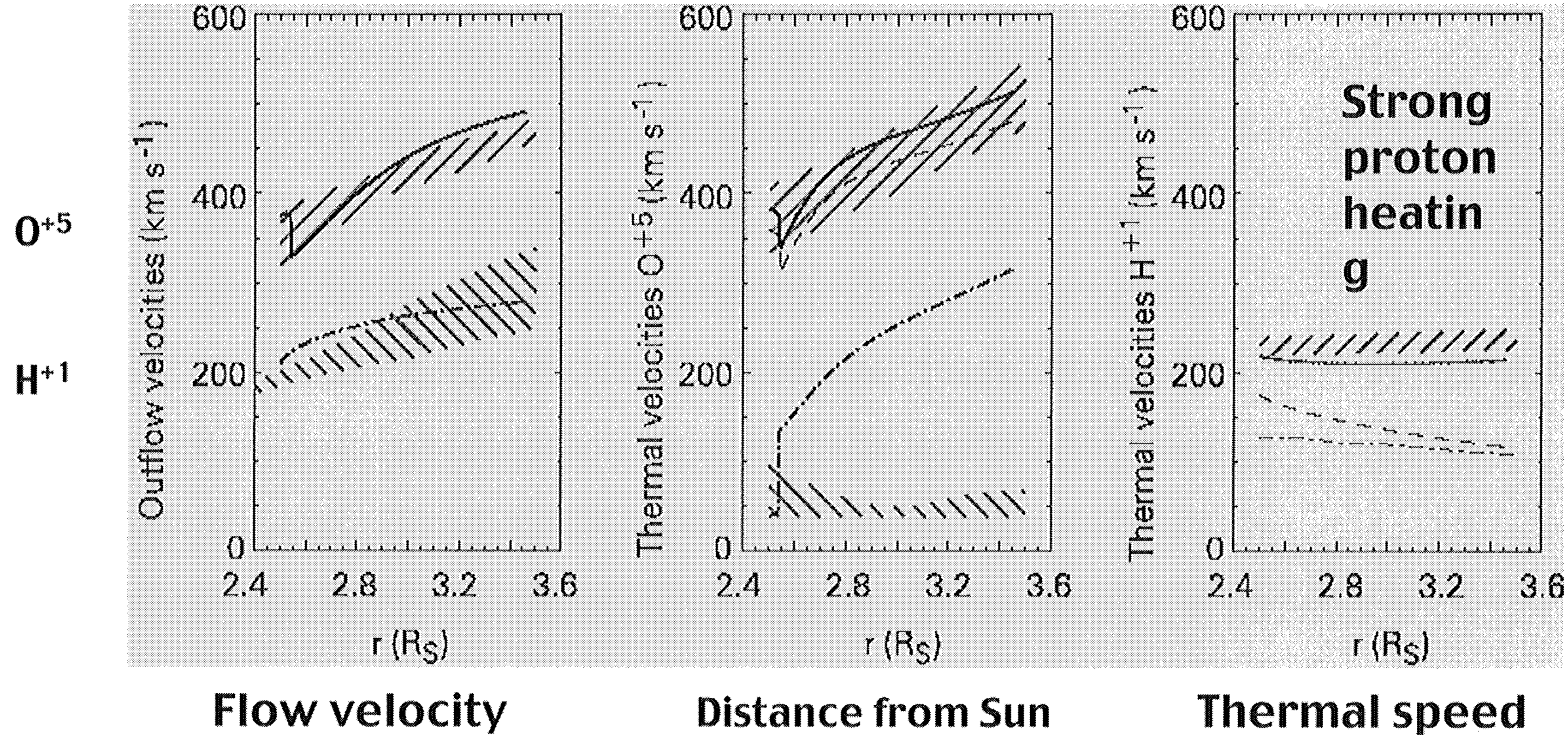
Self-consistent power spectrum

Height / km	**0**
	5000
	10000
	15000



Tu and Marsch, JGR, 106, 8233, 2001

Resonant heating and acceleration of ions by cyclotron waves

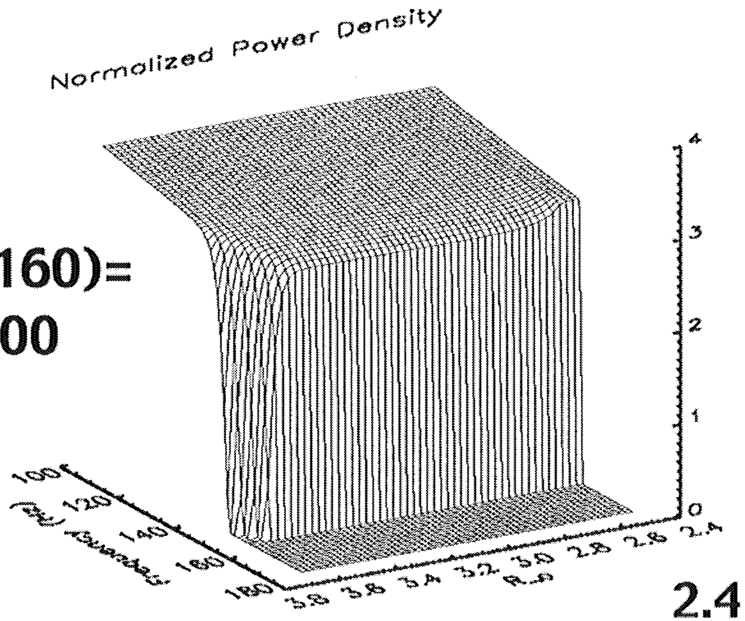


P(f)=300 nT²/Hz at 100 Hz at 2.6 R_s

Tu and Marsch, JGR, 106, 8233, 2001

Good agreement, but wrong O^{+5} anisotropy

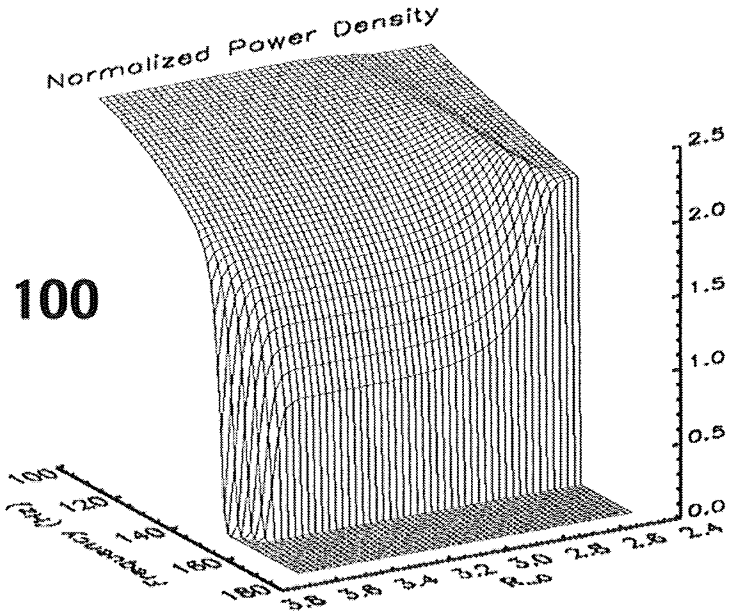
Evolution of wave power spectrum



P(160)=
1000

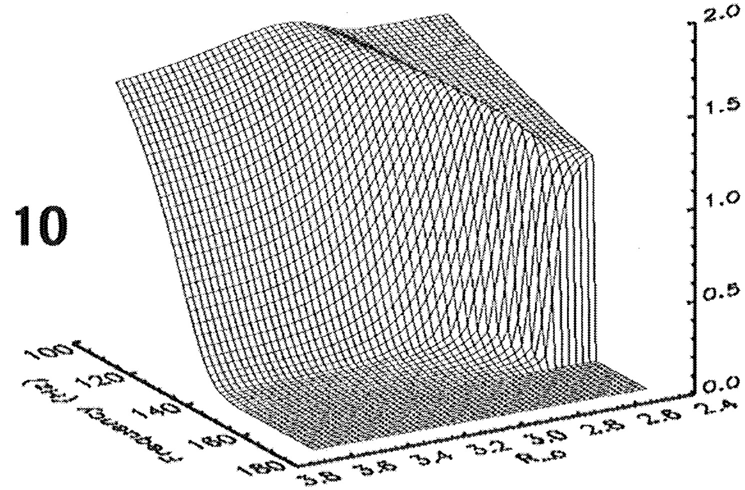
2.4 R_s

3.8 R_s Distance



100

$\delta b/B \approx$
0.01 at Ω_i



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Variable wave spectral density
P(f) [nT^2/Hz], f = 100–180 Hz

Tu and Marsch, A&A, 368, 1071, 2001

Reduced velocity distributions

Number of particles

$$F_{j\|}(w_\|) = 2\pi \int_0^\infty dw_\perp w_\perp f_j(w_\perp, w_\|)$$

Perpendicular thermal speed

$$F_{j\perp}(w_\|) = 2\pi \int_0^\infty dw_\perp w_\perp \frac{w_\perp^2}{2} f_j(w_\perp, w_\|)$$

Moments

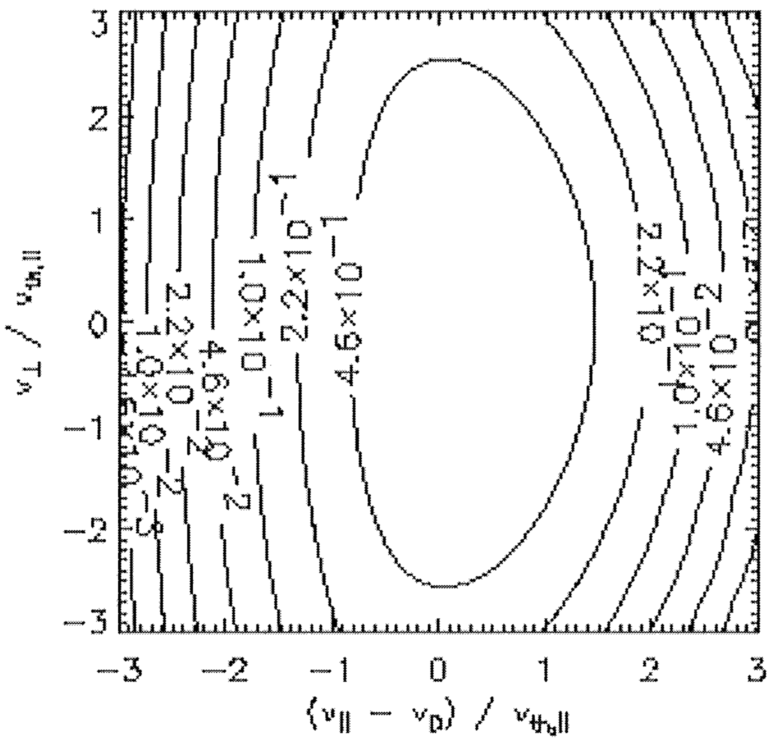
Normalisation

$$\int_{-\infty}^{\infty} dw_\| F_{j\|}(w_\|) \begin{pmatrix} 1 \\ w_\| \\ w_\|^2 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ V_{j\|}^2 \end{pmatrix}$$

$$\int_{-\infty}^{\infty} dw_\| F_{j\perp}(w_\|) = V_{j\perp}^2$$

Marsch, Nonlinear Proc. Geophys., 5, 111, 1998

Model ion velocity distribution in coronal hole



Oxygen O^{+5} ion VDF at 1.44 R_s

Waves+collisions+mirror force

$$W_{j\perp}^2(w_\parallel) = \frac{F_{j\perp}(w_\parallel)}{F_{j\parallel}(w_\parallel)}$$

$$\frac{T_{j\perp}}{T_{j\parallel}}(w_\parallel) = \frac{W_{j\perp}^2(w_\parallel)}{V_{j\parallel}^2}$$

$$f_j(w_\parallel, w_\perp) = \frac{F_{j\parallel}(w_\parallel)}{2\pi W_{j\perp}^2(w_\parallel)} \exp(-\frac{w_\perp^2}{2W_{j\perp}^2(w_\parallel)})$$

Vocks and Marsch, ApJ, in press, 2001

Semi-kinetic model of wave-ion interaction in the corona

Parallel VDF

$$\frac{\partial F_{\|}}{\partial t} + v_{\|}\frac{\partial F_{\|}}{\partial s} + \left(\frac{q}{m}E_{\|} - g(s)\right)\frac{\partial F_{\|}}{\partial v_{\|}} + \frac{1}{2A(s)}\frac{\partial A(s)}{\partial s}\cdot$$

$$2\left(\frac{\partial F_{\perp}}{\partial v_{\|}} + v_{\|}F_{\|}\right) = \frac{\delta F_{\|}}{\delta t} + \frac{\delta F_{\|}}{\delta t}|_{Coul.}$$

Perpendicular VDF

$$\frac{\partial F_{\perp}}{\partial t} + v_{\|}\frac{\partial F_{\perp}}{\partial s} + \left(\frac{q}{m}E_{\|} - g(s)\right)\frac{\partial F_{\perp}}{\partial v_{\|}} + \frac{1}{2A(s)}\frac{\partial A(s)}{\partial s}\cdot$$

$$4\left(v_{j\perp}^2\frac{\partial F_{\perp}}{\partial v_{\|}} + v_{\|}F_{\perp}\right) = \frac{\delta F_{\perp}}{\delta t} + \frac{\delta F_{\perp}}{\delta t}|_{Coul.}$$

Vocks and Marsch, GRL, 28, 1917, 2001

Reduced diffusion equations

Number of particles

$$\frac{\delta}{\delta t}F_{j\|}(w_\|) = \frac{\partial}{\partial w_\|}D_j(w_\|)\frac{\partial}{\partial w_\|}F_{j\perp}(w_\|) - \frac{\partial}{\partial w_\|}\left(A_j(w_\|)F_{j\|}(w_\|)\right)$$

Perpendicular thermal speed

$$\frac{\delta}{\delta t}F_{j\perp}(w_\|) = 2\ V_{j\perp}^2\frac{\partial}{\partial w_\|}D_j(w_\|)\frac{\partial}{\partial w_\|}F_{j\perp}(w_\|) - 3\ A_j(w_\|)\frac{\partial}{\partial w_\|}F_{j\perp}(w_\|) - 2\ F_{j\perp}(w_\|)\frac{\partial}{\partial w_\|}A_j(w_\|) + H_j(w_\|)F_{j\|}(w_\|)$$

Marsch, Nonlinear Proc. Geophys., 5, 111. 1998

Diffusive transport coefficients

Diffusion

Acceleration

Heating

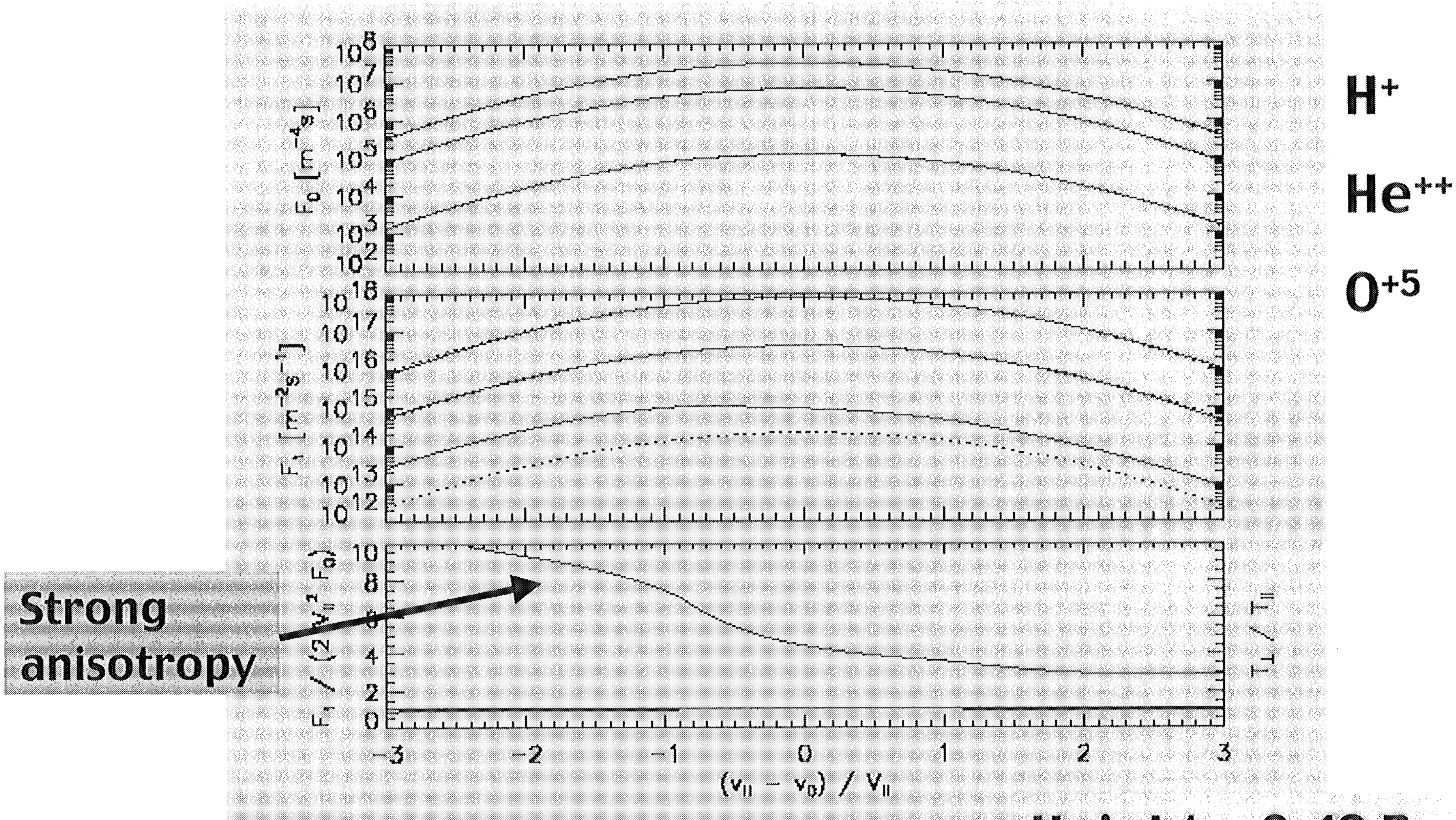
$$\begin{pmatrix} D_j(w_\parallel) \\ A_j(w_\parallel) \\ H_j(w_\parallel) \end{pmatrix} = \sum_M \frac{1}{(2\pi)^3} \int_{-\infty}^{\infty} d^3k \hat{\mathcal{B}}_M(\mathbf{k}) \times$$

$$\times \sum_{s=-\infty}^{\infty} \overline{\nu}_j(\mathbf{k}, s; w_\parallel) \begin{pmatrix} 1 \\ \frac{s\Omega_j}{k_\parallel} \\ (\frac{s\Omega_j}{k_\parallel})^2 \end{pmatrix}$$

Wave-particle relaxation rate and resonance condition

Marsch, Nonlinear Proc. Geophys., in press. 2001

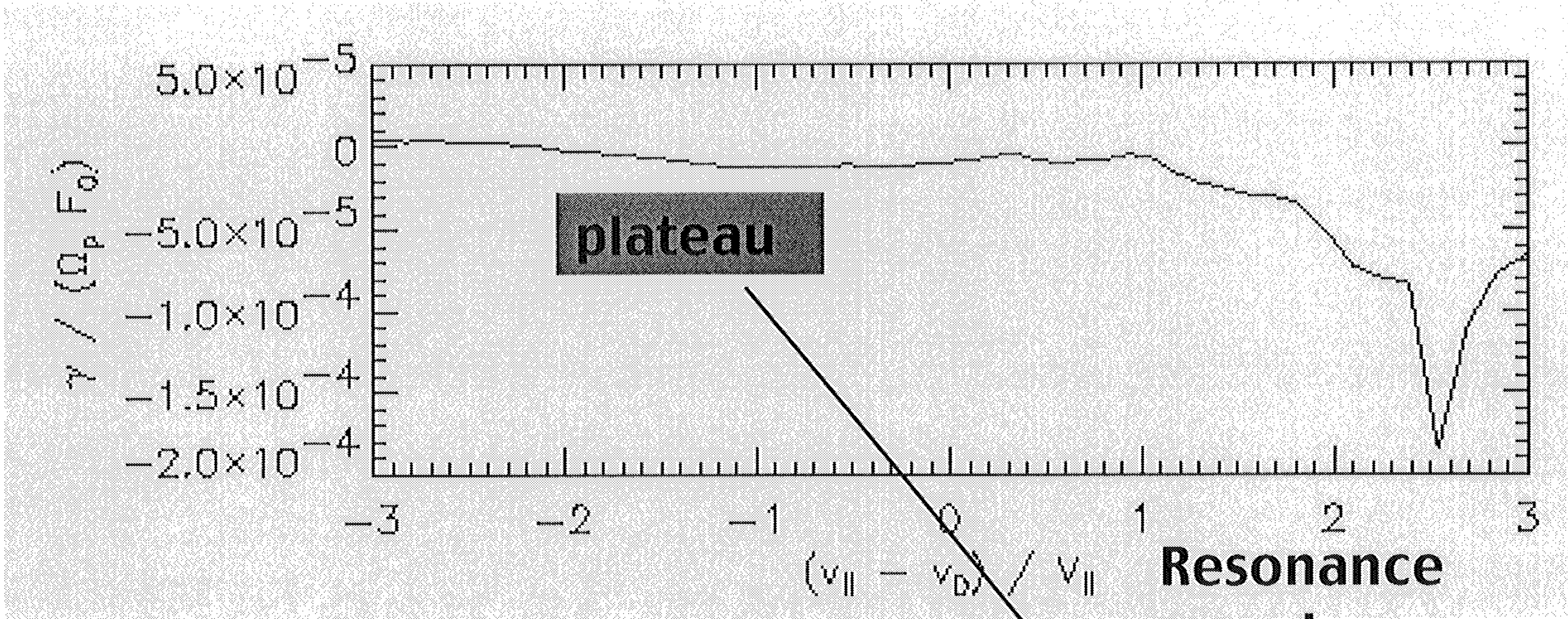
Reduced velocity distributions and anisotropy in coronal hole

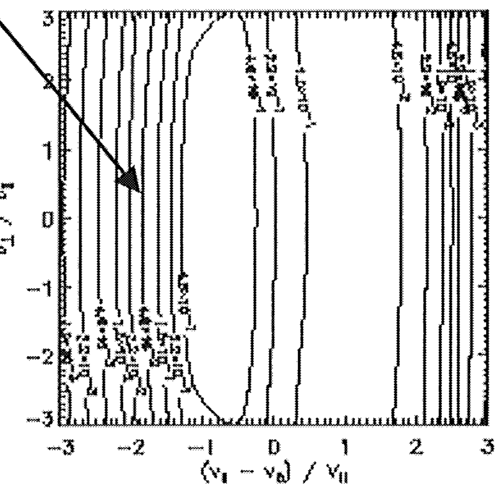


Vocks and Marsch, GRL, 28, 1917, 2001

Height = 0.43 R_s

Plateau at marginal stability





- Vanishing O^{+5} damping rate for ion-cyclotron waves
- Large temperature anisotropy

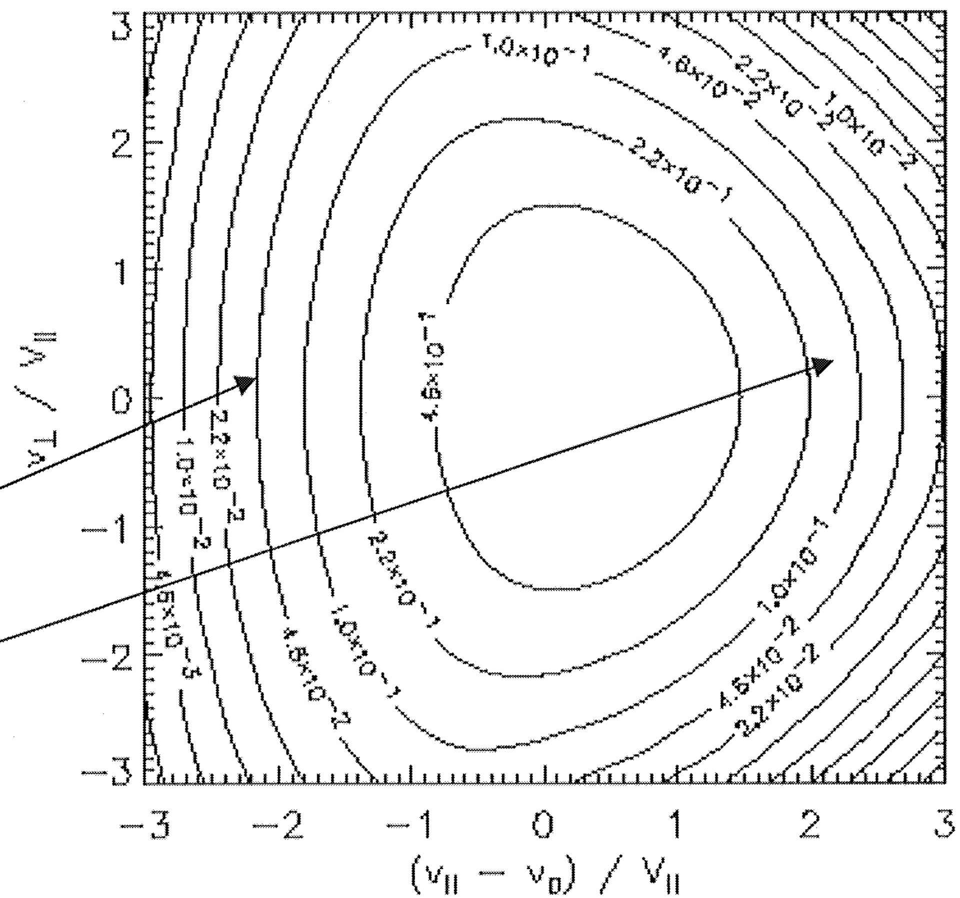
Vocks and Marsch, ApJ, 2002

1.44 R_S

Gyrotropic velocity distribution of oxygen ions in corona

- Mirror force
- Waves particle interactions
- Coulomb collisions

Heat flux and anisotropy at 1.73 R_S



Vocks and Marsch, ApJ, 2002

Obervations and semi-kinetic models of solar corona and wind

- Coronal imaging and spectroscopy indicate strong deviations of the plasma from thermal equilibrium

- Semi-kinetic particle models with with self-consistent wave spectra provide valuable physical insights

- Such models describe some essential features of the observations of the solar corona and solar wind

- But the thermodynamics of the solar corona and solar wind requires a fully-kinetic approach

- Turbulence transport as well as cascading and dissipation in the kinetic domain are not understood