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AUTUMN COLLEGE ON PLASMA PHYSICS

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Kinetic Physics of the Solar Corona and Solar Wind - II

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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

Ions and electrons – velocity distributions and kinetics

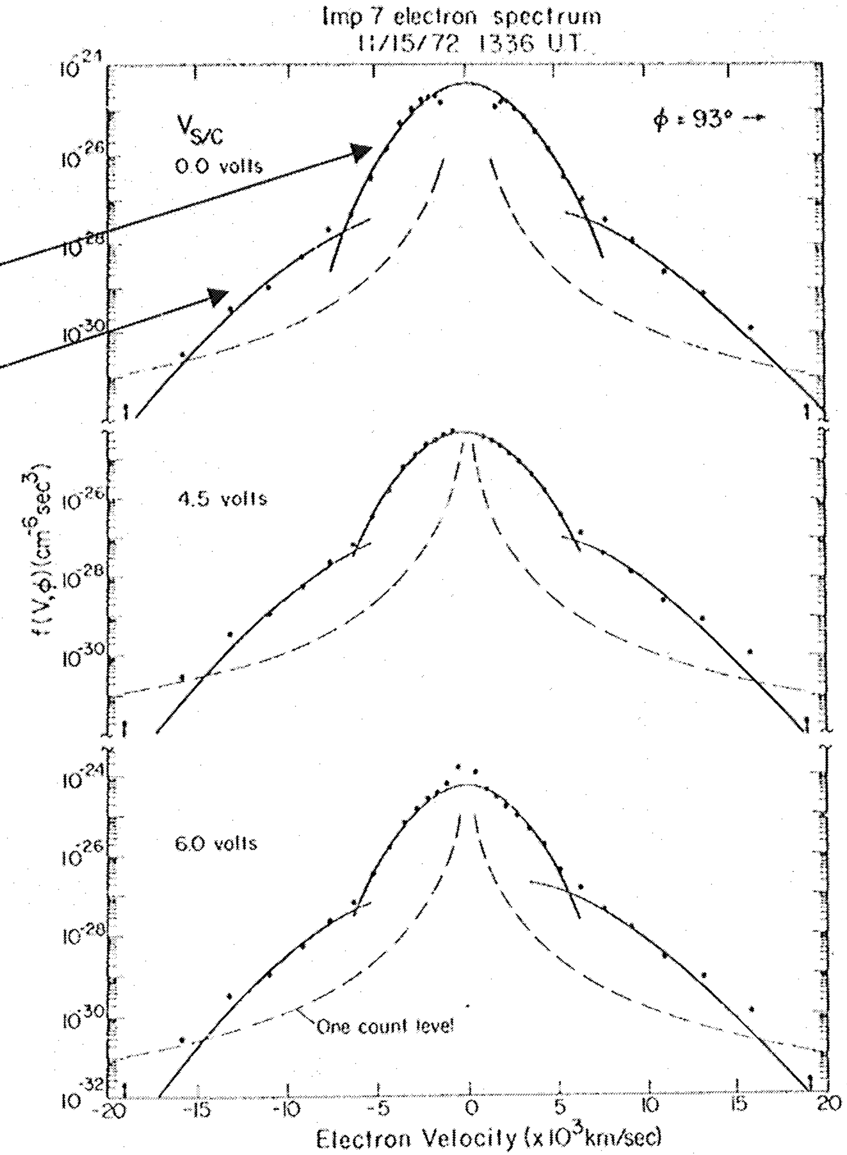
- Solar wind protons and alpha particles
- Heavy minor ions and elemental composition
- Solar wind electrons
- Coulomb collisions in coronal holes and solar wind
- Transport in a weakly collisional plasma
- Plasma waves in the solar wind
- Evidence for effects of waves on ion distributions
- Kinetic instabilities and pitch–angle scattering
- Coronal heating and ion–cyclotron resonance
- Kinetic modelling of ions in coronal holes and funnels
- Radial temperature profiles of ions and electrons
- Heating of coronal funnels and holes

Electron energy spectrum

IMP spacecraf t

Two solar wind electron populations:

- **Core (96%)**
- **Halo (4%)**

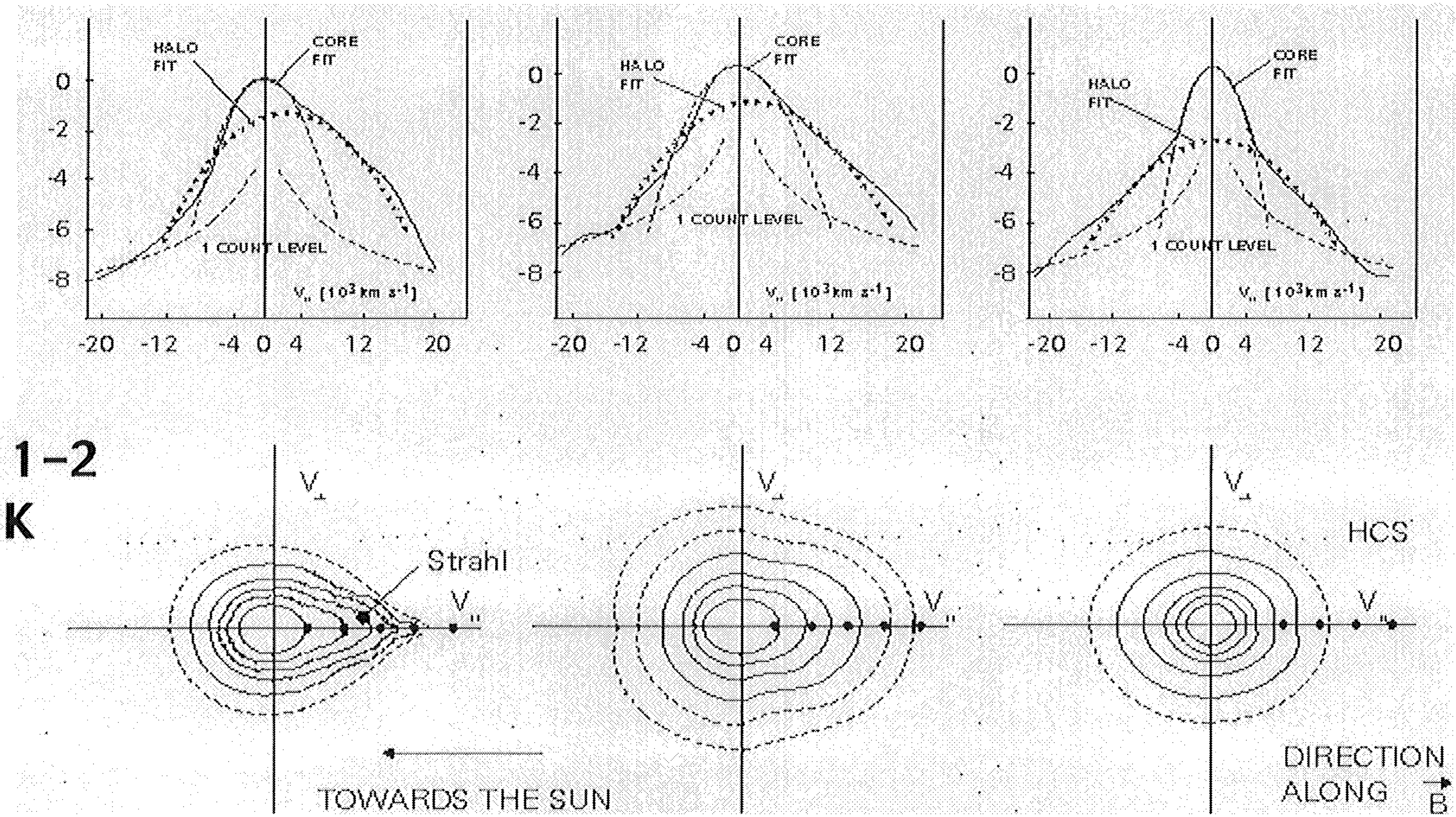


Core: local, collisional, bound by electrostatic potential

Halo: global, collisionless, free to escape (exopsheric)

Feldman et al., JGR, 80, 4181, 1975

Electron velocity distributions



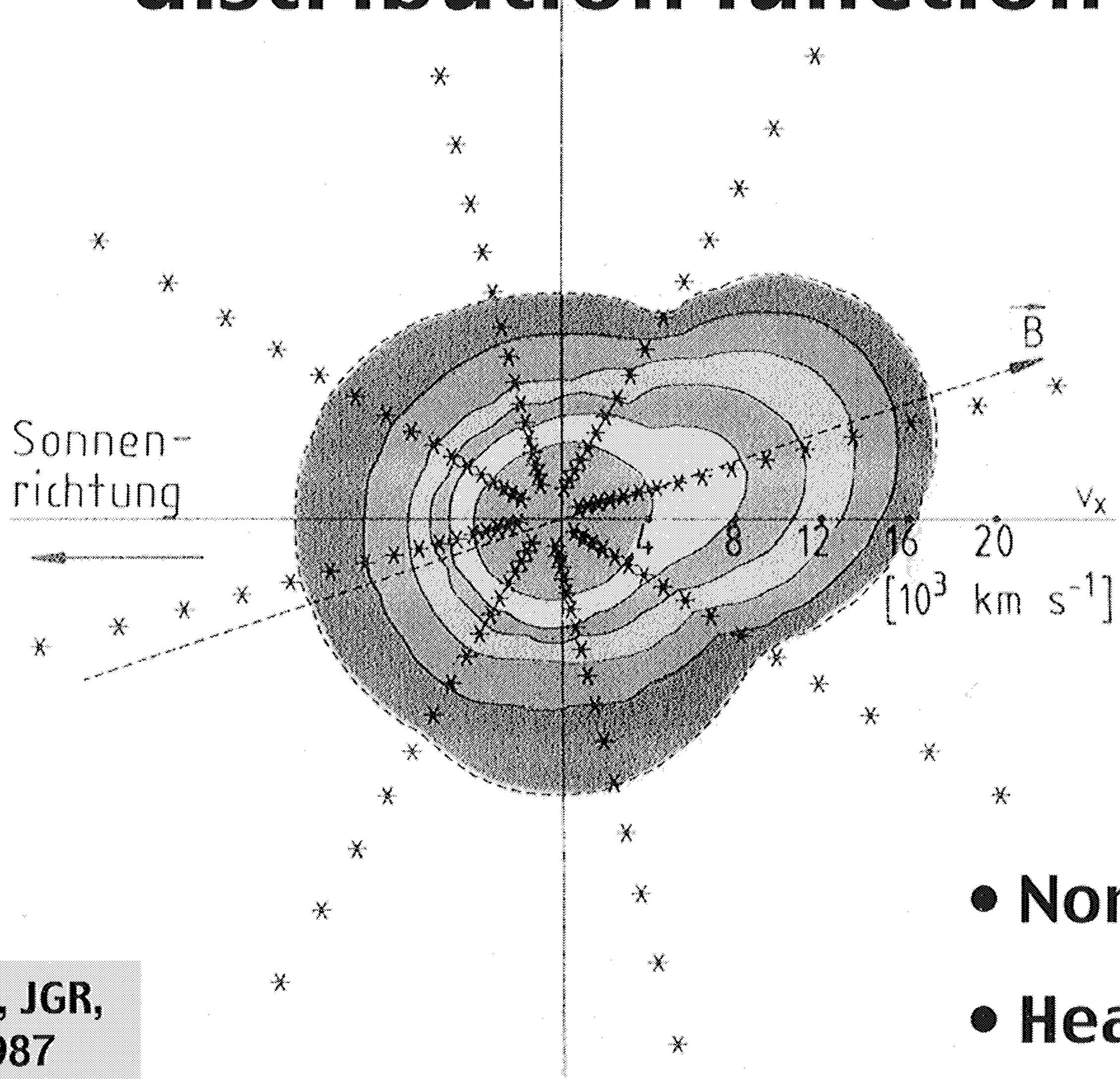
T_e = 1–2
10^5 K

high **intermediate speed** **low**

Pilipp et al., JGR, 92, 1075, 1987

Core (96%), halo (4%) electrons, and „strahl“

Electron velocity distribution function



Helios

Sun

n_e = 3–10 cm^{-3}

- Non–Maxwellian
- Heat flux tail

Pilipp et al., JGR, 92, 1075, 1987

Electron heat conduction

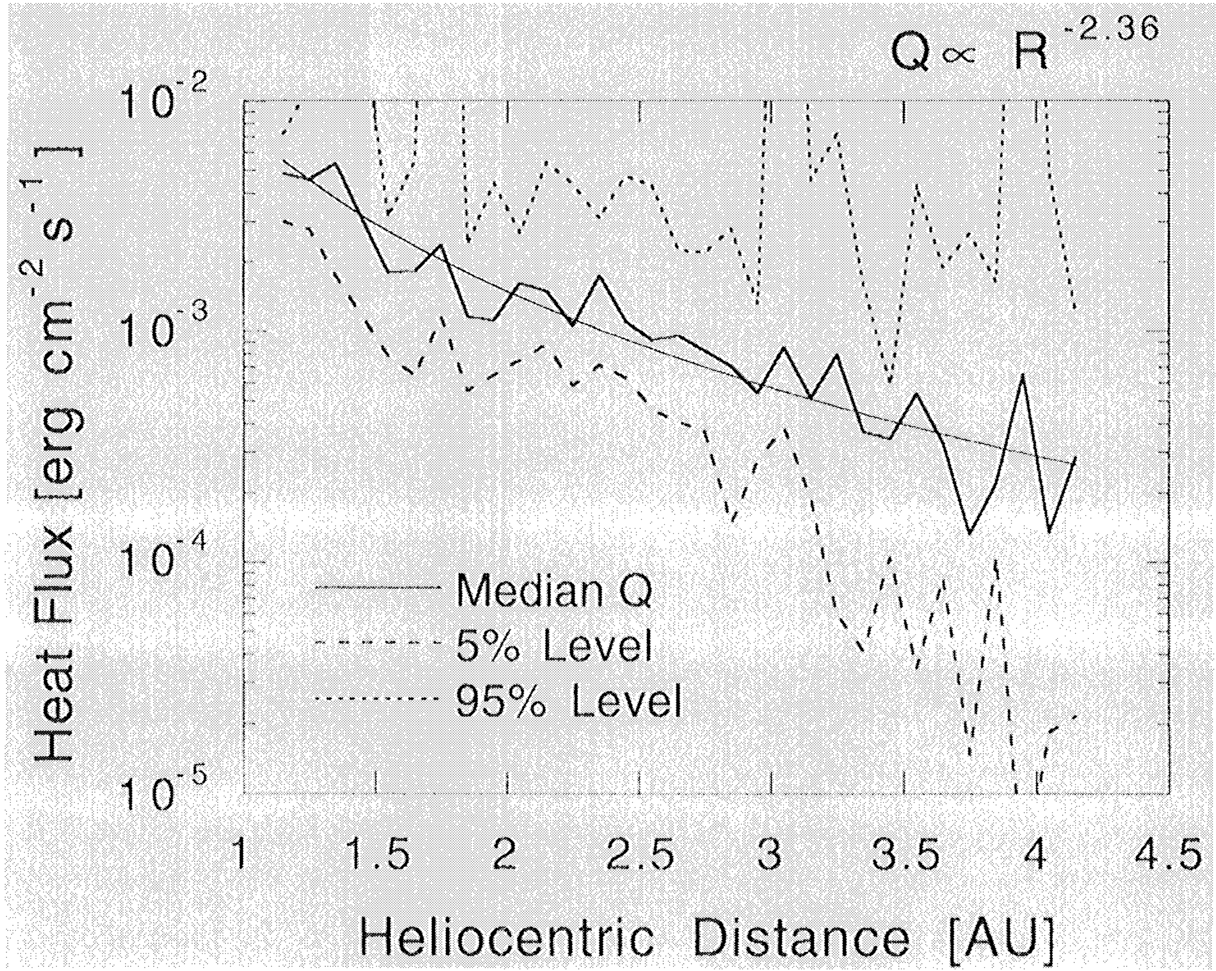
Heat carried by halo electrons!

$T_H = 7\, T_C$

Interplanetary potential:

$\Phi = 50\text{–}100$ eV

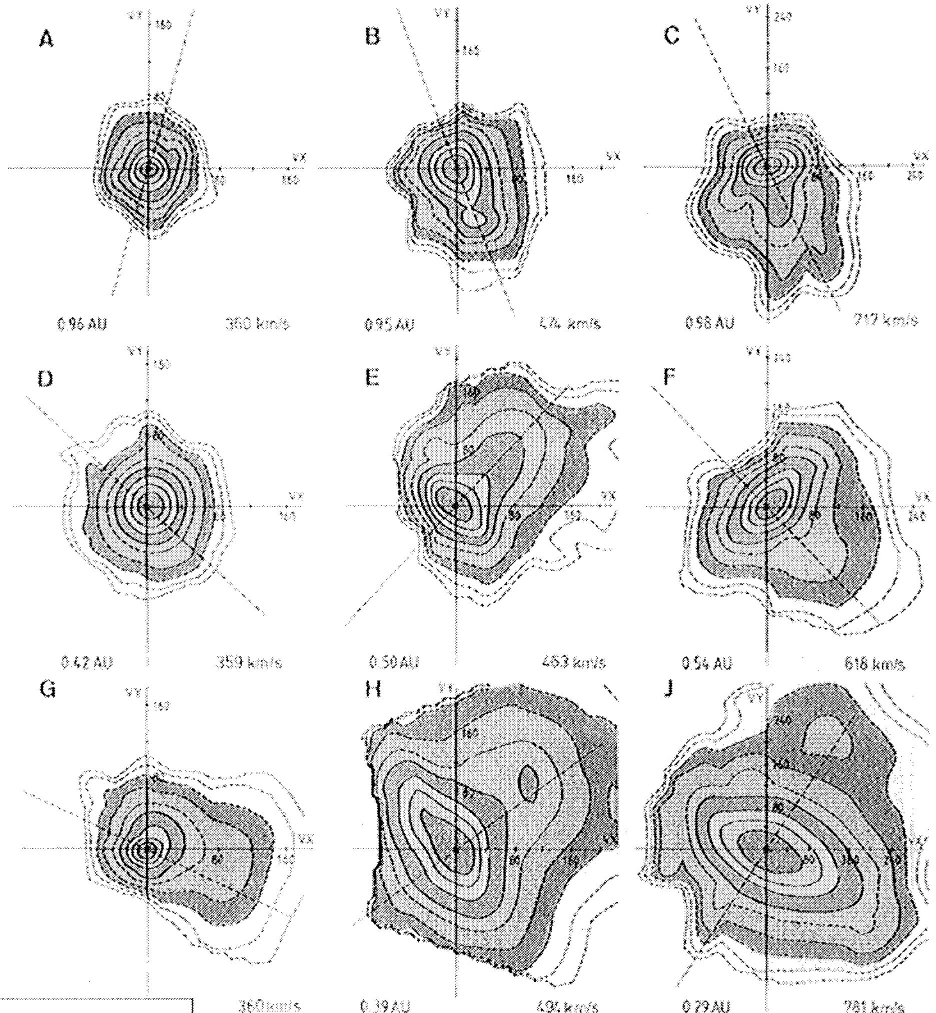
$\underline{E} = -1/n_e \, \underline{\nabla} \, p_e$



$$\underline{Q_e} \neq -\kappa \underline{\nabla}\, T_e$$

McComas et al., GRL, 19, 1291, 1992

Proton velocity distributions



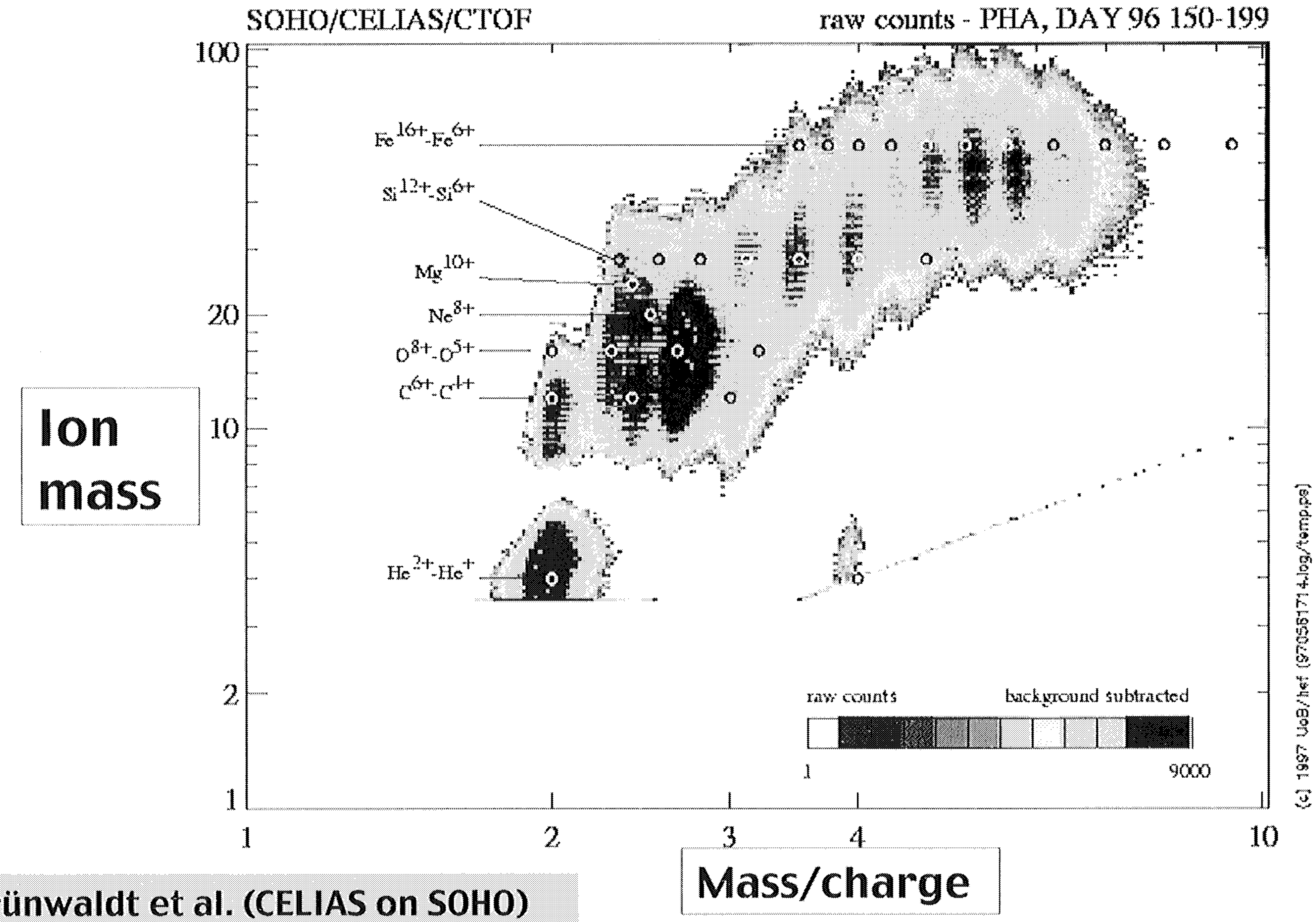
Helios

- **Temperature anisotropies**
- **Ion beams**
- **Plasma instabilities**
- **Interplanetary heating**

Plasma measurements made at 10 s resolution (> 0.29 AU from the Sun)

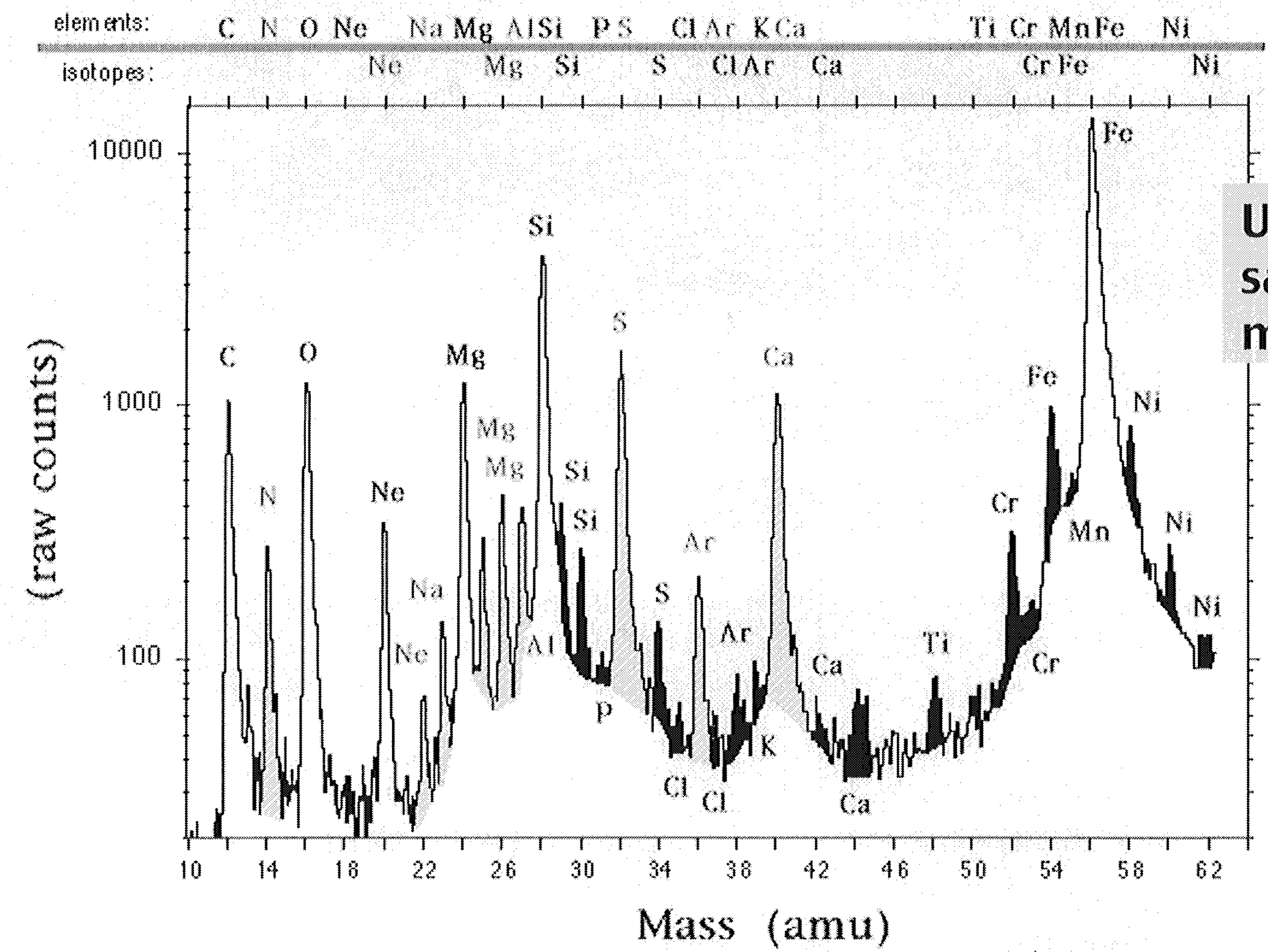
Marsch et al., JGR, 87, 52, 1982

Ion composition of the solar wind



Grünwaldt et al. (CELIAS on SOHO)

Elements (isotopes) in the solar wind



Unfractionated sample of solar material!

SOHO CELIAS/MTOF

Ipavich et al., GRL, 1998

Kinetic processes in the solar corona and solar wind I

• Plasma is multi-component and nonuniform

→ complexity

• Plasma is dilute

→ deviations from local thermal equilibrium

→ suprathermal particles (electron strahl)

→ global boundaries are reflected locally

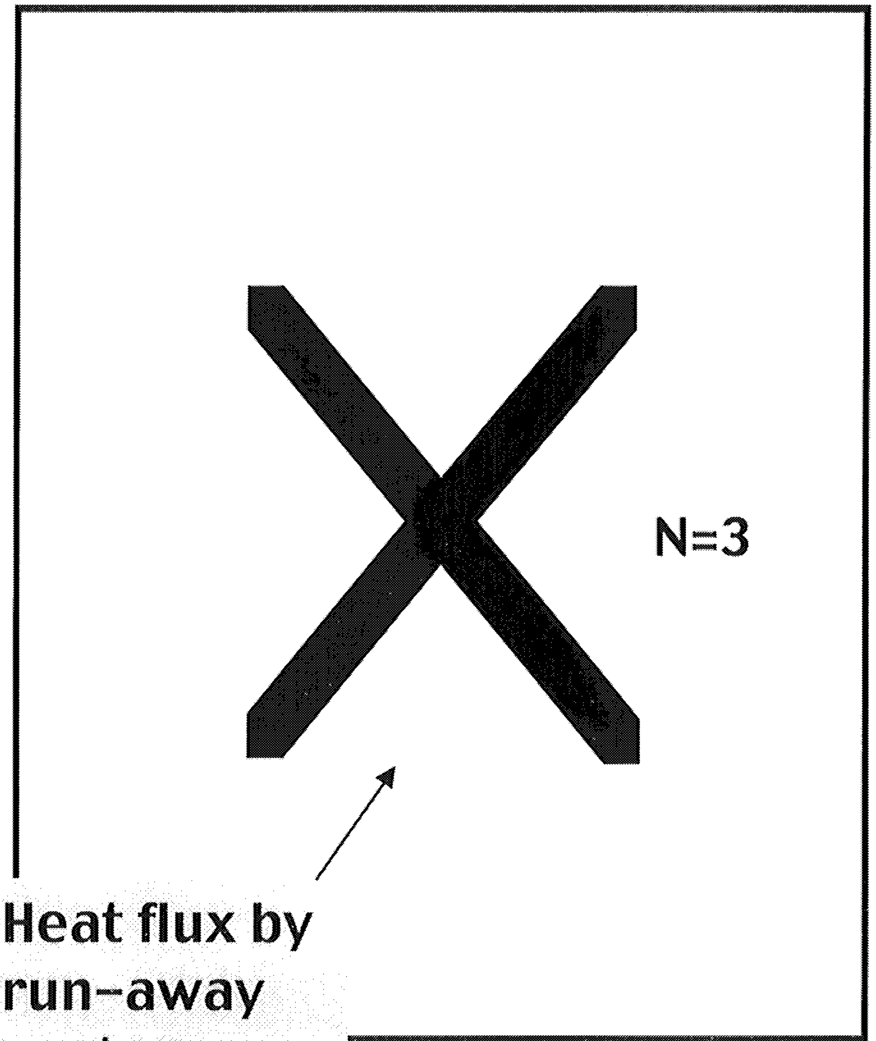
Problem: Thermodynamics of the plasma, which is far from equilibrium.....

Coulomb collisions

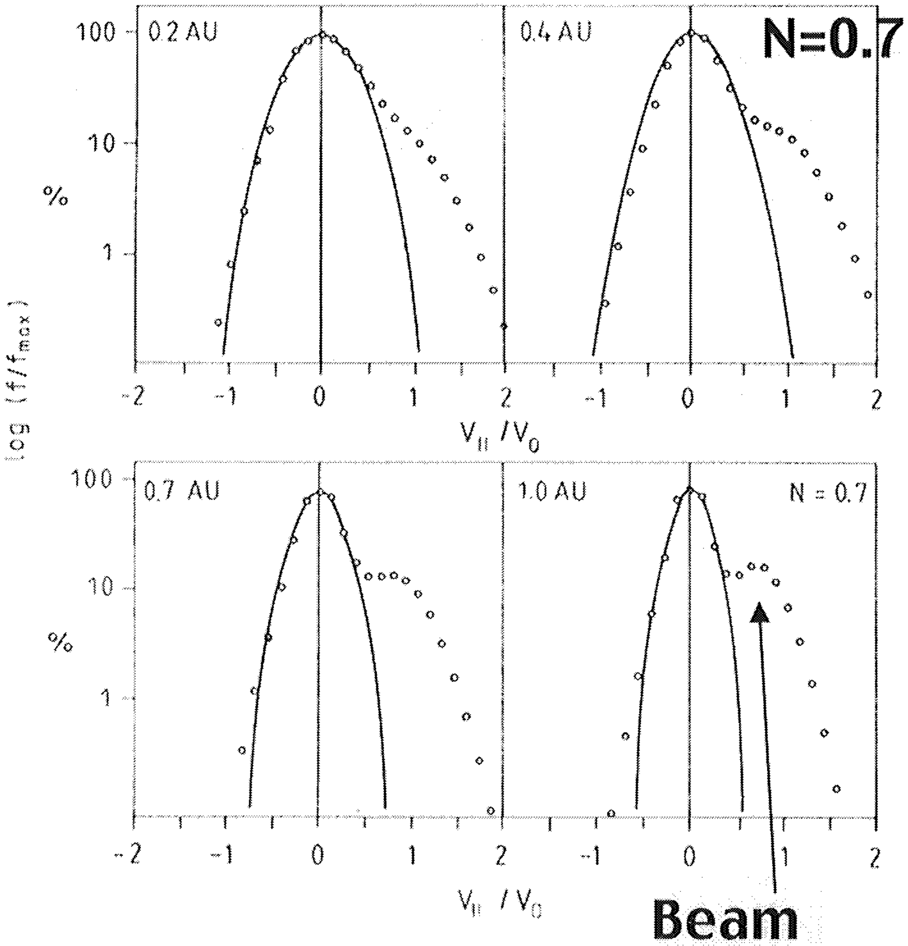
Parameter	Chromo -sphere	Corona ($1R_S$)	Solar wind (1AU)
n_e (cm^{-3})	10^{10}	10^7	10
T_e (K)	10^3	1-2 10^6	10^5
λ (km)	10	1000	10^7

- Since N < 1, Coulomb collisions require kinetic treatment!
- Yet, only a few collisions (N $\geq$ 1) remove extreme anisotropies!
- Slow wind: N > 5 about 10%, N > 1 about 30–40% of the time.

Coulomb collisions in slow wind

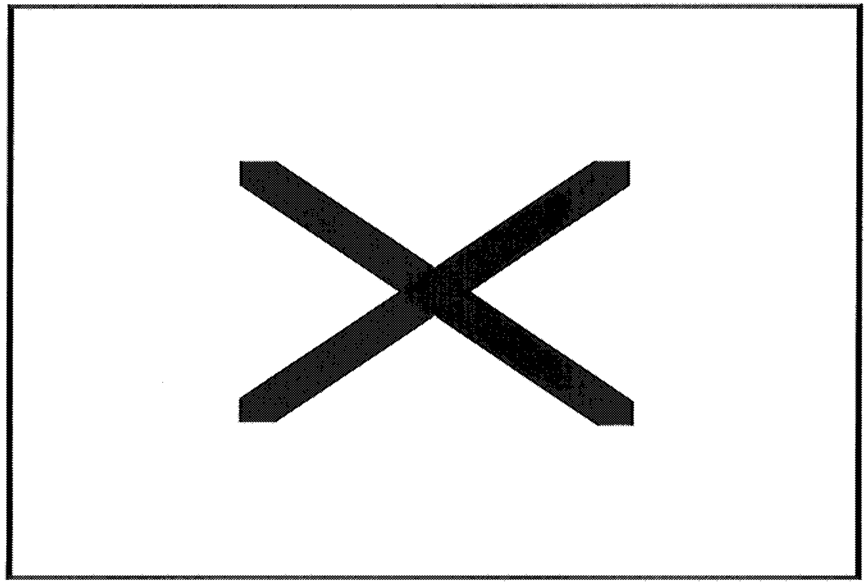


Heat flux by run-away protons



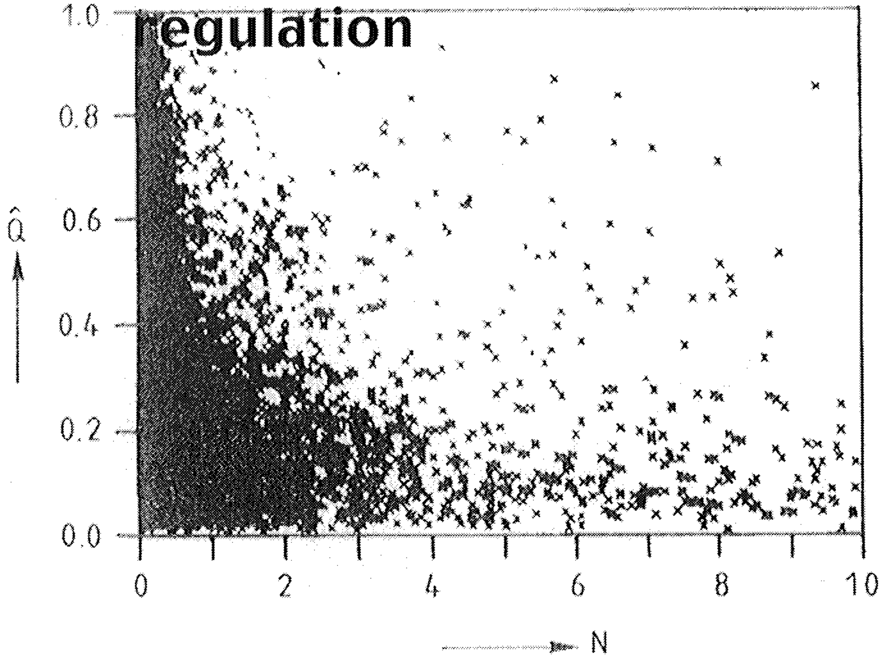
Marsch and Livi, JGR, 92, 7255, 1987

Proton Coulomb collision statistics



- Fast protons are collisionless!
- Slow protons show collision effects!

Proton heat flux regulation

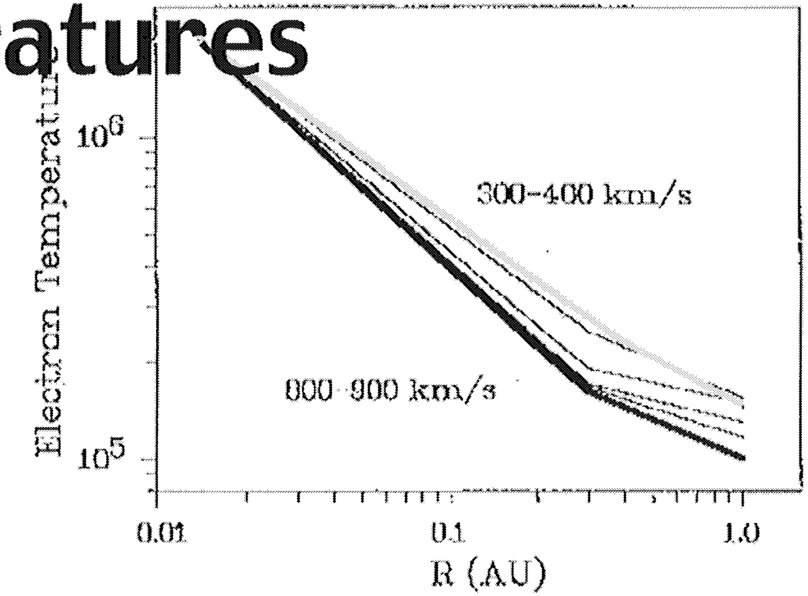


$$N = \tau_{exp} \nu_c \sim n_p V^{-1} T_p^{-3/2}$$

Livi et al., JGR, 91, 8045, 1986

Proton and electron temperatures

Electrons are cool!

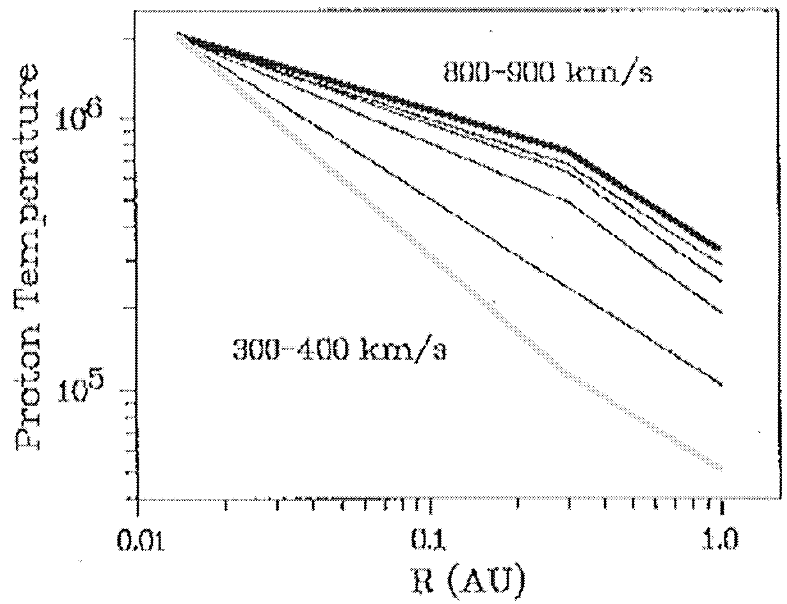


slow wind

↓

fast wind

Protons are hot!



fast wind

↓

slow wind

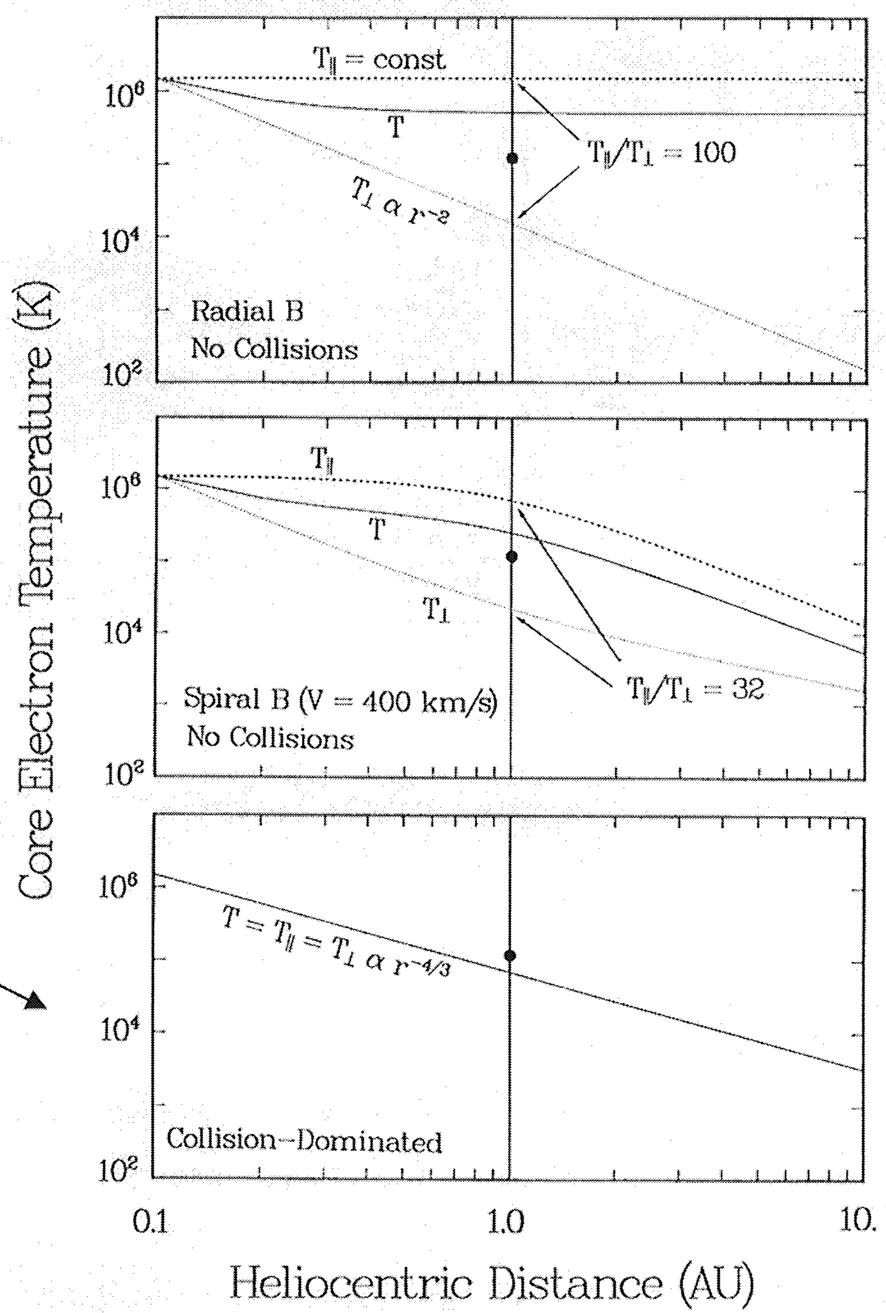
Marsch, 1991

Collisions and geometry

Double adiabatic invariance, → extreme anisotropy not observed!

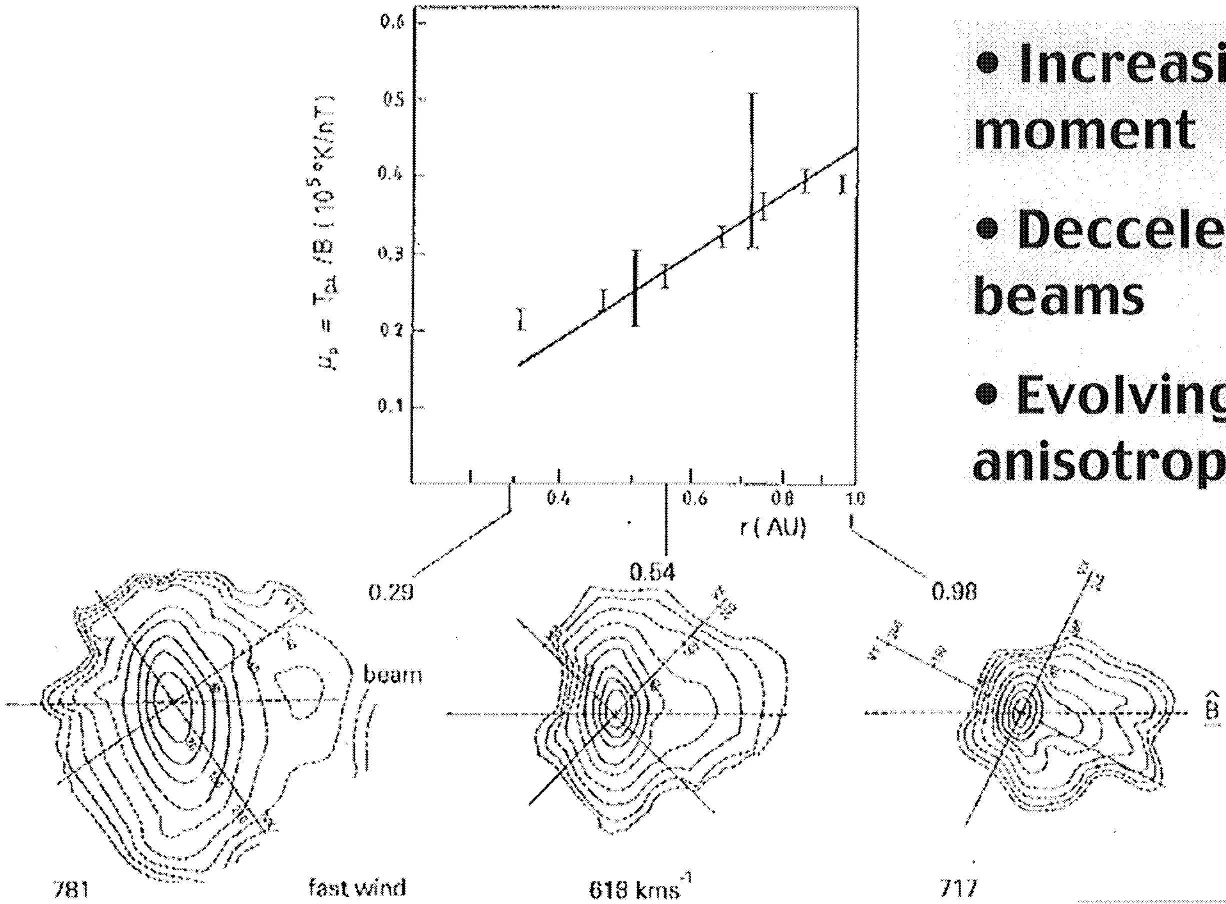
Spiral reduces anisotropy!

Adiabatic collision-dominated → isotropy, is not observed!



Philipps and Gosling, JGR, 1989

Heating of protons by cyclotron and Landau resonance



- Increasing magnetic moment
- Deccelerating proton/ion beams
- Evolving temperature anisotropy

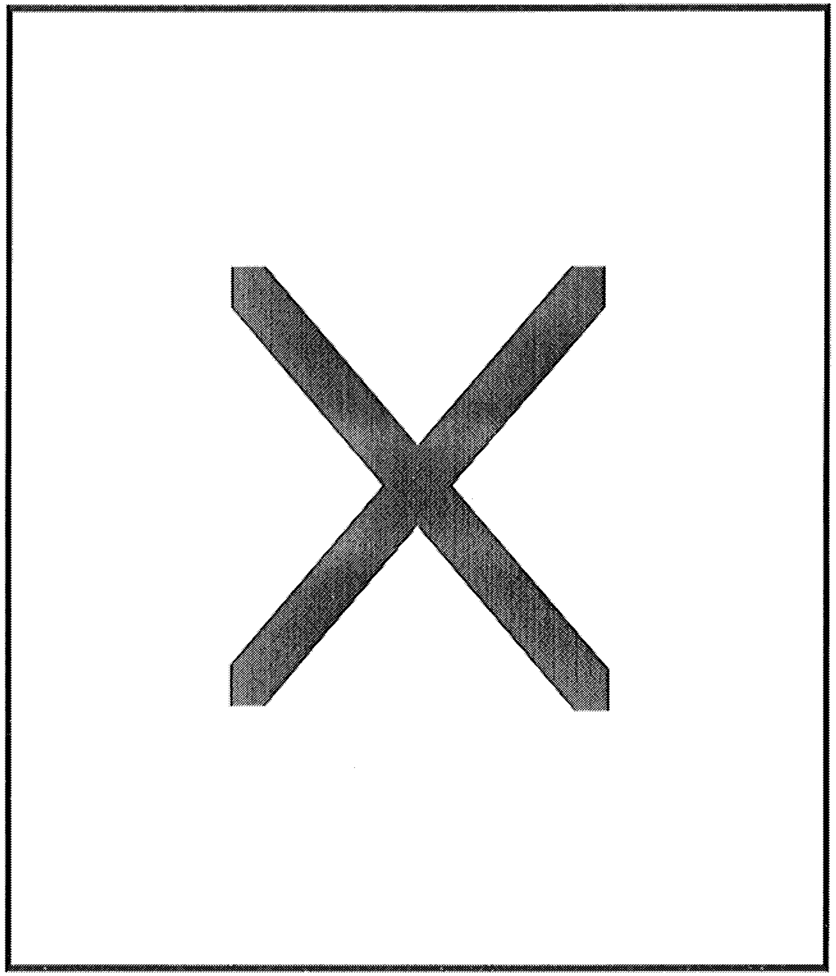
Velocity distribution functions

Marsch et al., JGR, 87, 52-72, 1982

Kinetic plasma instabilities

- Observed velocity distributions at margin of stability
- Selfconsistent quasi- or non-linear effects not well understood
- Wave-particle interactions are the key to understand ion kinetics in corona and solar wind!

Marsch, 1991; Gary, Space Science Rev., 56, 373, 1991



Wave-particle interactions

Dispersion relation using measured or model distribution functions $f(\underline{v})$, e.g. for electrostatic waves:

$$\varepsilon_L(\underline{k},\omega) = 0 \rightarrow \omega(\underline{k}) = \omega_r(\underline{k}) + i\gamma(\underline{k})$$

Dielectric constant is functional of $f(\underline{v})$, which may when being non-Maxwellian contain free energy for wave excitation.

$\gamma(\underline{k}) > 0 \rightarrow$ micro-instability......

Resonant particles:

$\omega(\underline{k}) - \underline{k}\cdot\underline{v} = 0$ (Landau resonance)

$\omega(\underline{k}) - \underline{k}\cdot\underline{v} = \pm\,\Omega_j$ (cyclotron resonance)

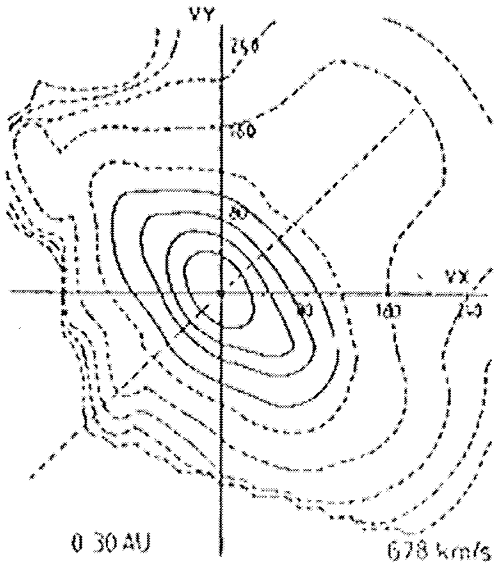
→ Energy and momentum exchange between waves and particles. Quasi-linear or non-linear relaxation.....

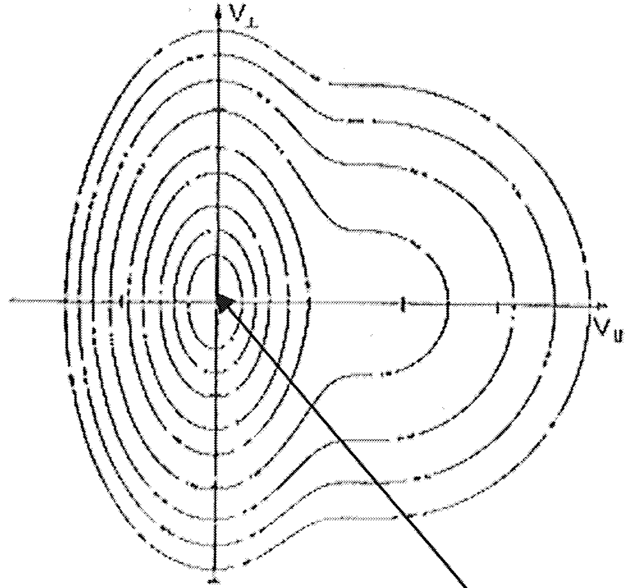
Proton temperature anisotropy

- Measured and modelled proton velocity distribution
- Growth of ion-cyclotron waves!
- Anisotropy-driven instability by large pe

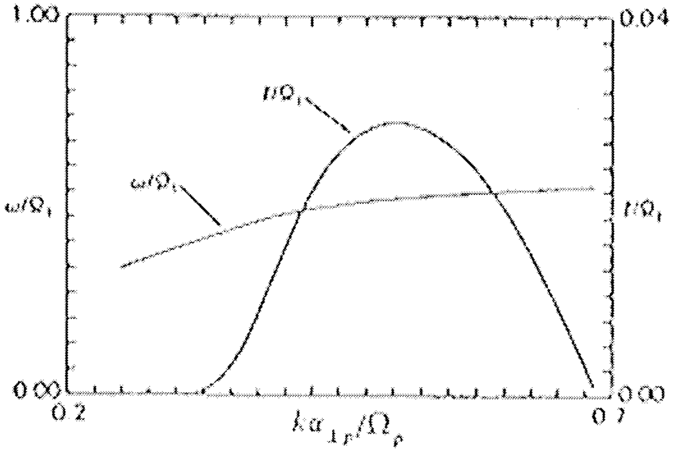
$\omega \approx 0.5\Omega_p$ ⊥

$\gamma \approx 0.05\Omega_p$





anisotropy



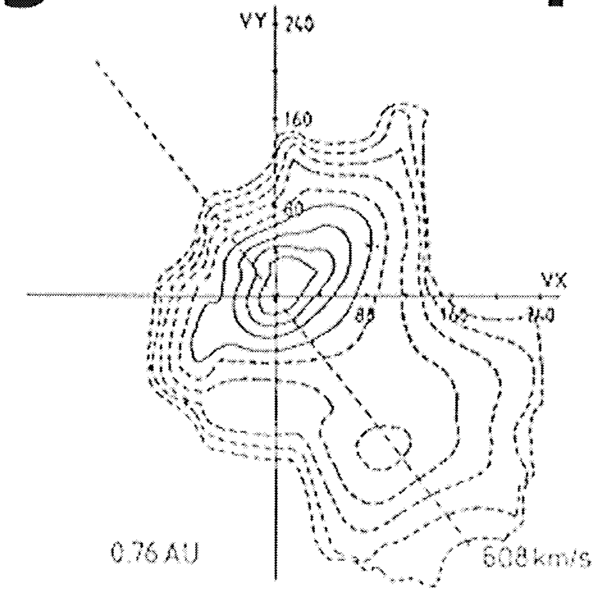
Marsch, 1991

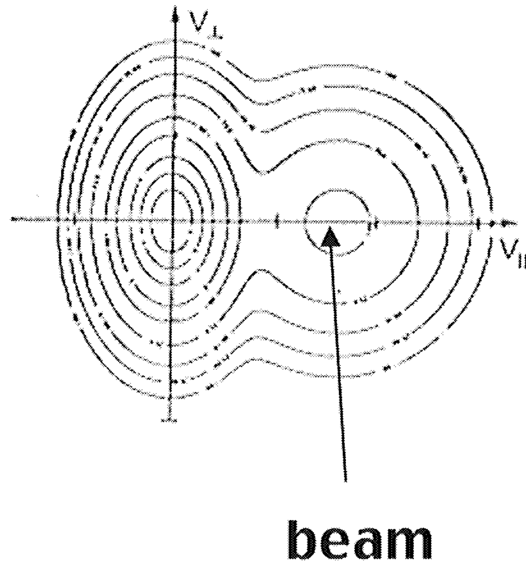
Wave regulation of proton beam

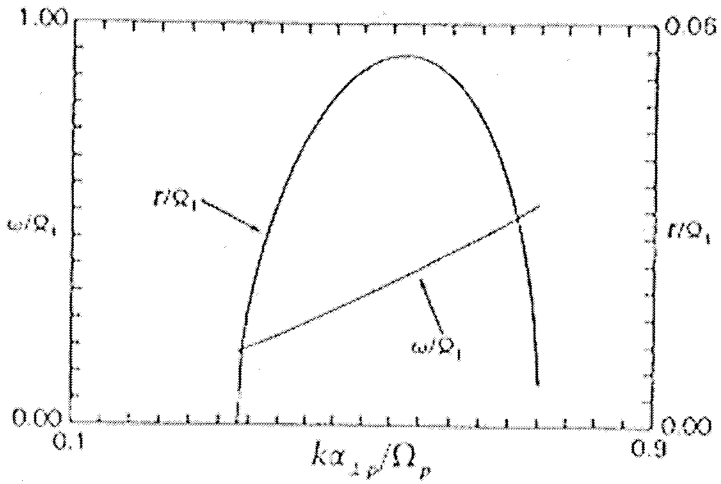
- Measured and modelled velocity distribution
- Growth of fast mode waves!
- Beam-driven instability, large drift speed

$\omega \approx 0.4\Omega_p$

$\gamma \approx 0.06\Omega_p$



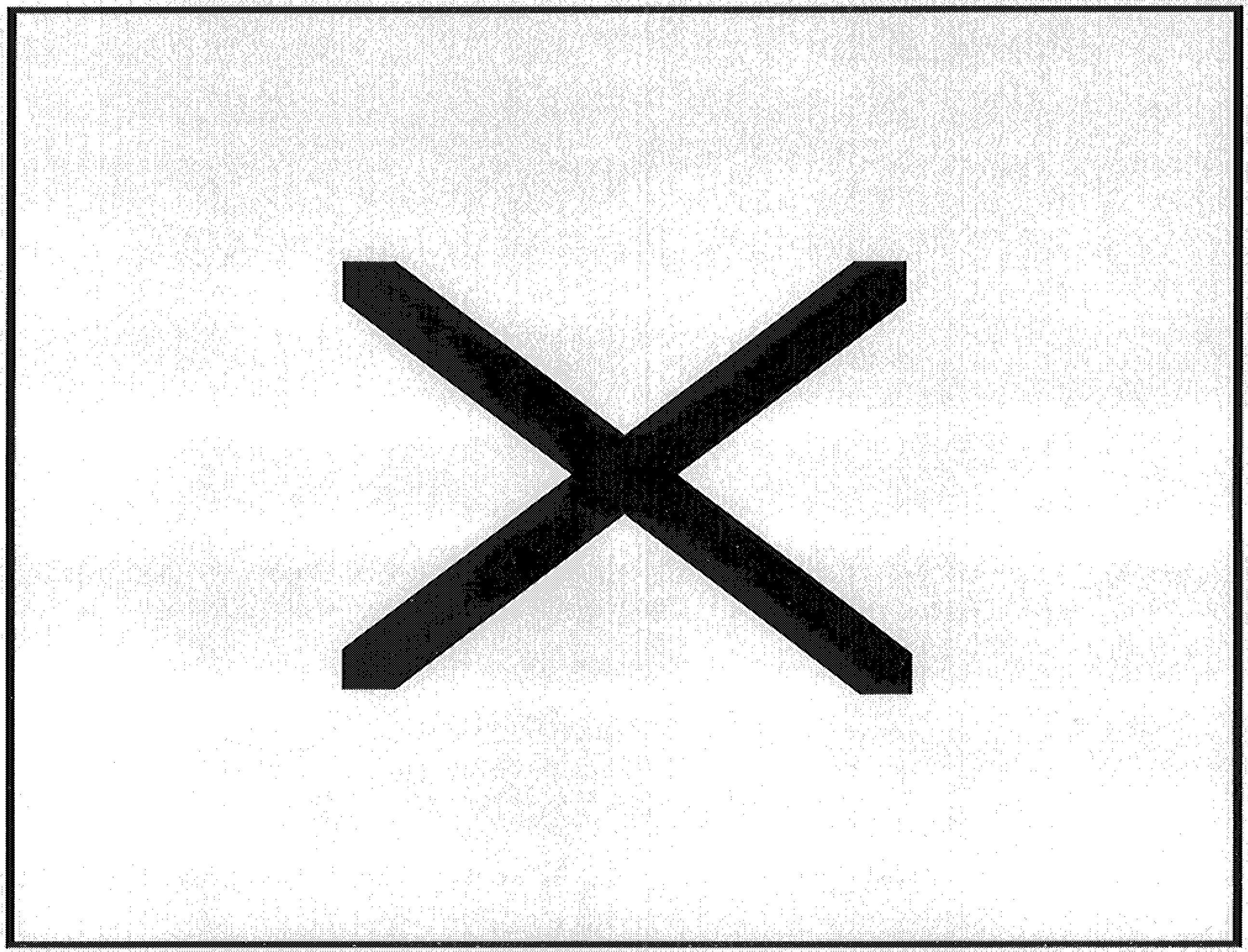




Marsch, 1991

Electromagnetic ion beam instabilities

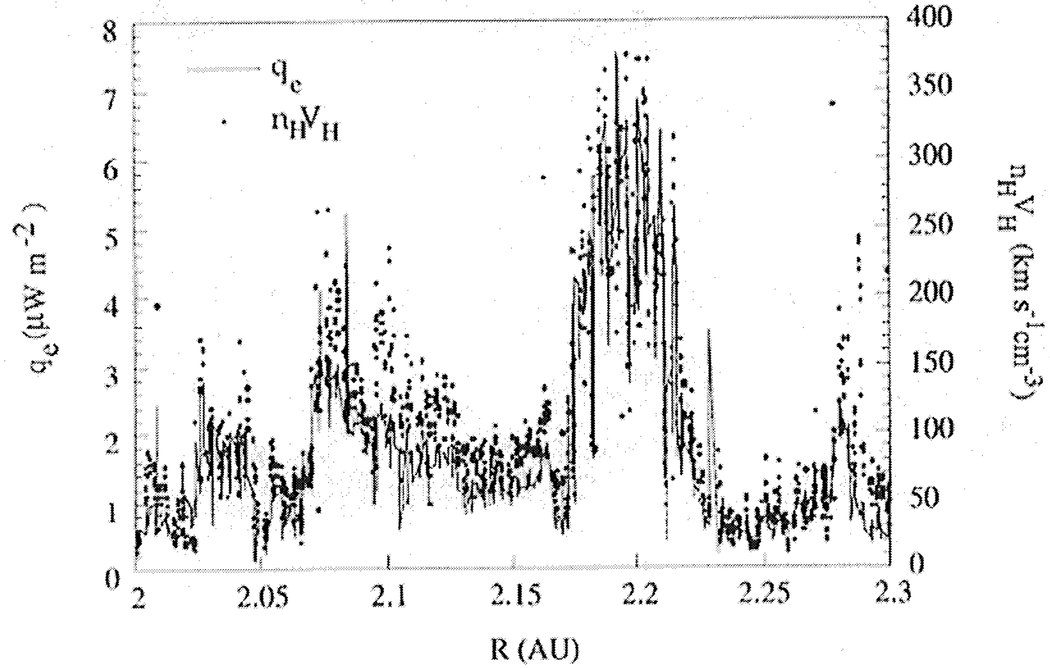
Maximum growth rate

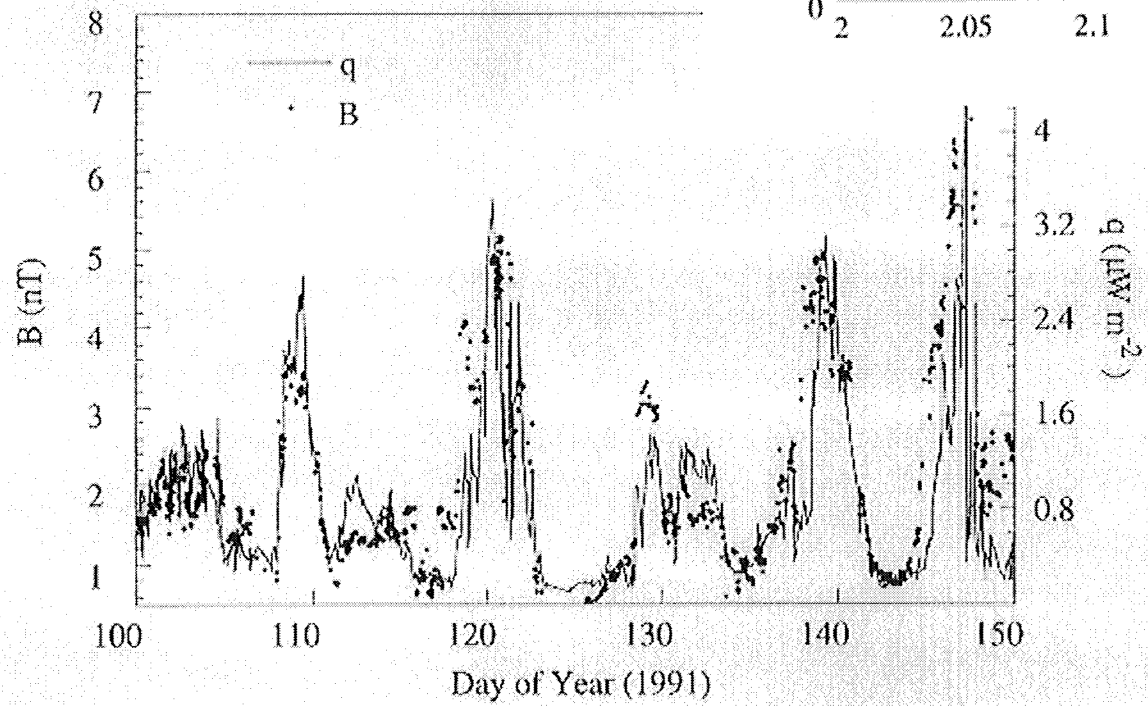


Daughton and Gary, JGR, 1998

Proton beam drift speed

Whistler regulation of electron heat flux





- Halo electrons carry heat flux
- Heat flux varies with B or V_A
- Whistler instability regulates drift

Sime et al., JGR, 1994

Kinetic processes in the solar corona and solar wind II

• Plasma is multi–component and nonuniform

→ multi–fluid or kinetic physics is required

• Plasma is dilute and turbulent

→ free energy for micro–instabilities

→ resonant wave–particle interactions

→ collisions by Fokker–Planck operator

Problem: Transport properties of the plasma, which involves multiple scales.....

Length scales in the solar wind

Macrostructure – fluid scales

• Heliocentric distance:	r	150 Gm (1 AU)
• 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!

Theoretical description

Boltzmann-Vlasov kinetic equations for protons, alpha-particles (4%), minor ions and electrons

↙ ↘

Distribution functions

Kinetic equations

+ Coulomb collisions (Landau)
+ Wave-particle interactions
+ Micro-instabilities (Quasilinear)
+ Boundary conditions

→ **Particle velocity distributions and field**

Momen ts

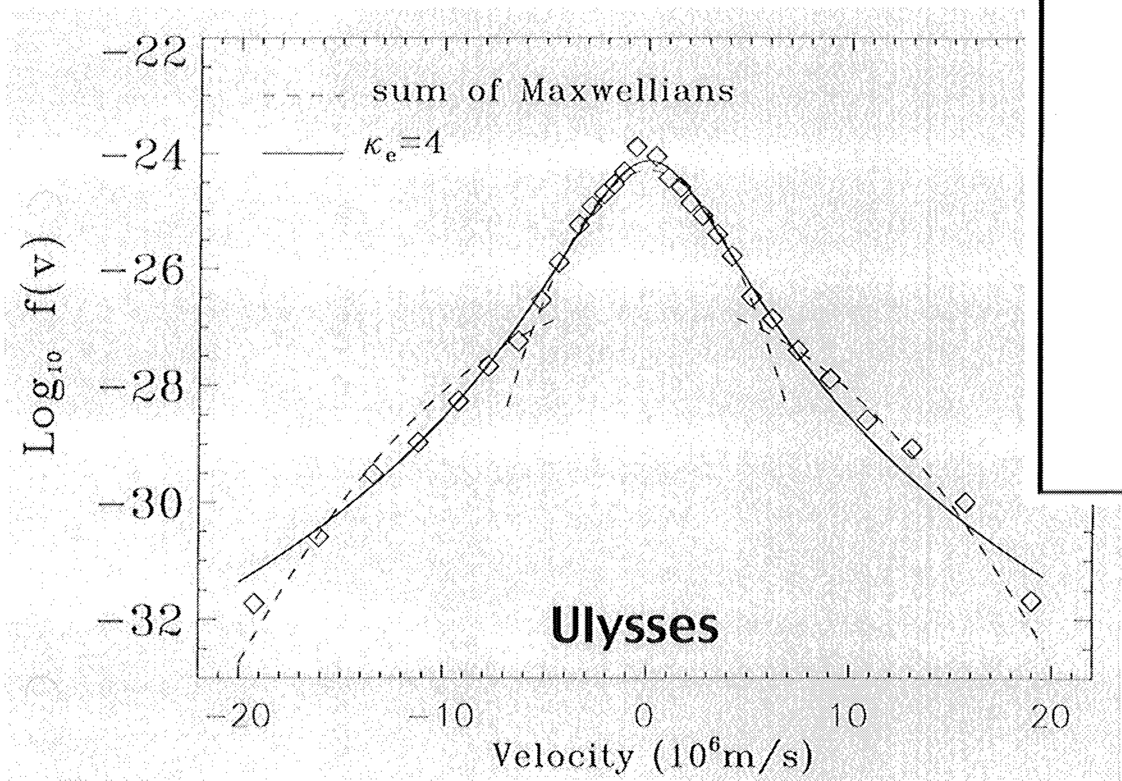
Multi-Fluid (MHD) equations

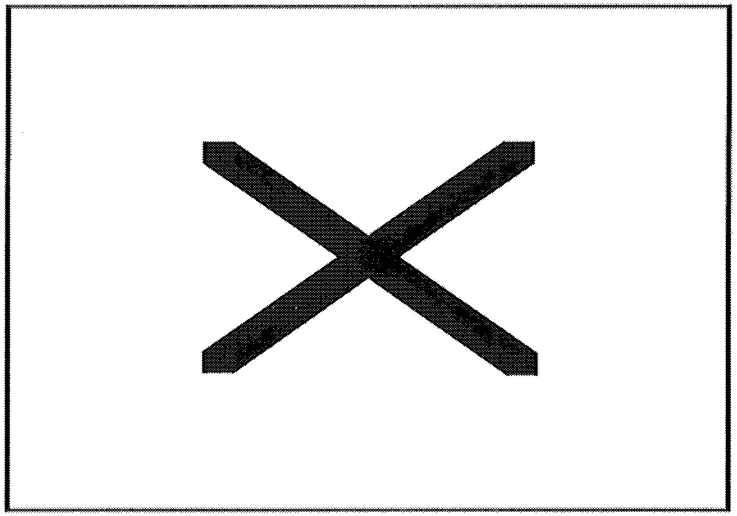
+ Collision terms
+ Wave (bulk) forces
+ Energy addition
+ Boundary conditions

→ **Single/multi fluid parameters**

Solar electron exosphere and velocity filtration

That suprathermal electrons drive solar wind through electric field is not compatible with coronal and in-situ observations!





Maksimovic et al., A&A, 1997

Fluid equations

- Mass flux: $F_M = \rho\, V A \qquad \rho = n_p m_p + n_i m_i$
- Magnetic flux: $F_B = B A$
- Total momentum equation:

  $V\, d/dr\, V = -1/\rho\, d/dr\, (p + p_w) - GM_S/r^2 + a_w$

- Thermal pressure: $p = n_p k_B T_p + n_e k_B T_e + n_i k_B T_i$
- MHD wave pressure: $p_w = (\delta B)^2/(8\pi)$
- Kinetic wave acceleration: $a_w = (\rho_p a_p + \rho_i a_i)/\rho$
- Stream/flux-tube cross section: $A(r)$

Energy equations

Parallel thermal energy

$$\frac{d}{dr}v_{\|j}^2 = -2v_{\|j}^2\left(\frac{1}{u_j}\frac{du_j}{dr}\right) + \frac{2q_{\|j}}{u_j} + (Q_{\|j} + S_{\|j})/u_j$$

w–p terms + sources + sinks

Perpendicula rthermal energy

$$\frac{d}{dr}v_{\perp j}^2 = -v_{\perp j}^2\left(\frac{1}{A}\frac{dA}{dr}\right) + \frac{q_{\perp j}}{u_j} + (Q_{\perp j} + S_{\perp j})/u_j$$

Heating functions: $q_{\perp,\|}$ .... ?

Wave energy absorption/emission by wave–particle interactions !

Conduction/collisional exchange of heat + radiative losses

Heating and acceleration of ions by cyclotron and Landau resonance

$$\begin{pmatrix} \frac{\partial}{\partial t} U_{j\|} \\ \frac{\partial}{\partial t} V_{j\|}^2 \\ \frac{\partial}{\partial t} V_{j\perp}^2 \end{pmatrix} \quad \begin{matrix} = a_j & \text{acceleration} \\ = 2\, q_{j\|} & \text{parallel heating} \\ = q_{j\perp} & \text{perpendicular heating} \end{matrix}$$

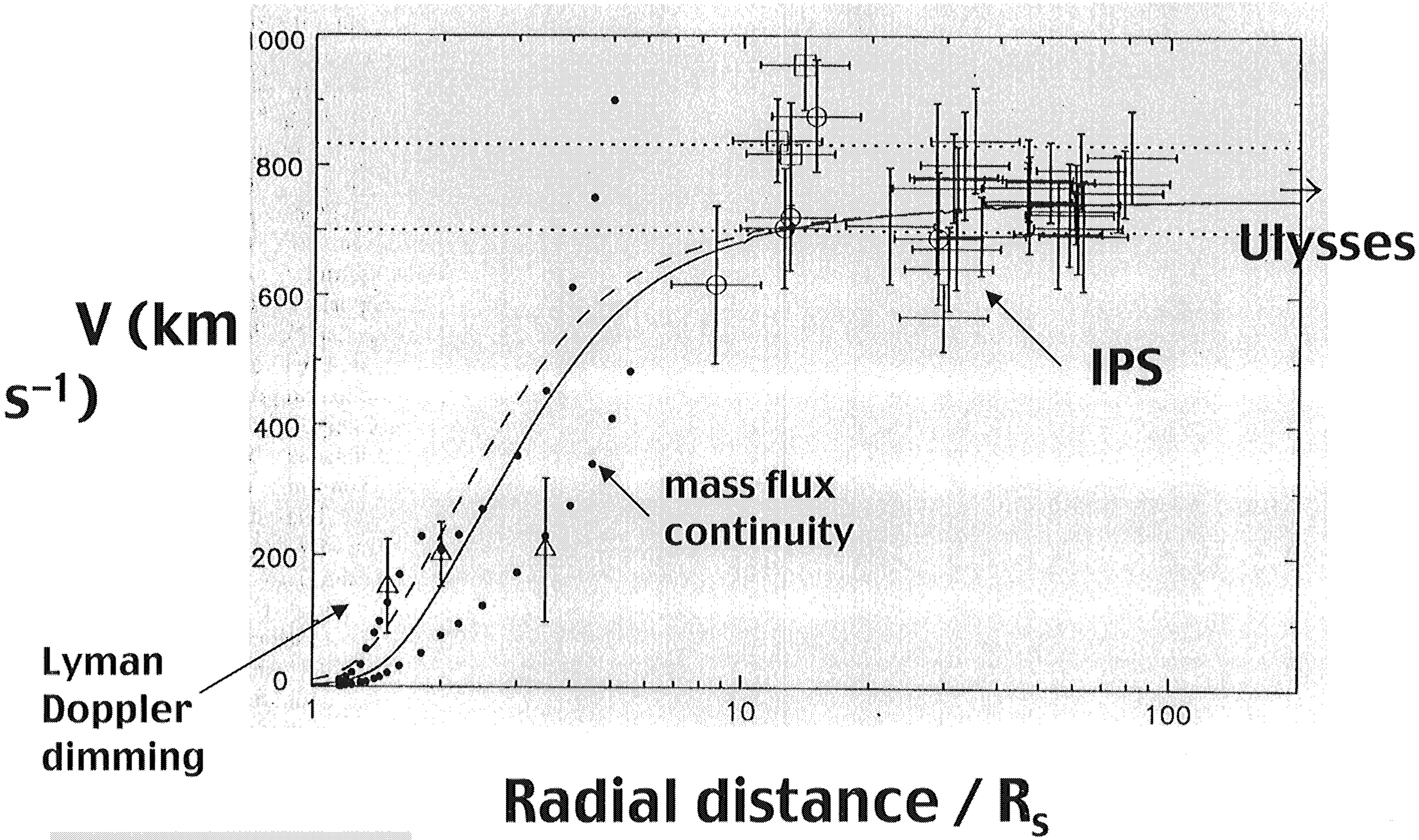
$$= \frac{1}{(2\pi)^3} \int_{-\infty}^{+\infty} d^3k \sum_M \mathcal{B}_M(\mathbf{k}) \left(\frac{\Omega_j}{k}\right)^2 \frac{1}{1 - |\hat{\mathbf{k}} \cdot e_M(\mathbf{k})|^2}$$

$$\times \sum_{s=-\infty}^{+\infty} \mathcal{R}_j(\mathbf{k}, s) \begin{pmatrix} k_\| \\ 2k_\| w_j(\mathbf{k}, s) \\ s\Omega_j \end{pmatrix}$$

Wave spectrum ?
Wave dispersion ?
Resonance function ?

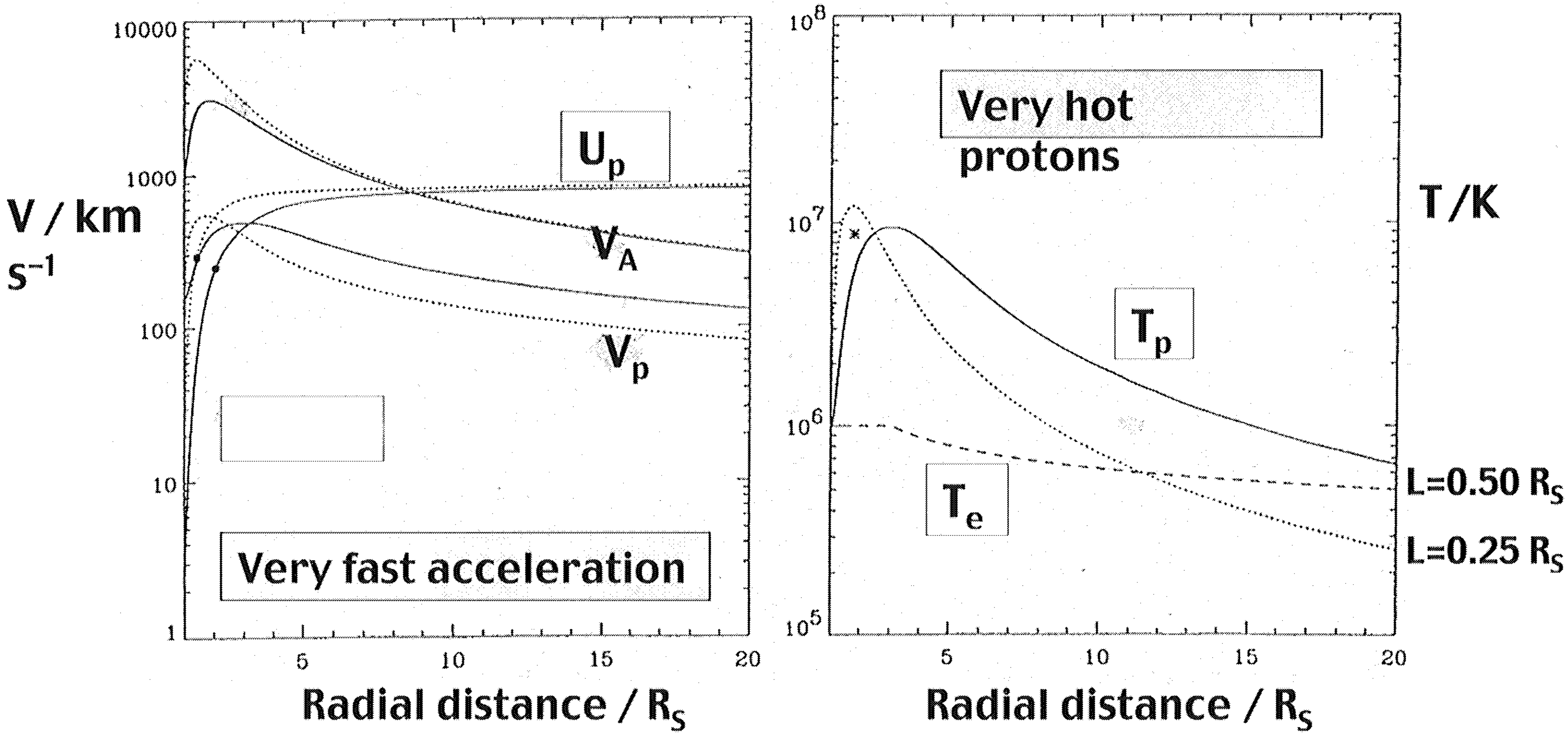
Marsch and Tu, JGR, 106, 227, 2001

Fast solar wind speed profile



Esser et al., ApJ, 1997

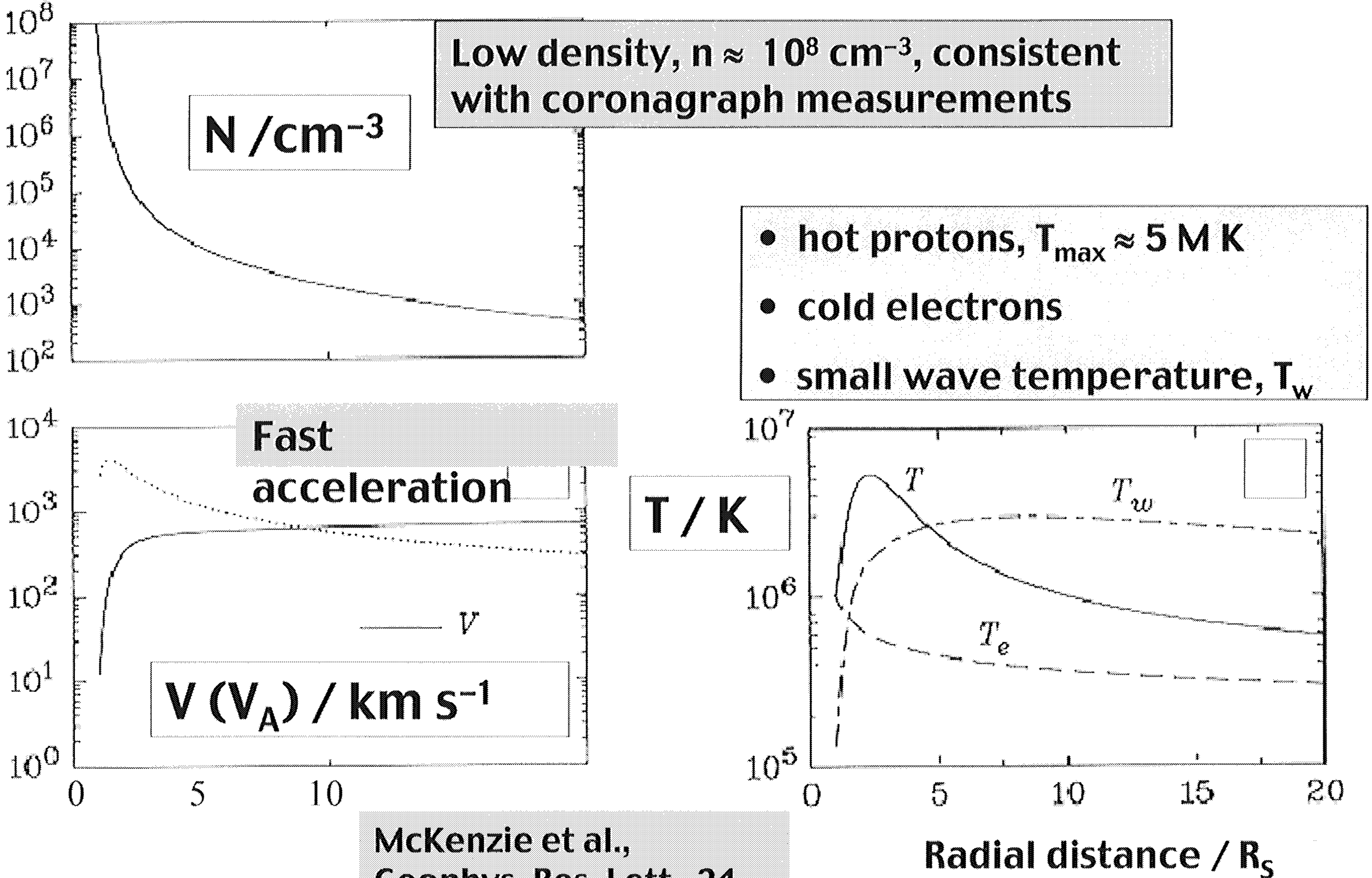
Rapid acceleration of the high-speed solar wind



McKenzie et al., A&A, 303, L45, 1995

Heating: $Q = Q_0 \exp(-(r - R_S)/L)$; Sonic point: $r \approx 2\ R_S$

Model of the fast solar wind



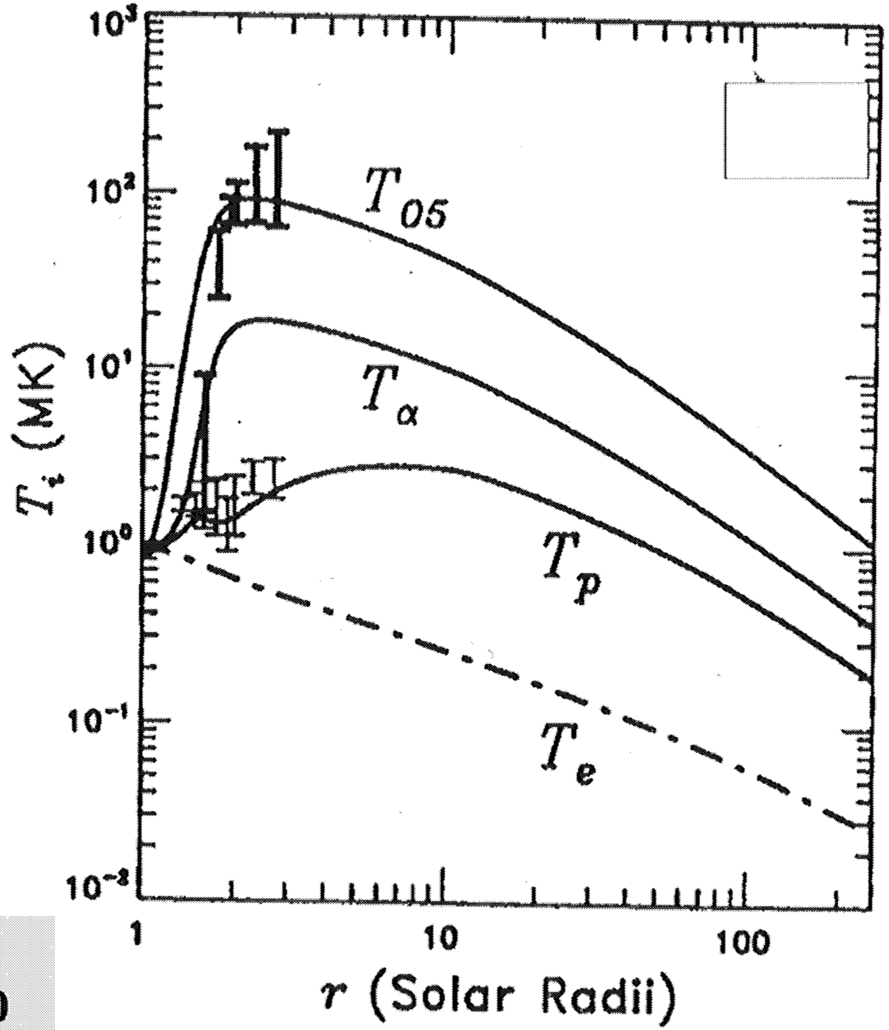
McKenzie et al., Geophys. Res. Lett., 24, 2877. 1997

Four–fluid model for turbulence driven heating of coronal ions

• Four–fluid 1–D corona/wind model

• Quasi–linear heating and acceleration by dispersive ion-cyclotron waves

• Rigid power-law spectra with index: $-2 \leq \gamma \leq -1$



Hu, Esser & Habbal, JGR, 105, 5093, 2000

• No wave absorption

• Turbulence spectra not self-consistent

Preferential heating of heavy ions by waves

Multi-fluid equations

Momentum equation

$$\frac{1}{2}\frac{d}{dr}u_j^2 = -\frac{1}{n_j}\frac{d}{dr}(n_j v_{\|j}^2) - \frac{1}{M_j n_e}\frac{d}{dr}(n_e v_e^2) - \frac{v_0^2}{r^2} - \frac{1}{A}\frac{dA}{dr}(v_{\|j}^2 - v_{\perp j}^2) + F_j^w + F_j^{dis}$$

Wave acceleration.....?

Parallel energy equation

$$\frac{d}{dr}v_{\|j}^2 = -2v_{\|j}^2\left(\frac{1}{u_j}\frac{du_j}{dr}\right) + \frac{2q_{\|j}}{u_j}$$

Perpendicular energy equation

$$\frac{d}{dr}v_{\perp j}^2 = -v_{\perp j}^2\left(\frac{1}{A}\frac{dA}{dr}\right) + \frac{q_{\perp j}}{u_j}$$

Wave heating $q_{\perp,\|}$ .... ?

Tu and Marsch, JGR, 106, 8233, 2001

Wave heating/acceleration rates for wave-particle interactions

$$\begin{pmatrix} \frac{\partial}{\partial t} U_{j\|} \\ \frac{\partial}{\partial t} V_{j\|}^2 \\ \frac{\partial}{\partial t} V_{j\perp}^2 \end{pmatrix}$$

$= F_j^{dis}$	wave acceleration
$= 2\, q_{j\|}$	parallel wave heating
$= q_{j\perp}$	perpendicular heating

$$= \frac{1}{(2\pi)^3} \int_{-\infty}^{+\infty} d^3k \sum_M \mathcal{B}_M(\mathbf{k}) \left(\frac{\Omega_j}{k}\right)^2 \frac{1}{1 - |\hat{\mathbf{k}} \cdot \mathbf{e}_M(\mathbf{k})|^2}$$

$$\times \sum_{s=-\infty}^{+\infty} \mathcal{R}_j(\mathbf{k}, s) \begin{pmatrix} k_{\|} \\ 2k_{\|} w_j(\mathbf{k}, s) \\ s\Omega_j \end{pmatrix}$$

- Wave spectrum and dispersion ?
- VDF and resonance function ?

Marsch and Tu, JGR, 106, 227, 2001

Resonant wave-absorption coefficient for bi-Maxwellian ions

Resonance function

$$\mathcal{R}_j(\mathbf{k},s) = \frac{2}{V_{j\perp}^4}\int_0^\infty dw_\perp w_\perp \exp(-\frac{1}{2}(\frac{w_\perp}{V_{j\perp}})^2)$$

$$\times \; |\, \mathbf{e}_M^*(\mathbf{k}) \cdot \mathbf{V}_j(\mathbf{k}; w_\perp, w_j(\mathbf{k},s) + U_{j\|}; s)\,|^2$$

Number of resonant ions

$$\times \; \sqrt{\frac{\pi}{2}}\frac{k_\|}{|\,k_\|\,|}\exp(-\frac{1}{2}\xi_j^2(\mathbf{k},s))$$

Pitch-angle gradient

$$\times \; \left(\xi_j(\mathbf{k},s)\,\frac{T_{j\perp}}{T_{j\|}} + s\frac{\Omega_j}{k_\| V_{j\|}}\right)$$

Marsch and Tu, JGR, 106, 227, 2001

Polarization vector

$$\mathbf{e}_M^\pm(\mathbf{k}) = e^{\mp i\psi}(\mathbf{e}_{Mx}(\mathbf{k}) \pm i\mathbf{e}_{My}(\mathbf{k}))$$

Current matrix element

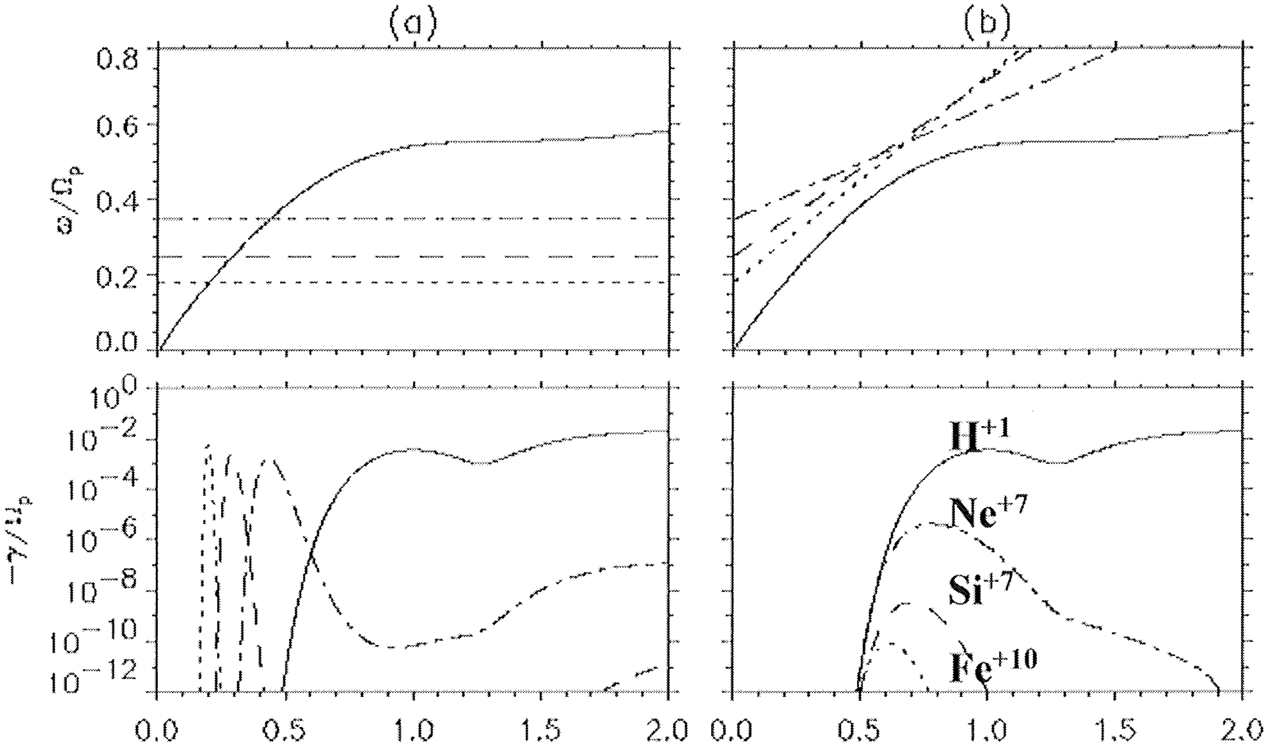
$$|\,\mathbf{e}_M^* \cdot \mathbf{V}_j\,|^2 = |\,\frac{v_\perp}{2}(J_{s-1}e_M^+ + J_{s+1}e_M^-) + v_\| J_s e_{Mz}\,|^2$$

Kinematics of ions in cyclotron resonance

Frequency

Damping rate

Zero drift



Finite drift

Wave vector (kV_A/Ω) Wave vector (kV_A/Ω)

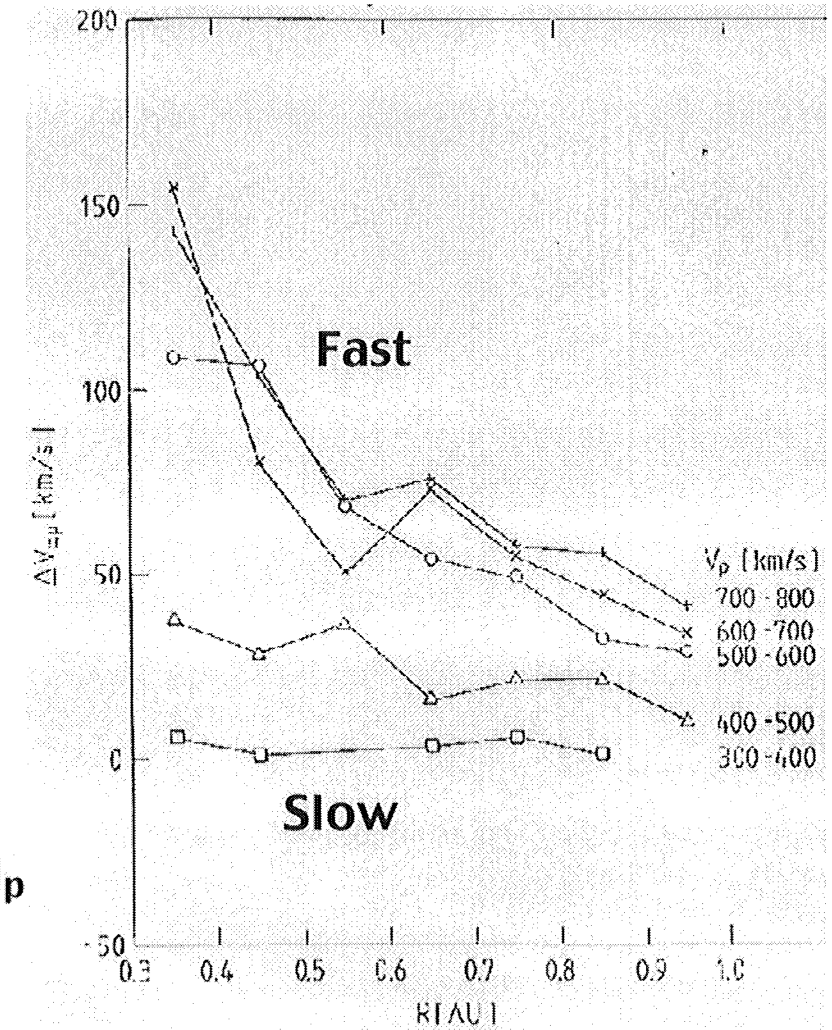
Tu et al., Space Sci. Rev., 87, 331, 1999

Cyclotron resonance condition: $\omega = \Omega - k \cdot v$

Ion differential streaming

$\Delta \underline{V}$ /kms^{-1}

$T_\alpha/T_p \geq m_\alpha/m_p$



Distance r /AU

- Alpha particles are faster than the protons!
- In fast streams the differential velocity is: $\Delta \underline{V} \leq \underline{V}_A$
- Heavy ions travel at alpha-particle speed

Marsch et al., JGR, 87, 52, 1982

Wave heating and acceleration of protons and oxygen ions

Machnumber ....

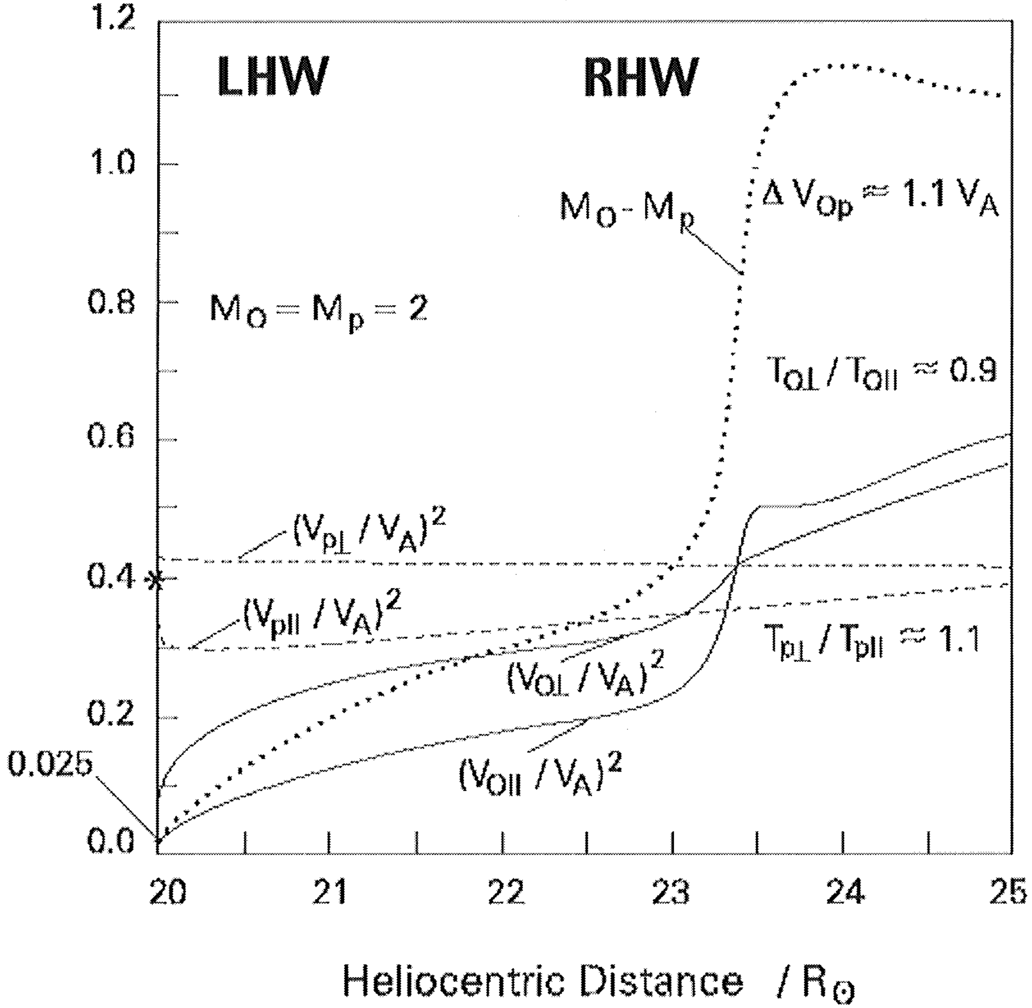
Thermal speed squared

(plasma beta)

H^{+1} - - - - - -

O^{+6} ———————

Preferential acceleration and heating of oxygen



Marsch, Nonlinear Proc. Geophys., 6, 149, 1999

Results from fluid and hybrid-kinetic models of corona and wind

- Multi-Fluid models with assumed heat sources reproduce well the bulk properties of the solar wind

- Thermodynamics of the solar corona and solar wind still requires a fully kinetic treatment

- Hybrid-kinetic models do not describe the detailed observations of the solar wind plasma adequately

- A semi-kinetic approach with with self-consistent spectra provides valuable first insights in the physics

- The problems of wave-energy transport as well as turbulent cascading and dissipation in the dispersive kinetic domain remain to be solved