Electron Kinetic Processes in the Solar Wind

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Seminar Talk at Uppsala University, Uppsala, Sweden,December 2013

Kinetic properties of corona and wind

- **Plasma is multi-component and non-uniform**

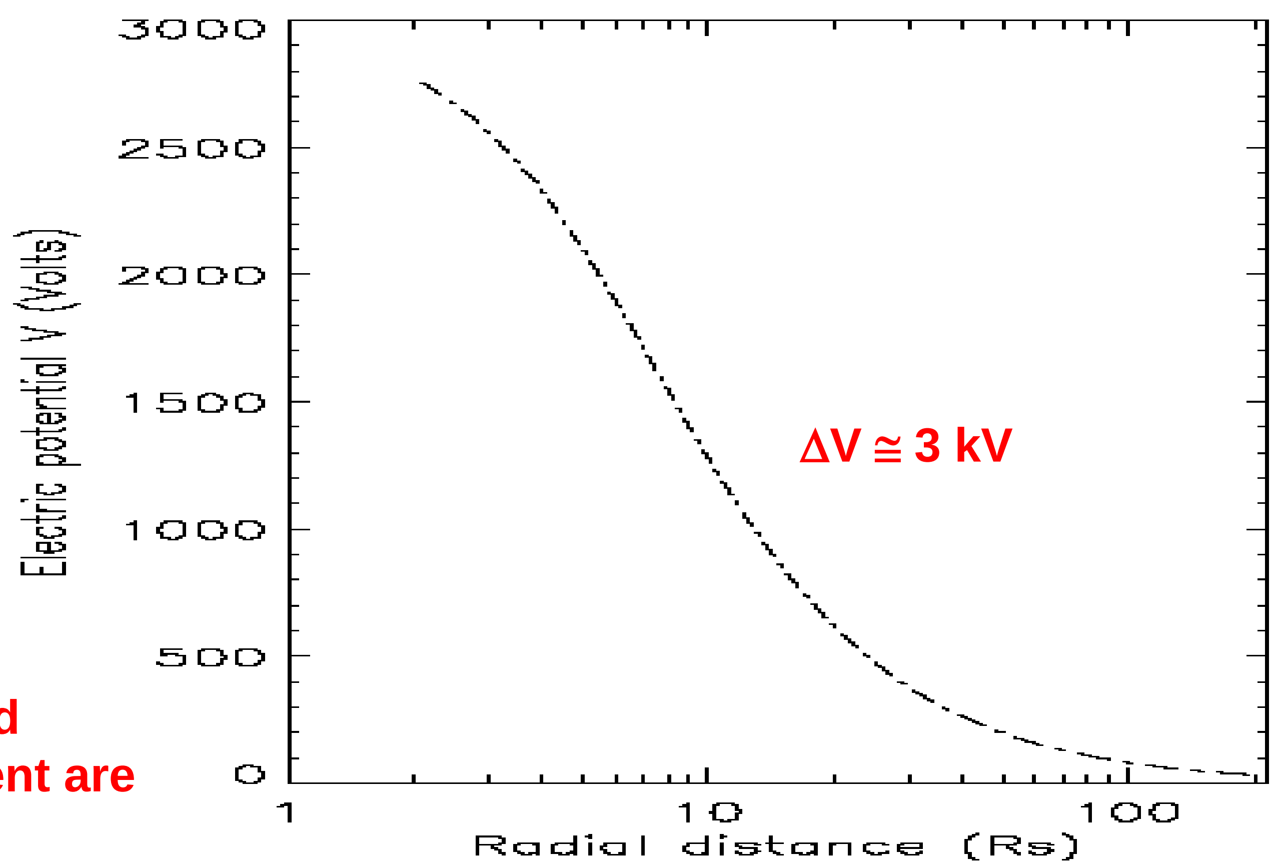
$\rightarrow$ multiple scales and complexity

- **Plasma is tenuous and turbulent**

$\rightarrow$ free energy for microinstabilities
$\rightarrow$ strong wave-particle interactions (diffusion)
$\rightarrow$ weak collisions (Fokker-Planck operator)
$\rightarrow$ strong deviations from local thermal equilibrium
$\rightarrow$ global boundaries are reflected locally
$\rightarrow$ suprathermal particles

Problem: Thermodynamics and transport….

Collisional fluid versus exosphere



Total energy and magnetic moment are conserved:

$$E = \frac{m}{2}(v_\perp^2 + v_\parallel^2) - \frac{m}{2}\Omega_\odot^2 r^2 \cos^2\lambda + m\Phi_{\rm g}(r) + q\Phi_{\rm e}(r), \quad \mu = \frac{m v_\perp^2}{2B(r)}$$

Kinetic Vlasov-Boltzmann theory

Description of particle velocity distribution function in phase space:

$$\frac{df}{dt} + \mathbf{w}\cdot\frac{\partial f}{\partial \mathbf{x}} + (\mathbf{w}\times\mathbf{\Omega})\cdot\frac{\partial f}{\partial \mathbf{w}} + (-\frac{d}{dt}\mathbf{u} + \frac{q}{m}\mathbf{E}')\cdot\frac{\partial f}{\partial \mathbf{w}} - \frac{\partial \mathbf{u}}{\partial \mathbf{x}} : \mathbf{w}\frac{\partial f}{\partial \mathbf{w}} = \frac{\delta f}{\delta t}$$

Convective derivative:

$$\frac{d}{dt} = \frac{\partial}{\partial t} + \mathbf{u}\cdot\frac{\partial}{\partial \mathbf{x}}$$

Relative velocity **w**, mean velocity **u**(**x**,t), gyrofrequency **Ω**, electric field **E'** in moving frame:

$$\mathbf{w} = \mathbf{v} - \mathbf{u}(\mathbf{x}, t),\ \mathbf{\Omega} = \frac{q\mathbf{B}}{mc},\ \mathbf{E}' = \mathbf{E} + \frac{1}{c}\mathbf{u}\times\mathbf{B}$$

Moments: Drift velocity, pressure (stress) tensor, heat flux vector

$$< \mathbf{w} >= 0, \mathcal{P} = nm < \mathbf{ww} >, \mathbf{Q} = nm < \mathbf{w}\frac{1}{2}w^2 >$$

$$\mathbf{\Pi} = \mathcal{P} - \mathcal{I}p \quad p = nk_BT = \frac{1}{3}Tr\mathcal{P}$$

Dum, 1990

Collisions and plasma turbulence

Coulomb collisions and wave-particle interactions can be represented by a second-order differential operator, including the acceleration vector A(v) and diffusion tensor *D*(v), in velocity space:

$$\frac{\delta f}{\delta t} = \frac{\partial}{\partial \mathbf{v}} \cdot \left(-\mathbf{A} + \mathcal{D} \cdot \frac{\partial}{\partial \mathbf{v}}\right) f$$

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

Collisional kinetics of solar wind electrons:

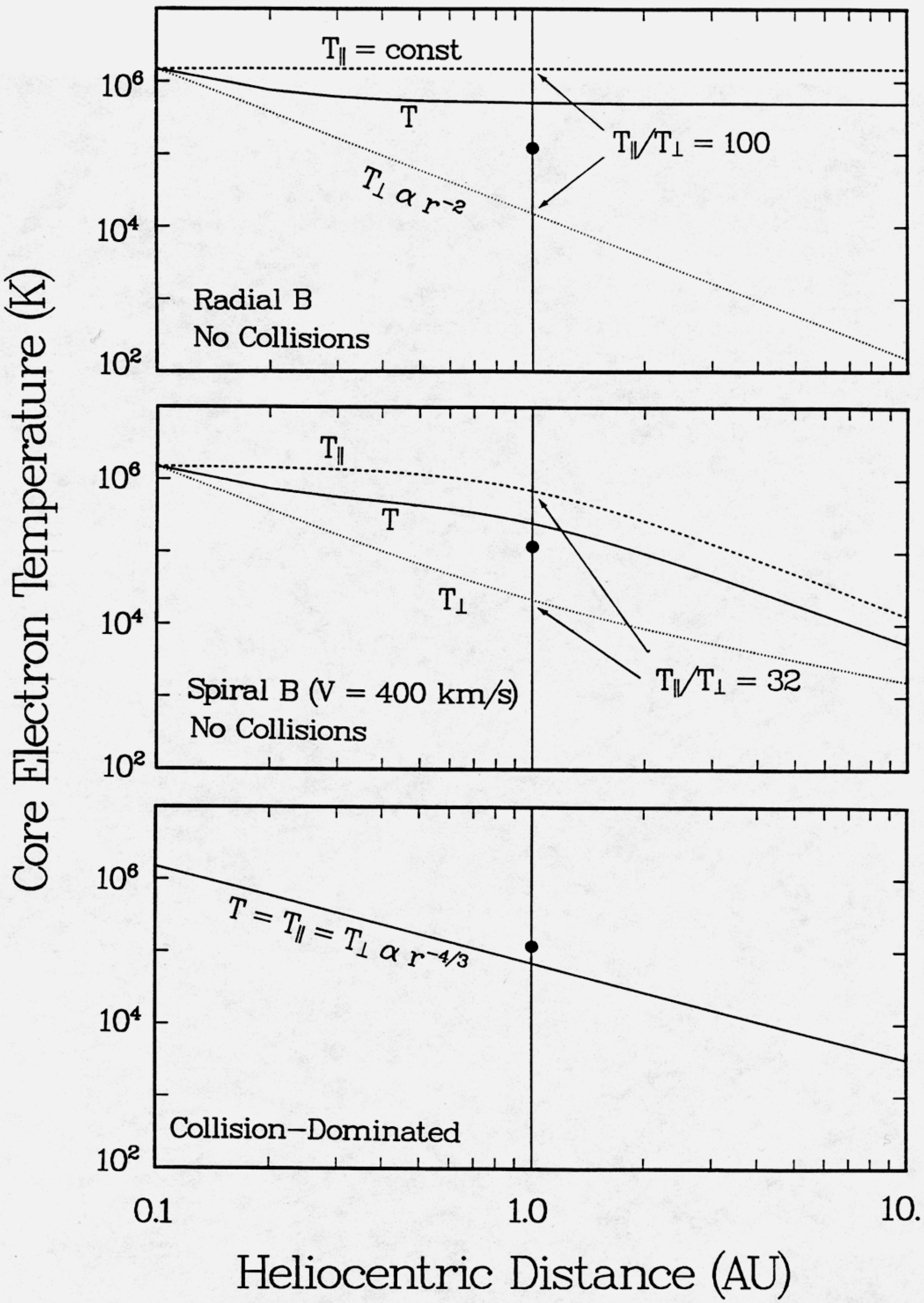
- Pierrard et al.
- Lie-Svendsen et al.

Collisions and geometry

Double adiabatic invariance,
$\rightarrow$ extreme anisotropy is not observed!

Spiral reduces anisotropy!

Adiabatic collision-dominated
$\rightarrow$ isotropy, is not observed!



Philipps and Gosling, JGR, 1989

Plasma waves and frequencies

- **Electrostatic** (Debye length, $\lambda_{Dj} \sim 2\pi/k_j \sim 1m$)
  - Langmuir and ion-acoustic: $\omega_j = k_j V_j$; $V_j = (k_B T_j/m_j)^{1/2}$

- **Electromagnetic** (Gyroradius, $r_j \sim V_j / \Omega_j \sim 100km$)
  - Whistler and lower-hybrid: Ω_e , $(\Omega_e \Omega_i)^{1/2}$
  - Alfvén and ion-cyclotron: Ω_p , Ω_α ; $\Omega_i = e_i B/m_i c$
  - Fast-mode and magneto-acoustic: $\Omega_j = k_{Aj} V_A$

Inside 1 AU these frequencies range from 10 Hz up to 100 MHz.

- **Gyrokinetic scale**: $\Omega_j = K_j V_{sw}$; at boundaries and ion pick-up
- **Doppler shift**: $\omega' = \omega + kV_{sw}$; in supersonic wind

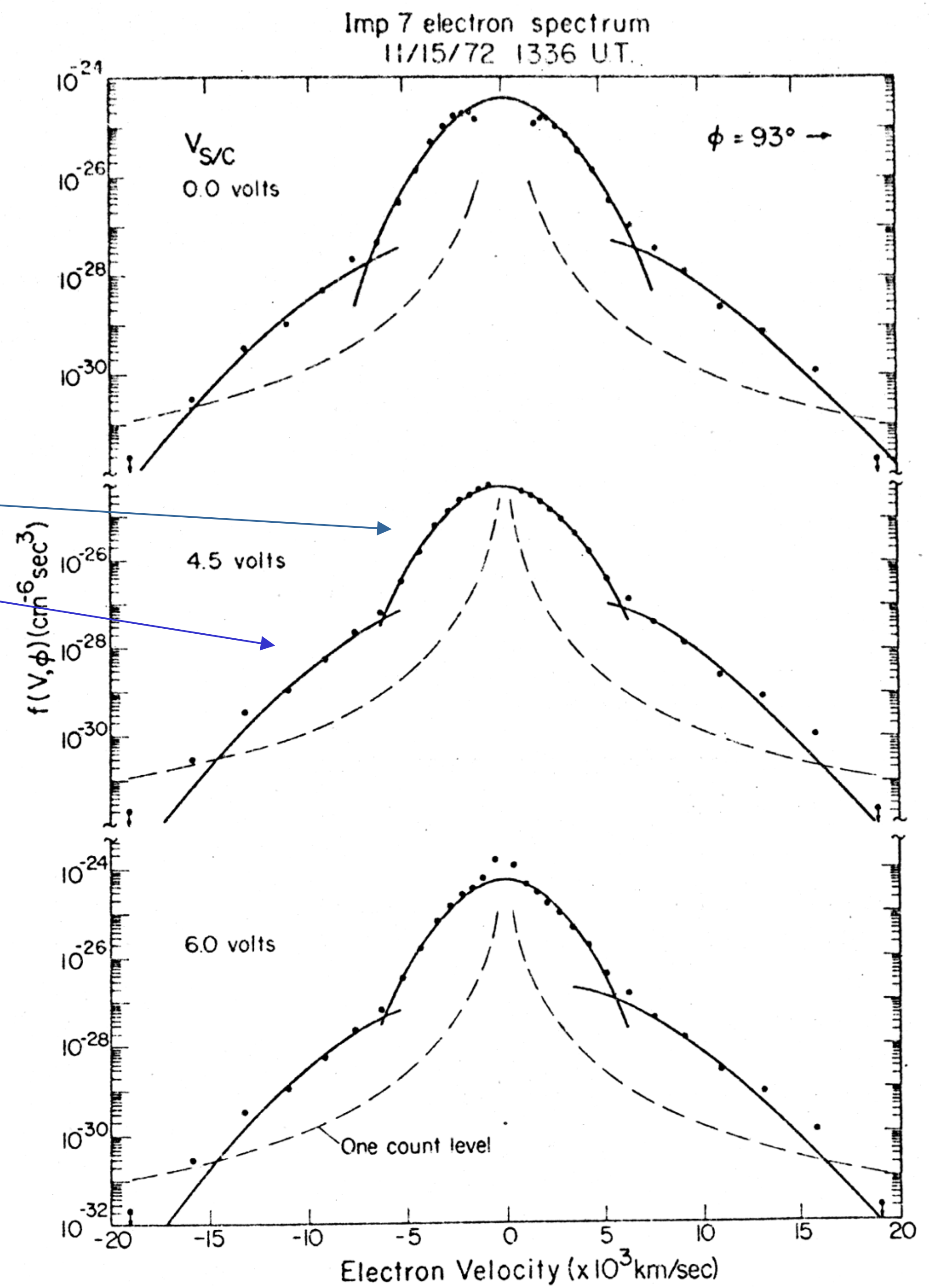
Solar Orbiter will measure the full electromagnetic (vector) fields and their fluctations.

Electron energy spectrum

IMP spacecraft

Two populations:

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

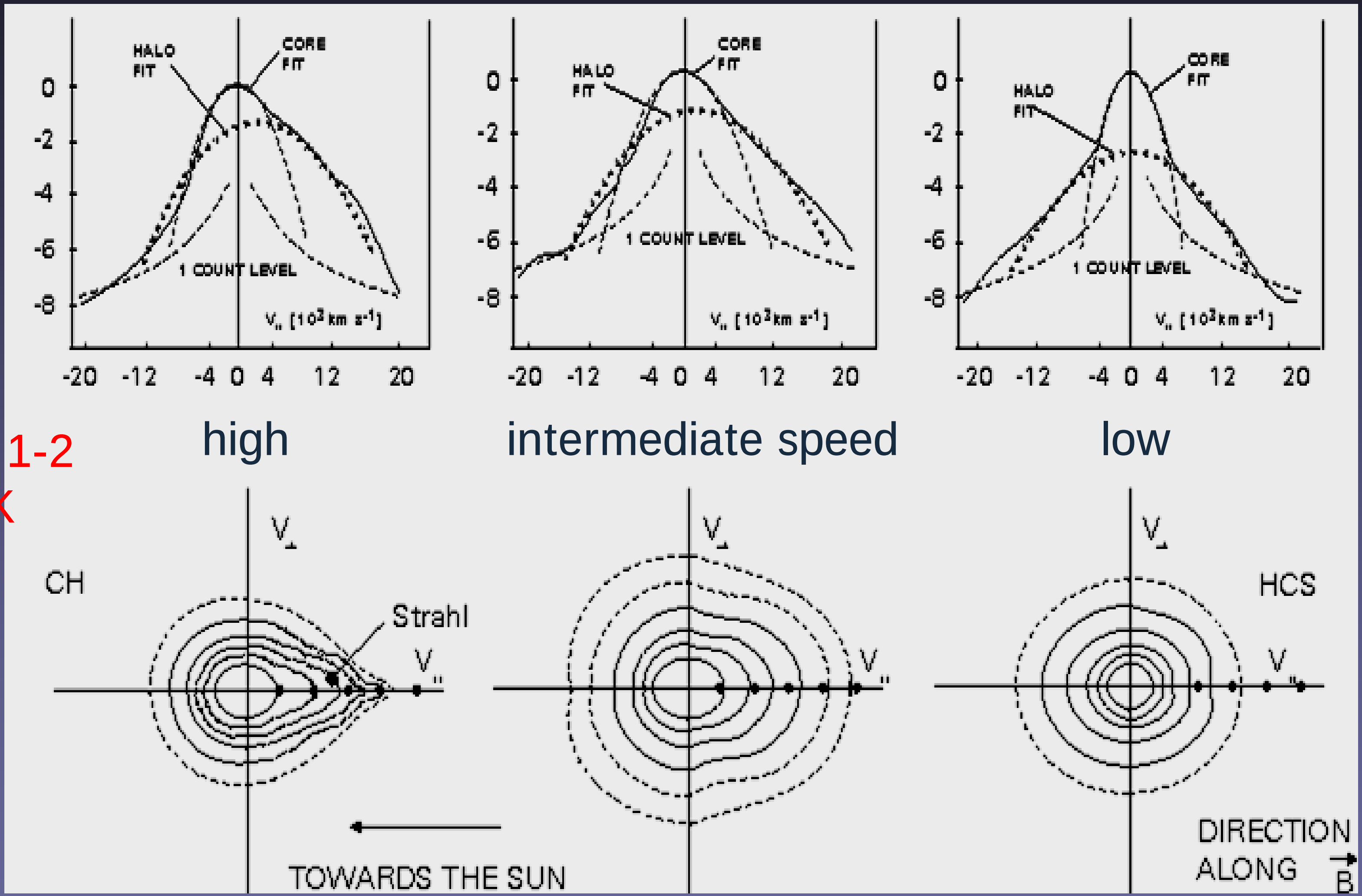


Core: local, collisional, **bound** by interplanetary electrostatic potential

Halo: global, collisionless, **free** to escape (exospheric)

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

Electron velocity distributions



T_e = 1-2 10^5 K

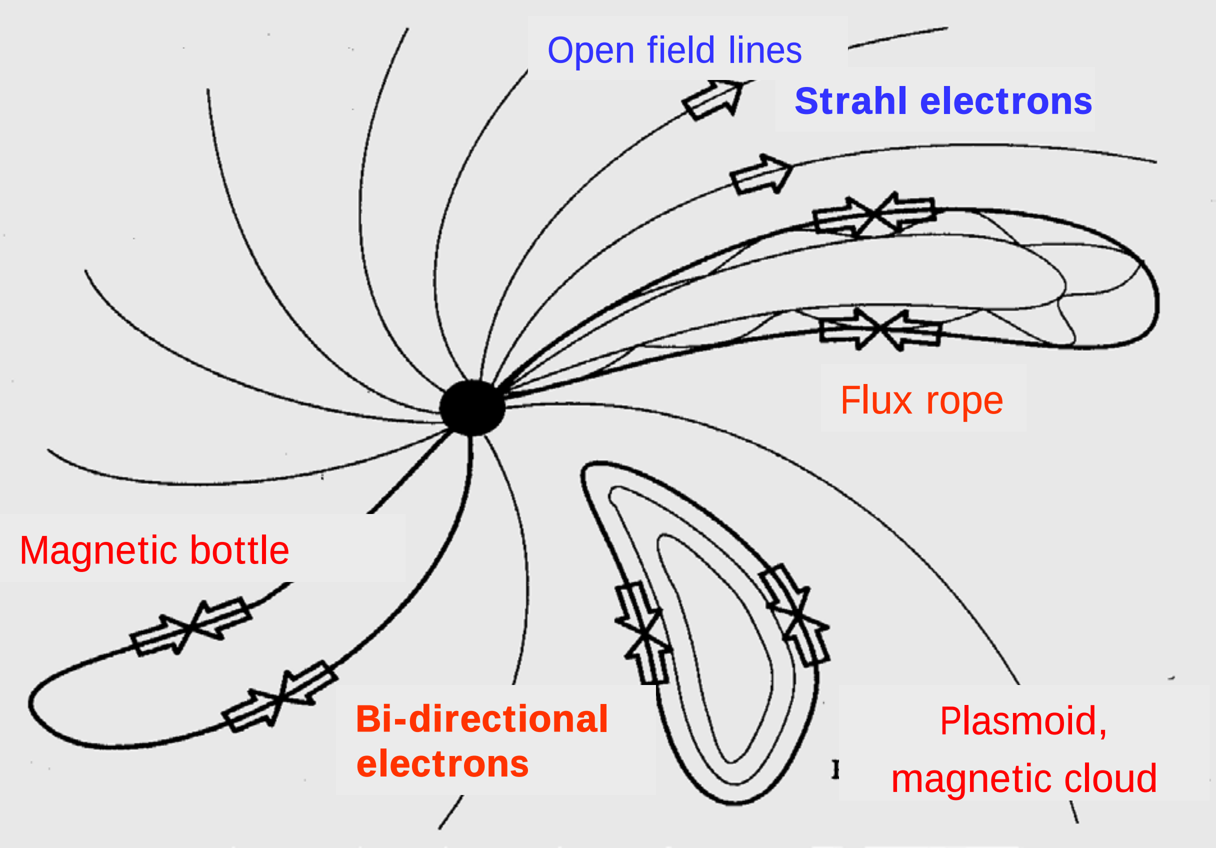
Helios

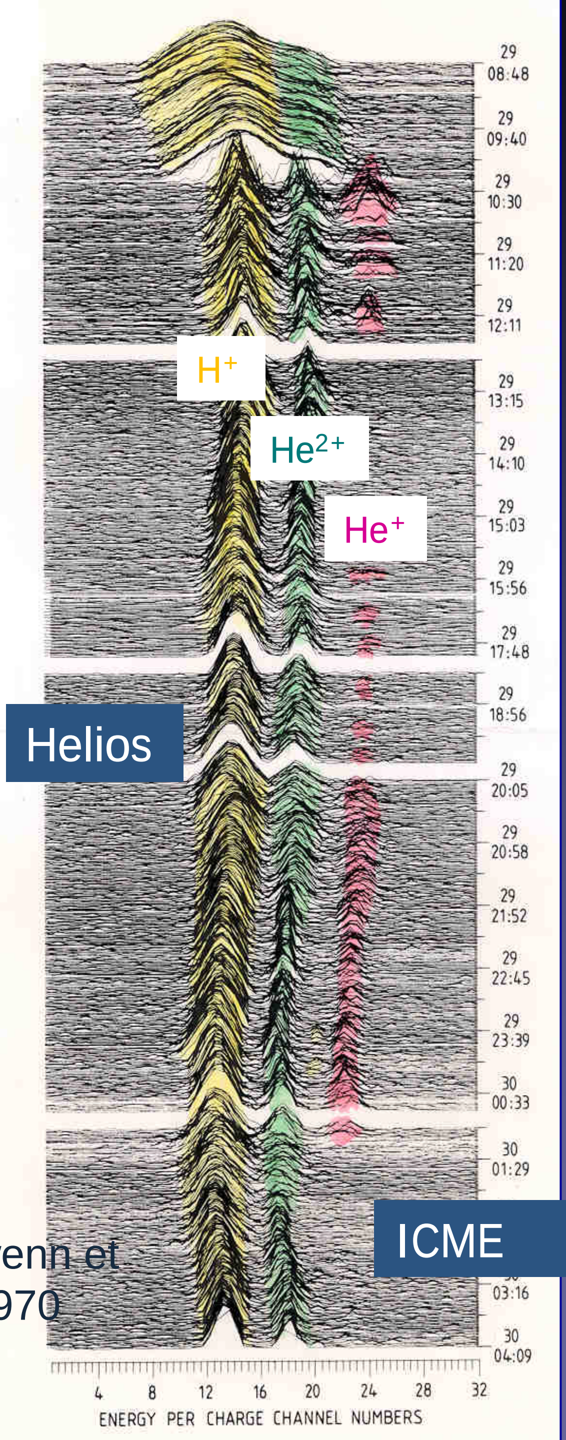
Pilipp et al., JGR, **92**, 1075, 1987

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

Bi-directional electron heatfluxes and rare He^+

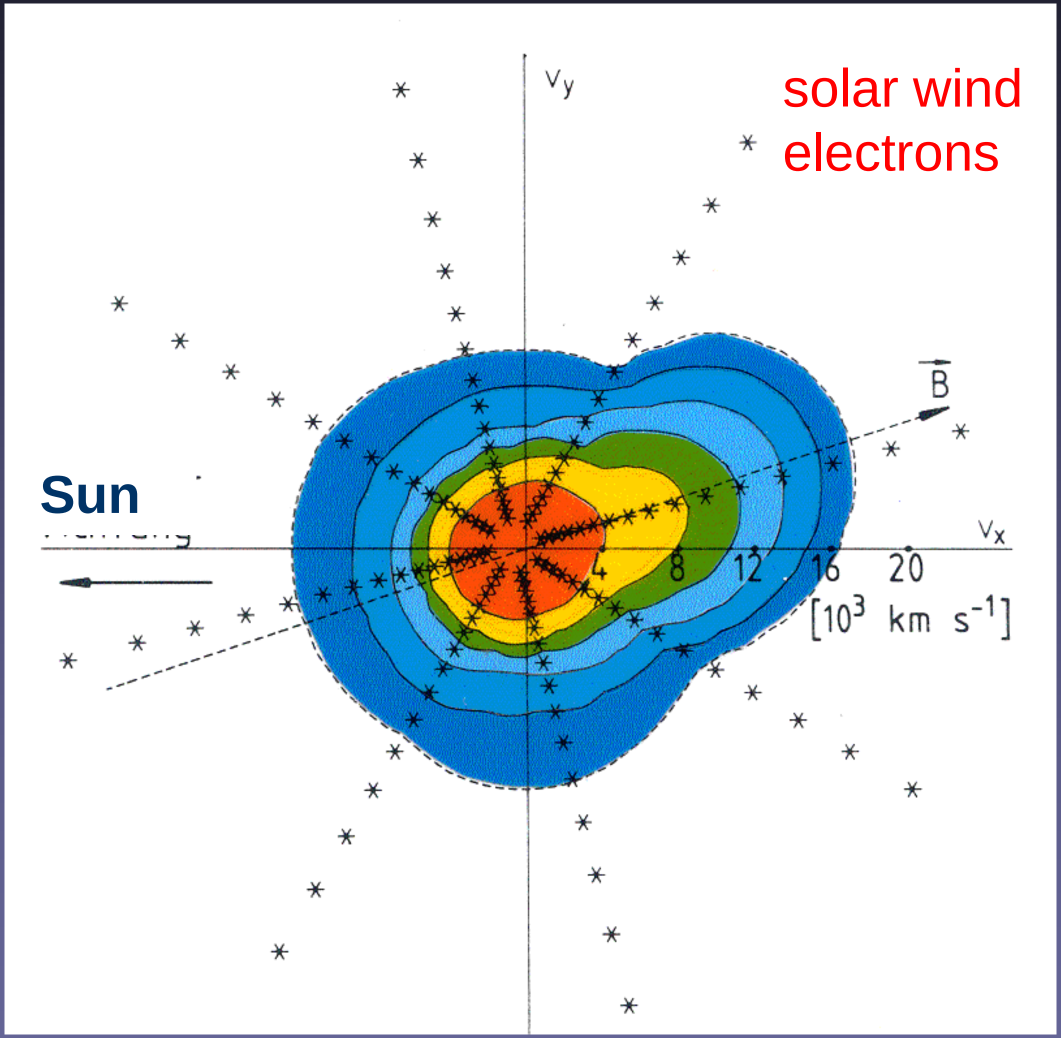
- Palmer et al., 1978, Solar energetic electrons indicate bottle
- Kutchko et al., 1982, Bi-dir. ions and trapped electrons in loop
- Pillipp et al., 1987, Double-strahl solar-wind electrons in loop
- Gosling et al., 1987, Bi-dir. suprathermal electrons in cloud





Schwenn et al., 1970

Invalidity of classical transport theory



n_e = 3-10 cm^{-3},

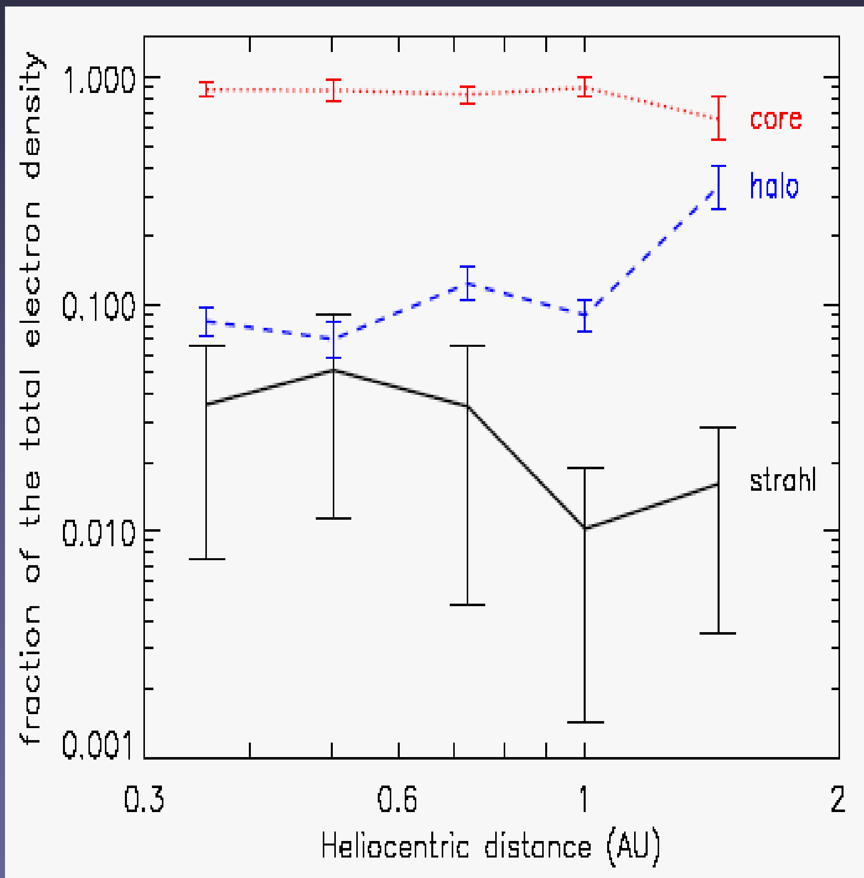
T_e = 1-2 10^5 K at 1 AU

- Strong heat flux tail: Strahl
- Collisional free path λ_c much larger than temperature-gradient scale L
- Polynomial expansion about a local Maxwellian hardly converges, as λ_c >> L

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

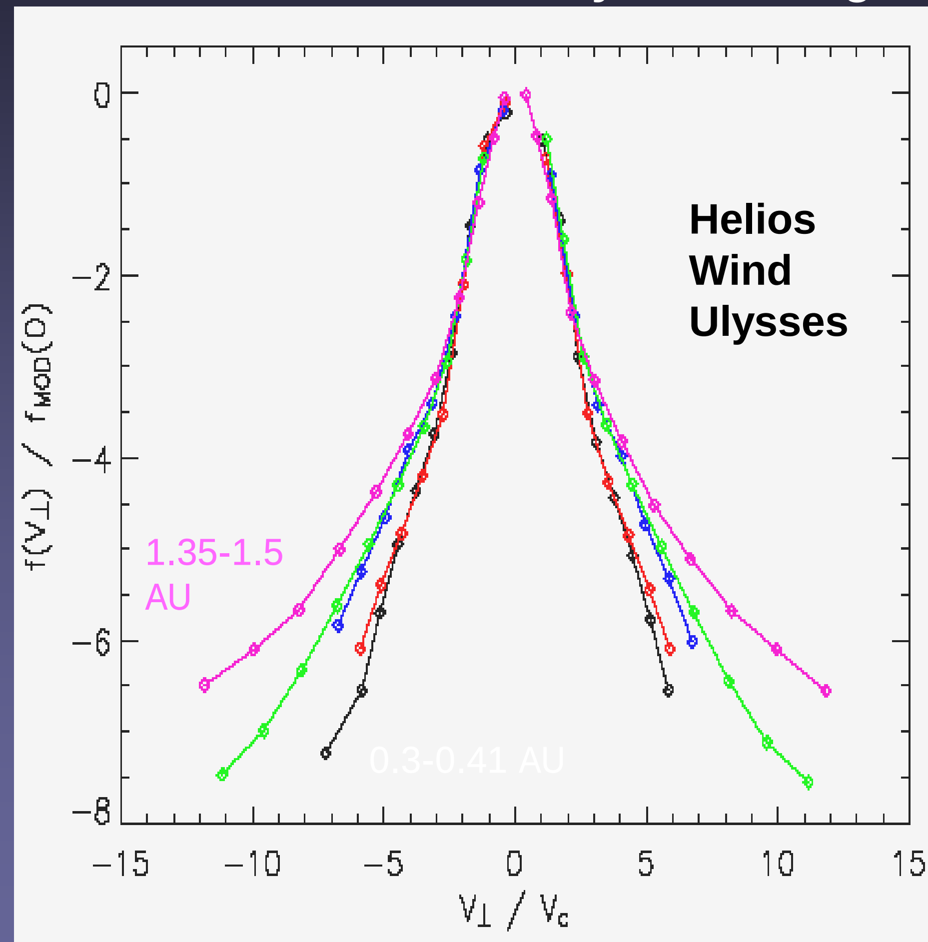
Solar wind electrons: Core-halo evolution

Halo is relatively increasing while strahl is diminishing.



Maksimovic et al., JGR, 2005

Normalized core remains constant while halo is relatively increasing.

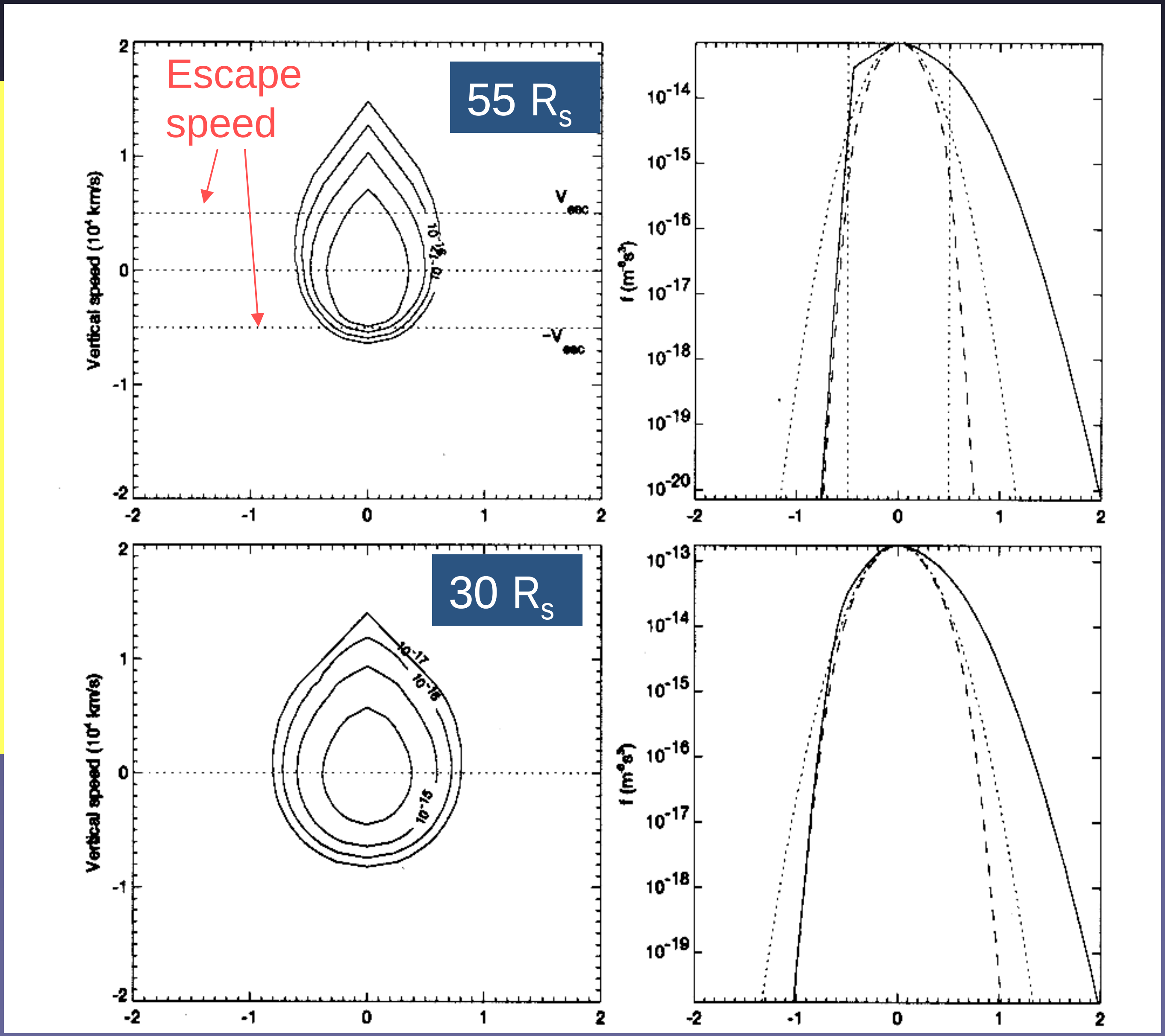


Scattering by meso-scale magnetic structures

Coulomb collisions and electrons

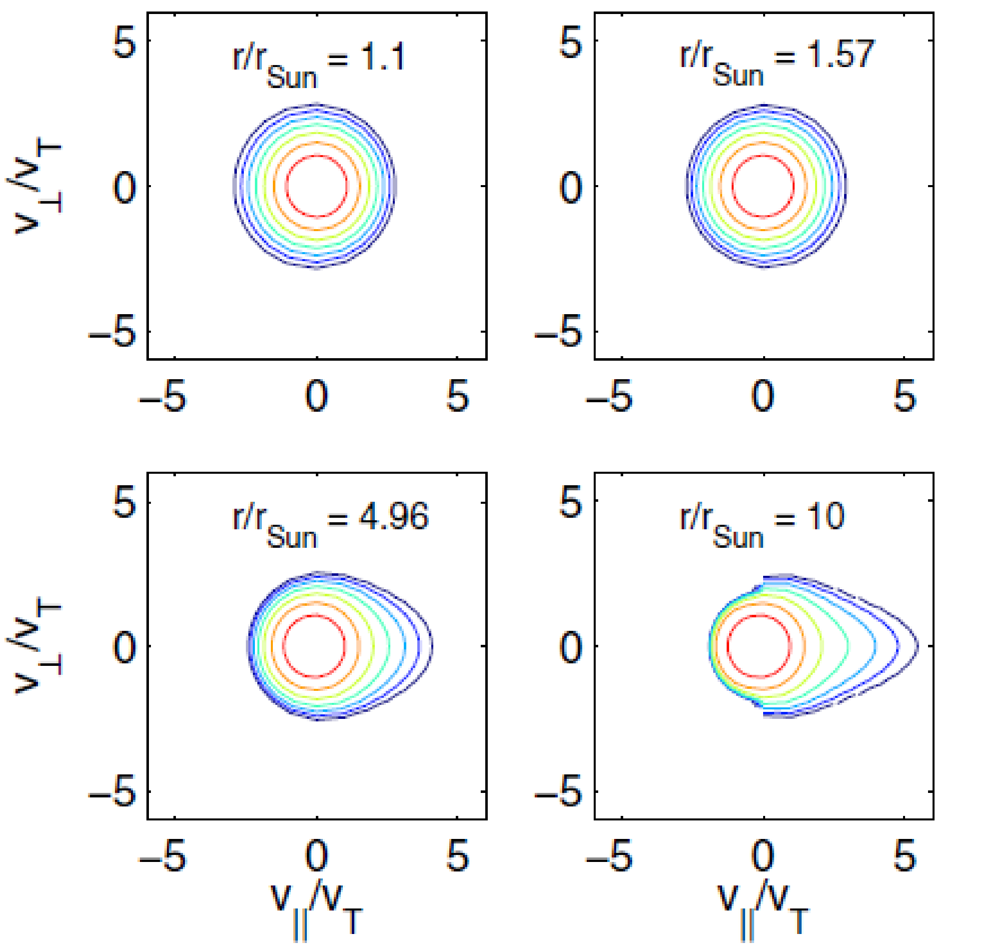
Integration of the full Fokker-Planck equation

- Velocity filtration is weak
- Strahl formation by escape electrons
- Core bound by electric field

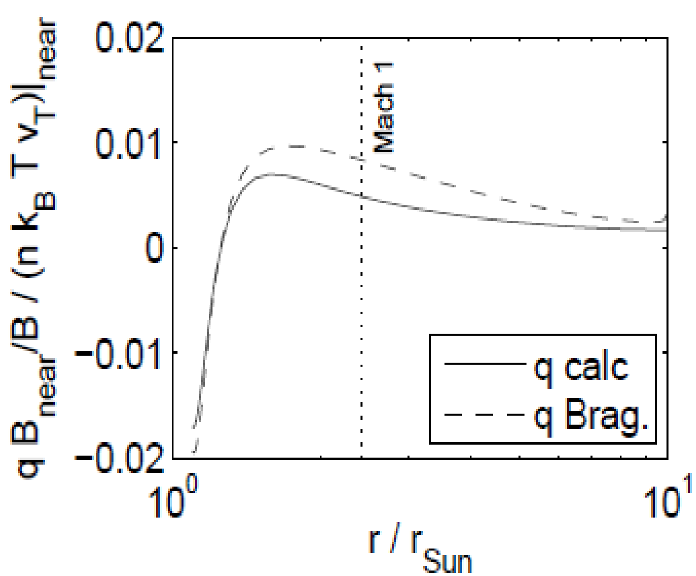


Lie-Svendson et al., JGR, **102**, 4701, 1997

Collisional core – runaway strahl



Collisional transport in corona with Fokker-Planck operator in Boltzmann equation with self-consistent electric field



Heat flux smaller than classical

Smith, Marsch, Helander, ApJ, 751, 2012

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)

$\rightarrow$ Energy and momentum exchange between waves and particles. Quasi-linear or non-linear relaxation.....

Electron heat conduction

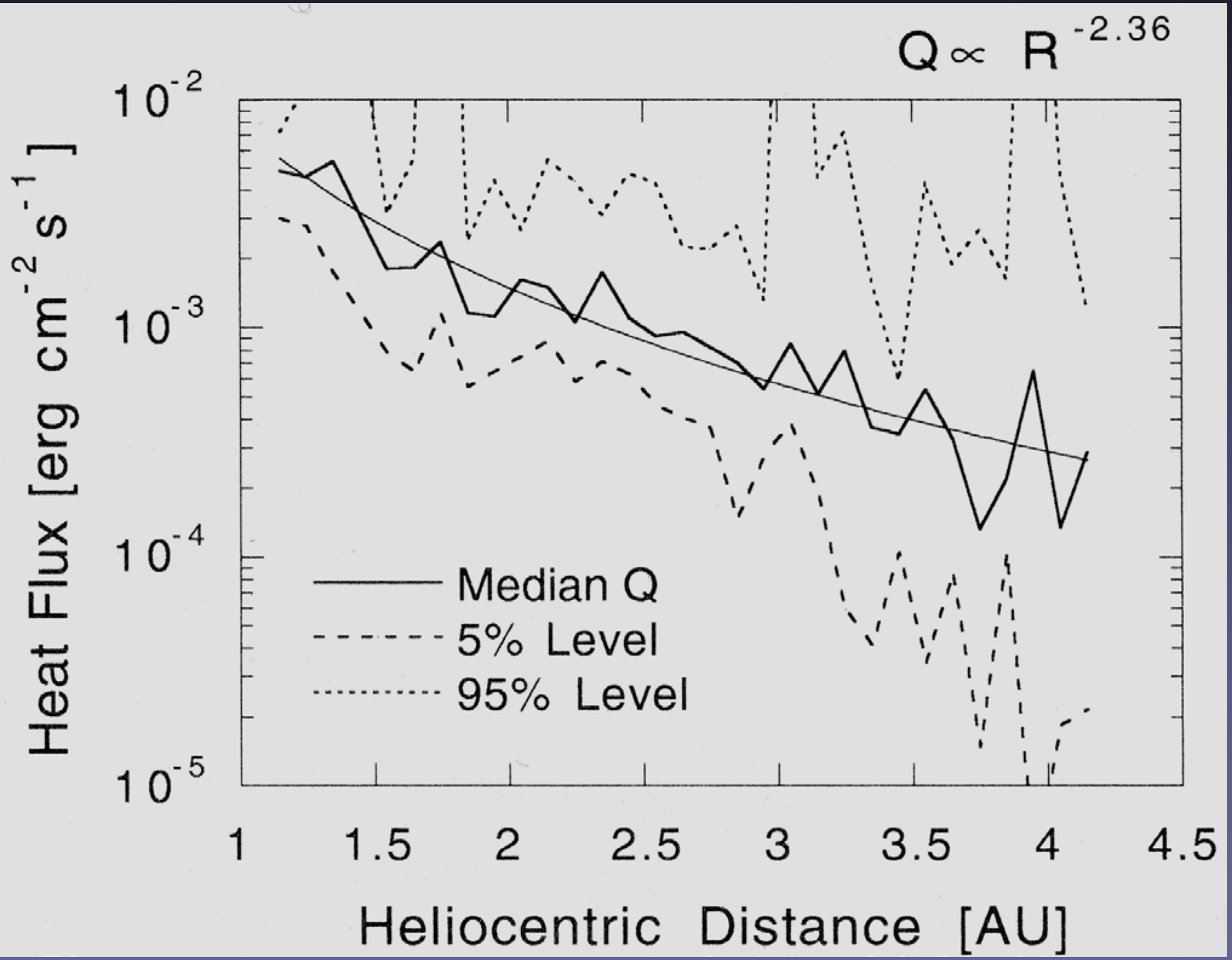
Heat carried by halo electrons!

$T_H = 7\ T_C$

Interplanetary potential:

Φ = 50-100 eV

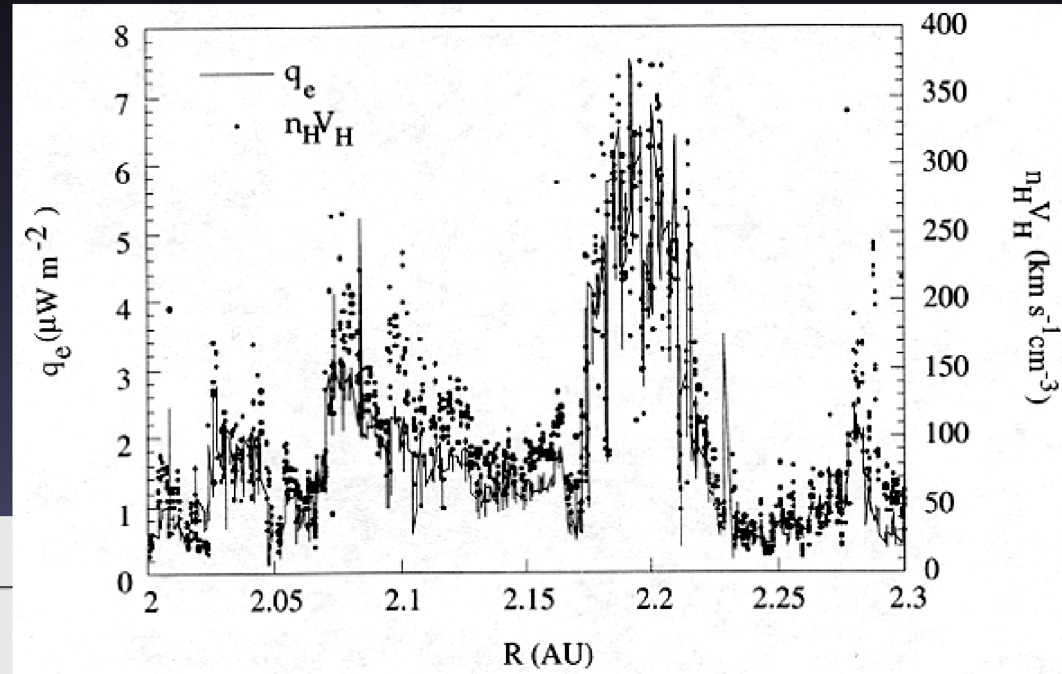
$\underline{E} = - 1/n_e\ \underline{\nabla}\ p_e$

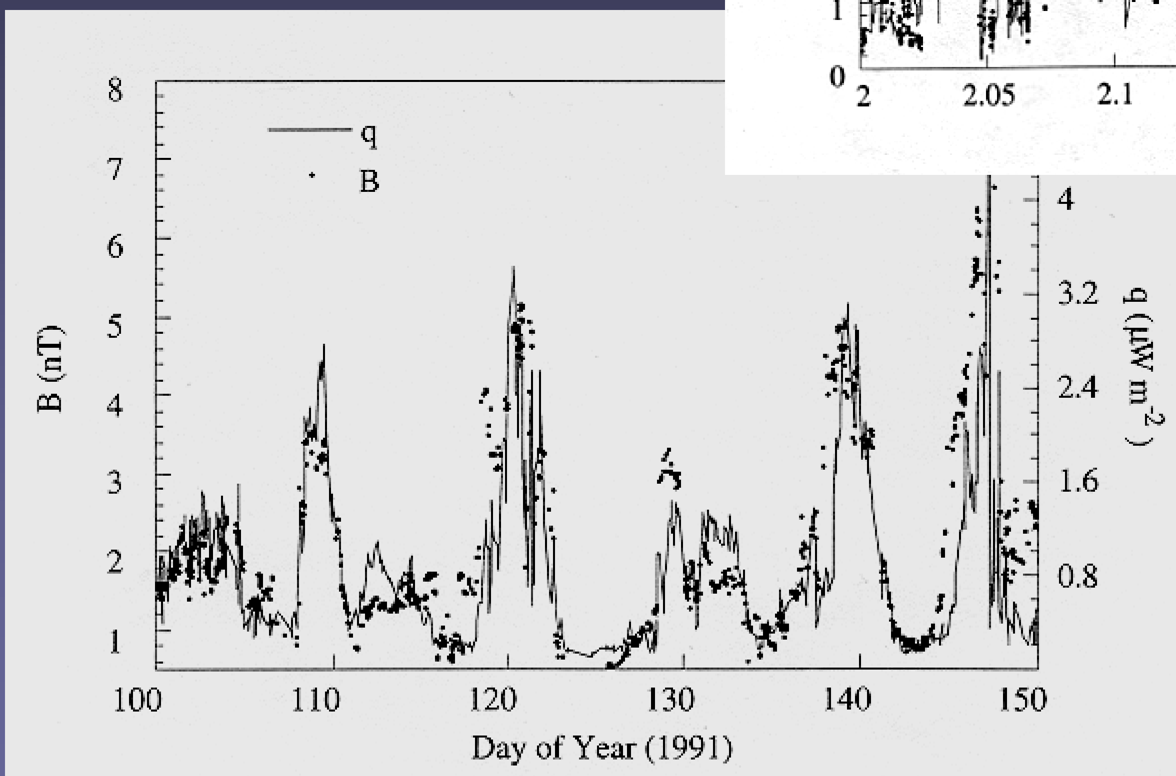


McComas et al., GRL, **19**, 1291, 1992

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

Whistler regulation of electron heat flux





- **Halo electrons carry heat flux**
- **Heat flux varies with <u>B</u> or <u>V</u>$_A$**
- **Whistler instability regulates drift**

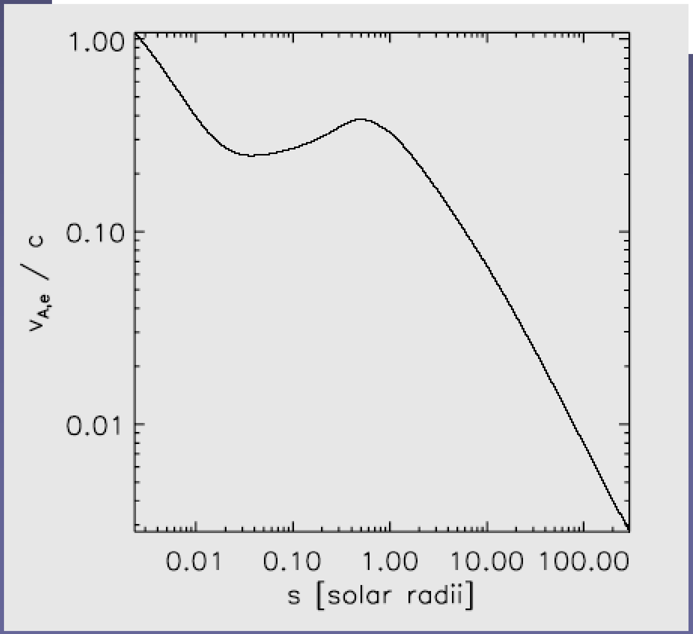
Sime et al., JGR, 1994

Suprathermal coronal electrons caused by wave-particle interactions I

$$\frac{\partial f}{\partial t} + v_\parallel \frac{\partial f}{\partial s} + \left(g_\parallel - \frac{e}{m_e} E_\parallel \right) \frac{\partial f}{\partial v_\parallel} + \frac{v_\perp}{2A} \frac{\partial A}{\partial s} \left(v_\perp \frac{\partial f}{\partial v_\parallel} - v_\parallel \frac{\partial f}{\partial v_\perp} \right)$$
$$= \left(\frac{\delta f}{\delta t} \right)_{w\text{-}p} + \left(\frac{\delta f}{\delta t} \right)_{\mathrm{Coul}} . \qquad (7)$$

Boltzmann equation with waves and collisions

A(s) flux tube area function



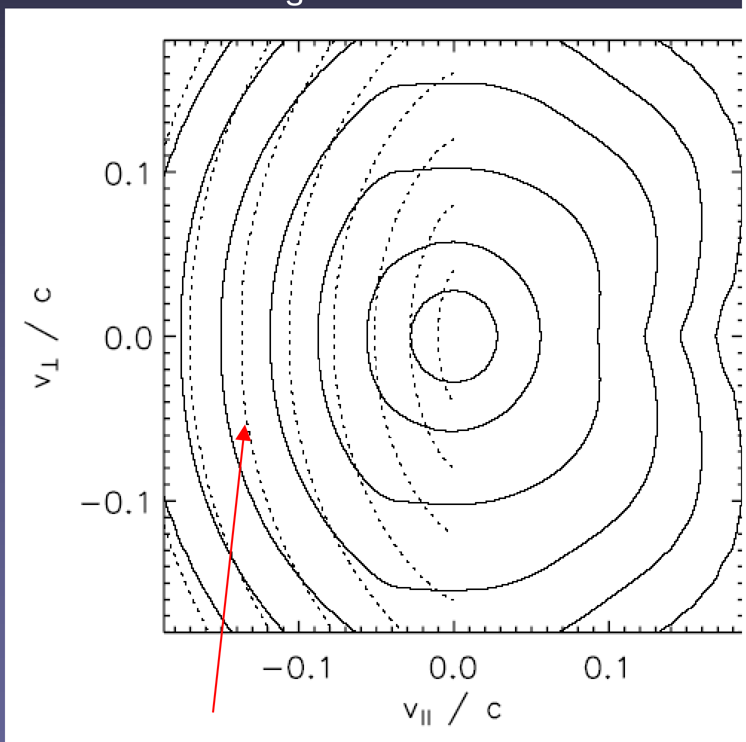
Electron pitch-angle scattering in the whistler wave field

Normalized phase speed $v_{A,e}/c$ in the solar corona

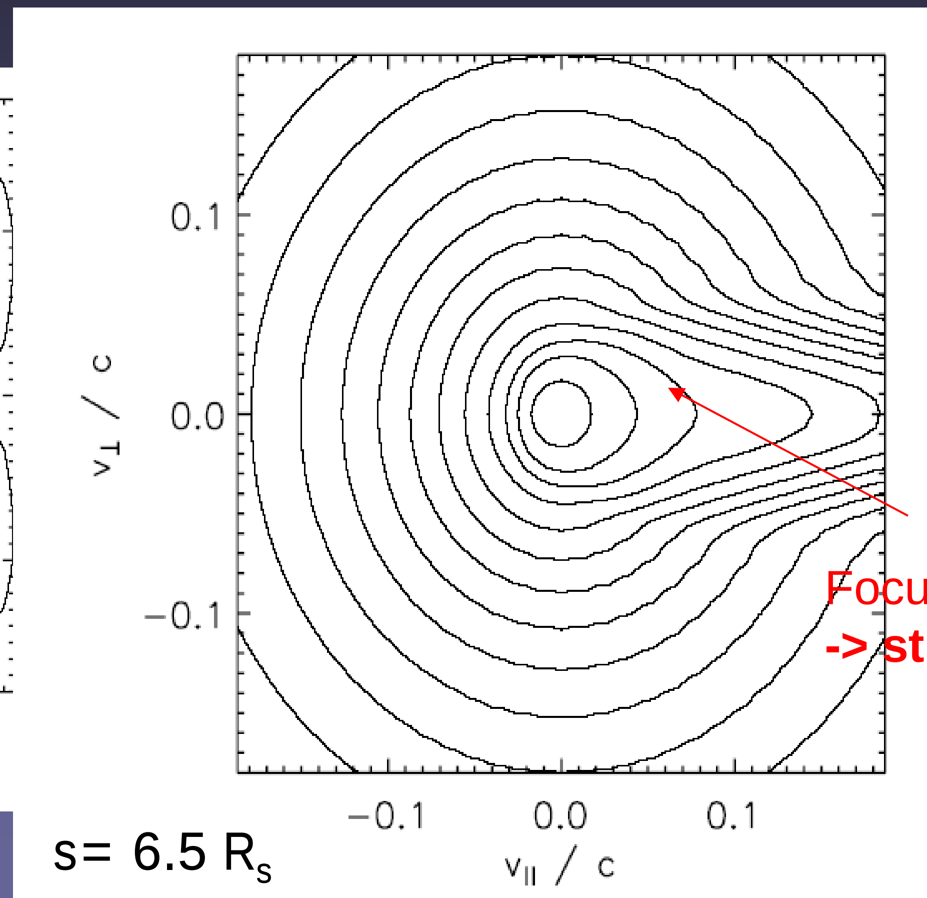
Vocks and Mann, Ap. J., **593**, 1134, 2003

Suprathermal coronal electrons caused by wave-particle interactions II

s= 0.014 R_s



Pitch-angle scattering
-> shell formation



Vocks and Mann, Ap. J., **593**, 1134, 2003

Conclusions

- Solar wind electron velocity distributions are shaped generally by large-scale forces (e.g., gravity, magnetic mirror force), Coulomb collisions and resonant interactions with high-frequency plasma waves.
- The core electrons are formed mainly by gravity and the interplanetary potential and isotropised by Coulomb collisions.
- The strahl electrons are free (they can climb the interplanetary potential) collisional run-away particles that strongly focus along the magnetic field.
- Collisional transport is non-classical and less effective than transport according to Braginskii's theory.
- Diffusion implies inelastic scattering of electrons by ion acoustic and whistler mode waves, and thus leads to turbulence dissipation at the electron kinetic scales.