The microstate of the solar wind

- Radial gradients of kinetic temperatures
- Velocity distribution functions
- Ion composition and suprathermal electrons
- Coulomb collisions in the solar wind
- Waves and plasma microinstabilities
- Diffusion and wave-particle interaction

Length scales in the solar wind

Macrostructure - fluid scales

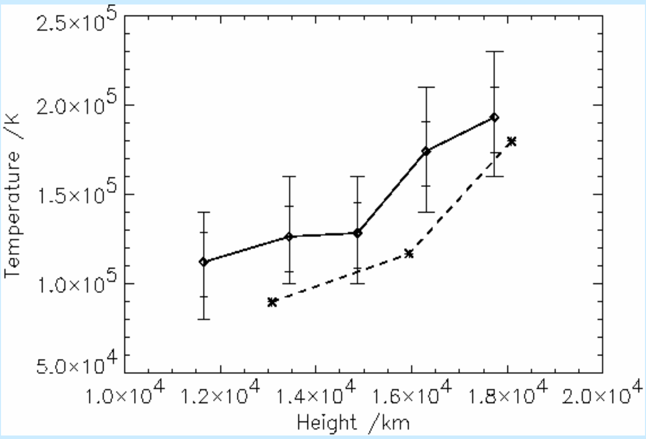
Heliocentric distance:	**r**	**150 Gm (1AU)**
Solar radius:	R_s	**696000 km (215 R_s)**
Alfvén waves:	λ	**30 - 100 Mm**

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!

Proton temperature at coronal base



SUMER / SOHO

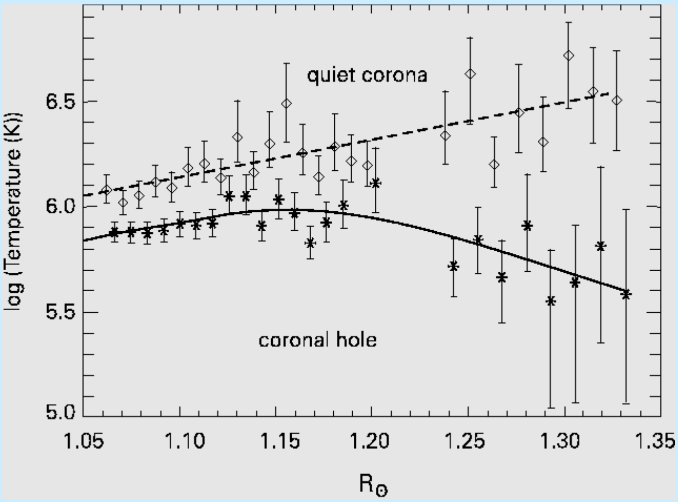
Hydrogen Lyman series

Transition Region at the base of north polar CH

Marsch et al., A&A, **359**, 381, 2000

Charge-exchange equilibrium: $T_H = T_p$
Turbulence broadening: ξ = 30 km s^{-1}

Electron temperature in the corona



Streamer belt, closed

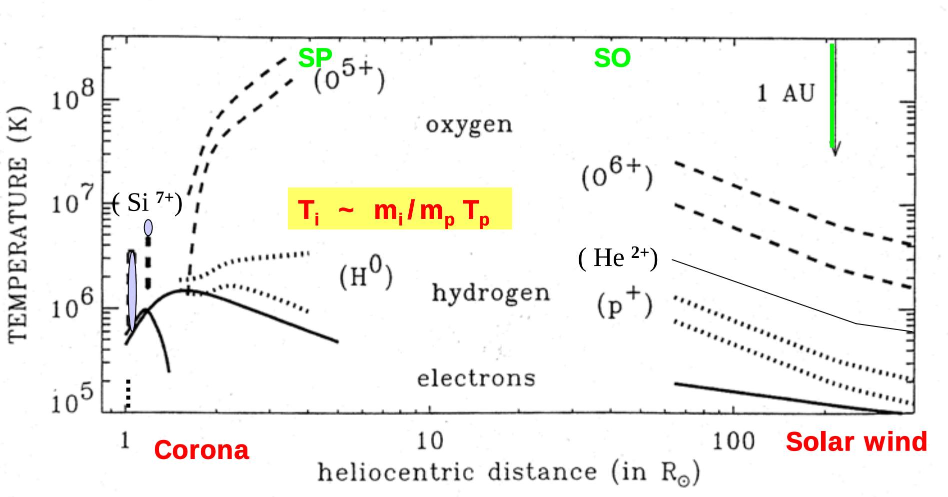
Coronal hole, open magnetically

David et al., A&A **336**, L90, 1998

Heliocentric distance

SUMER / CDS SOHO

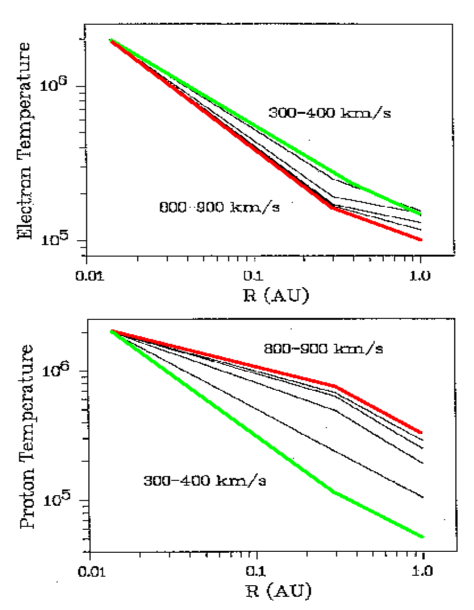
Temperature profiles in the corona and fast solar wind



Cranmer et al., Ap.J., 2000; Marsch, 1991

Proton and electron temperatures

Electrons are cool!



slow wind
↓
fast wind

Protons are hot!

fast wind
↓
slow wind

Marsch, 1991

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 power spectra

Moments

Multi-Fluid (MHD) equations

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

→ Single / multi fluid parameters

Velocity distribution functions

Statistical description: $f_j(\mathbf{x},\mathbf{v},t)d^3xd^3v$,

gives the probability to find a particle of species j with a velocity **v** at location **x** at time t in the 6-dimensional phase space.

Local thermodynamic equilibrium:

$$f_j^M(\mathbf{x},\mathbf{v},t) = n_j(2\pi v_j)^{-3/2} \exp[-(\mathbf{v}-\mathbf{U}_j)^2/v_j^2],$$

with number density, n_j, thermal speed, v_j, and bulk velocity, $\mathbf{U}_j$, of species j.

Dynamics in phase space: Vlasov/Boltzmann kinetic equation

Electron energy spectrum

IMP spacecraft

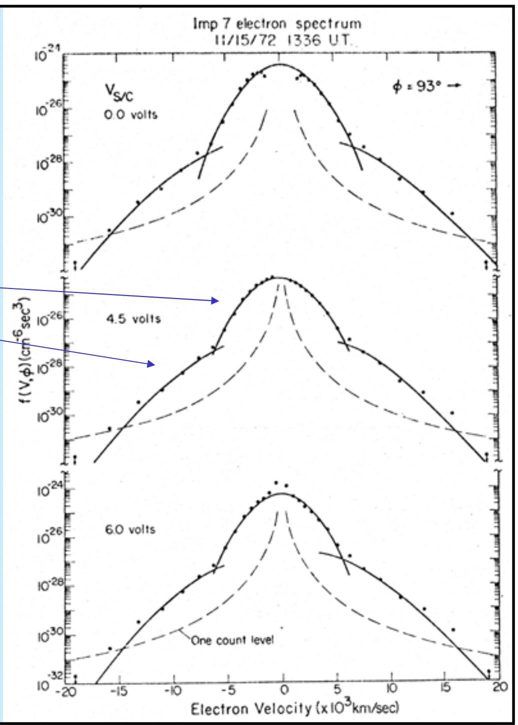
Two solar wind populations:

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

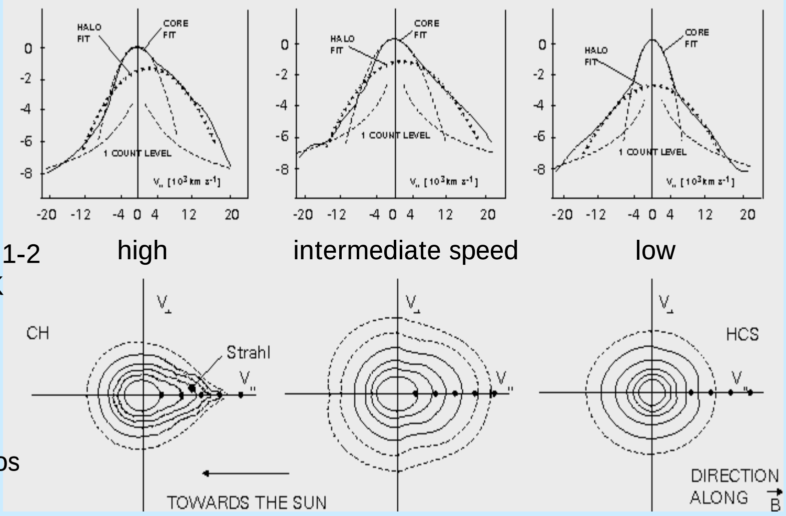
Core: local, collisional, **bound** by electrostatic potential

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

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



Electron velocity distributions



high

intermediate speed

low

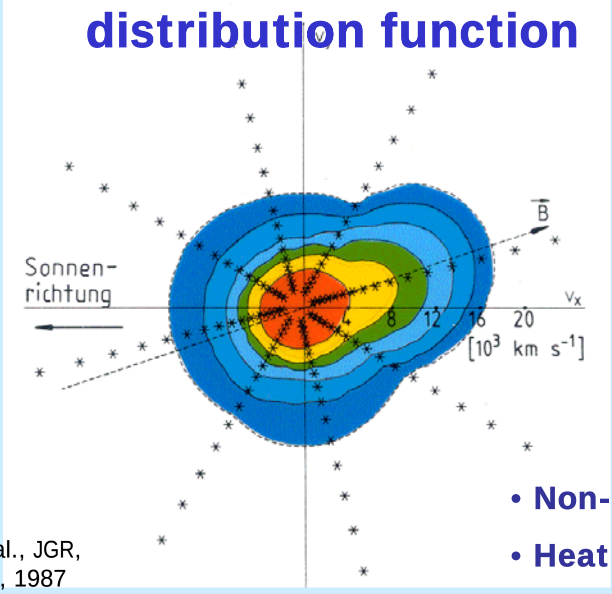
T_e = 1-2 10^5 K

Helios

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

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

Electron velocity distribution function



Helios

Sun

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

- **Non-Maxwellian**
- **Heat flux tail**

Fluid description

Moments of the Vlasov/Boltzmann equation:

Density: $n_j = \int d^3v \, f_j(\mathbf{x},\mathbf{v},t)$

Flow velocity: $\mathbf{U}_j = 1/n_j \int d^3v \, f_j(\mathbf{x},\mathbf{v},t) \, \mathbf{v}$

Thermal speed: $v_j^2 = 1/(3n_j) \int d^3v \, f_j(\mathbf{x},\mathbf{v},t) \, (\mathbf{v}-\mathbf{U}_j)^2$

Temperature: $T_j = m_j v_j^2 / k_B$

Heat flux: $Q_j = 1/2m_j \int d^3v \, f_j(\mathbf{x},\mathbf{v},t) \, (\mathbf{v}-\mathbf{U}_j) \, (\mathbf{v}-\mathbf{U}_j)^2$

Electron heat conduction

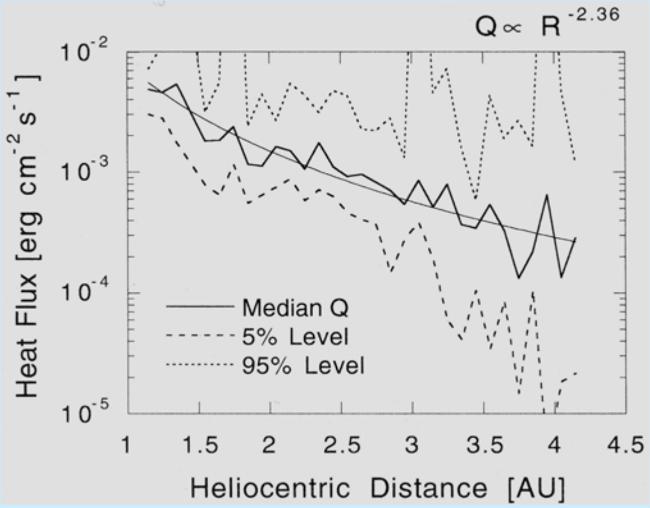
Heat carried by halo electrons!

$T_H = 7\, T_C$

Interplanetary potential:

Φ = 50-100 eV

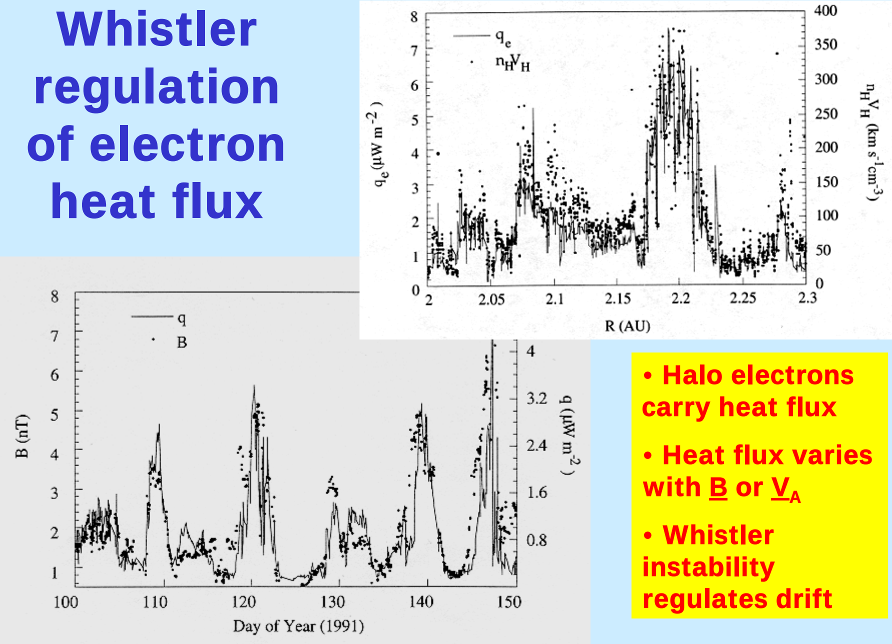
$\underline{E} = - 1/n_e\, \underline{\nabla}\, p_e$



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

$\underline{Q}_e \neq - \kappa \underline{\nabla}\, T_e$

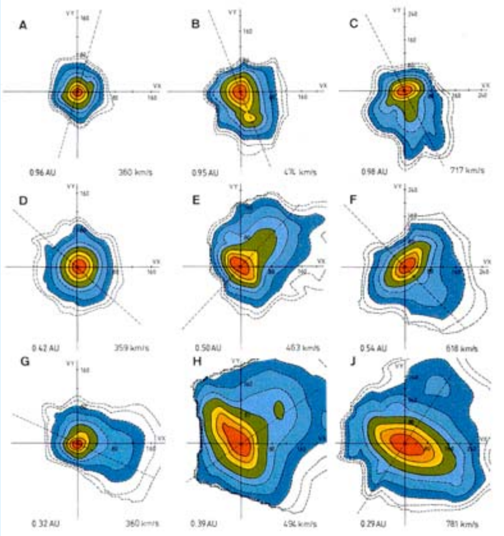
Whistler regulation of electron heat flux



- Halo electrons carry heat flux
- Heat flux varies with $\underline{B}$ or $\underline{V}_A$
- Whistler instability regulates drift

Sime et al., JGR, 1994

Proton velocity distributions



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

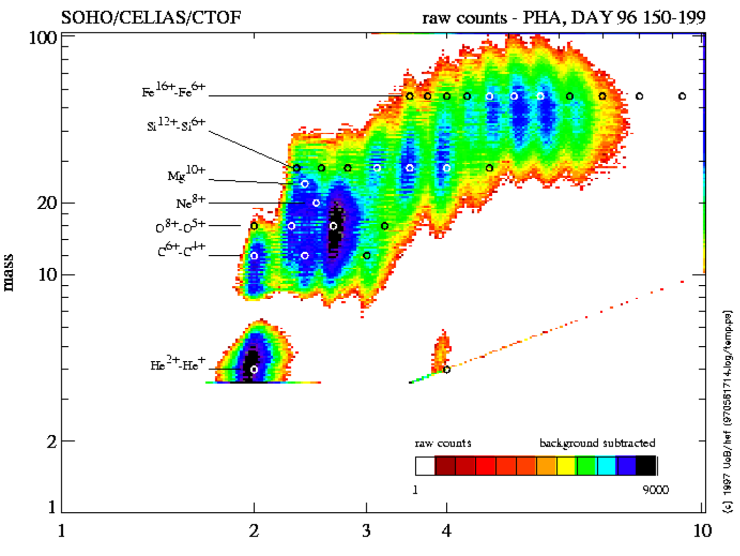
Plasma measurements
made at 10 s resolution
(> 0.29 AU from the Sun)

Helios

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

Ion composition of the solar wind

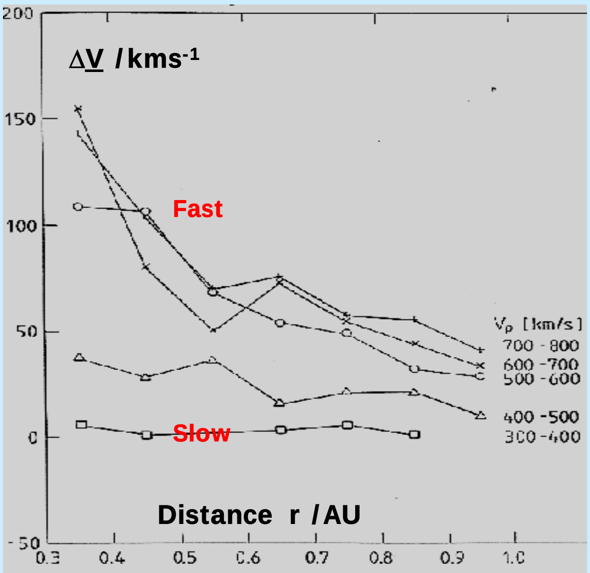
Ion mass



Mass/charge

Grünwaldt et al. (CELIAS on SOHO)

Ion differential streaming



- **Helios:**

Alpha particles are faster than the protons!

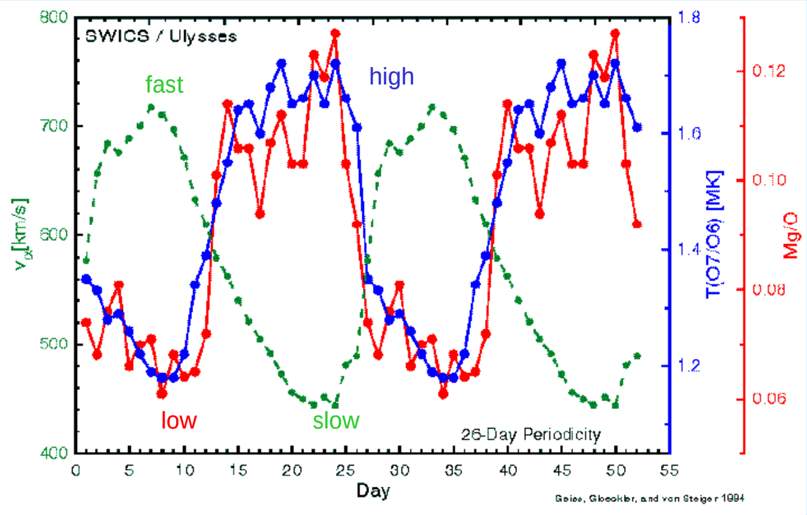
- **In fast streams the differential velocity $\Delta \underline{V} \leq \underline{V}_A$**

- **Ulysses:**

Heavy ions travel at alpha-particle speed!

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

Oxygen freeze-in temperature



Geiss et al., , 1996

Ulysses SWICS

Kinetic processes in the solar corona and solar wind I

- Plasma is multi-component and nonuniform

→ **complexity**

- Plasma has low density

→ **deviations from local thermal equilibrium**

→ **suprathermal particles (electron strahl)**

→ **global boundaries are reflected locally**

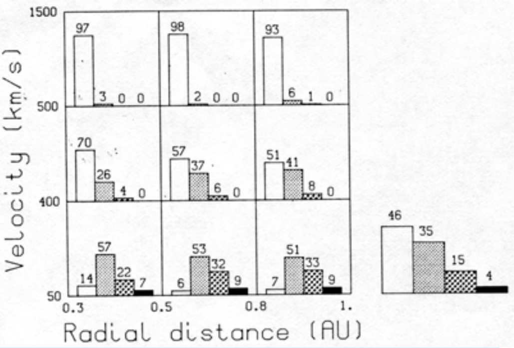
Problem: Thermodynamics of the plasma, which is far from equilibrium.....

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

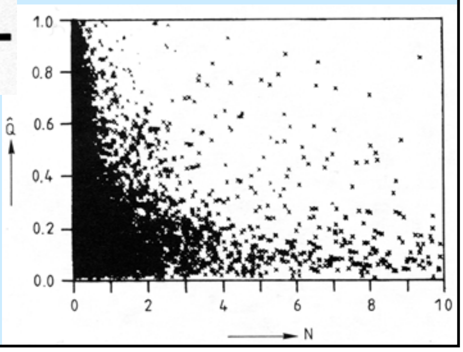
- Since N < 1, Coulomb collisions require kinetic treatment!
- Yet, only a few collisions ($N \geq 1$) remove extreme anisotropies!
- Slow wind: N > 5 about 10%, N > 1 about 30-40% of the time.

Proton Coulomb collision statistics



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

Proton heat flux regulation

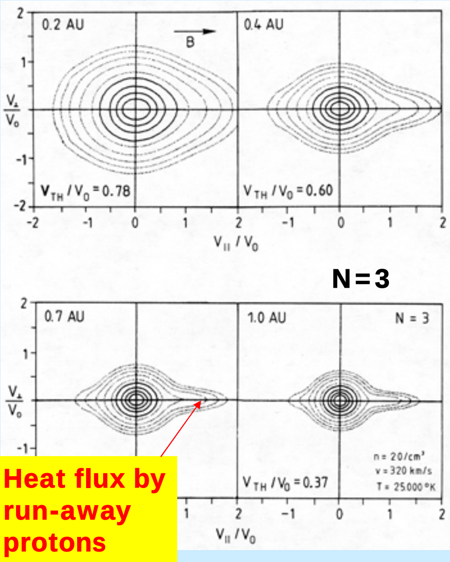


N: <0.1; [0.1, 1]; [1, 5]; >5

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

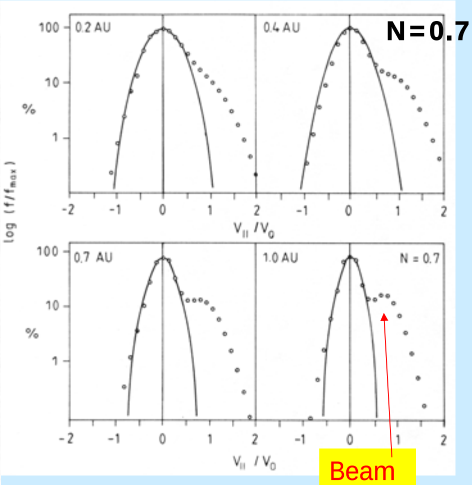
Livi et al., JGR, **91**, 8045, 1986

Coulomb collisions in slow wind



N=3

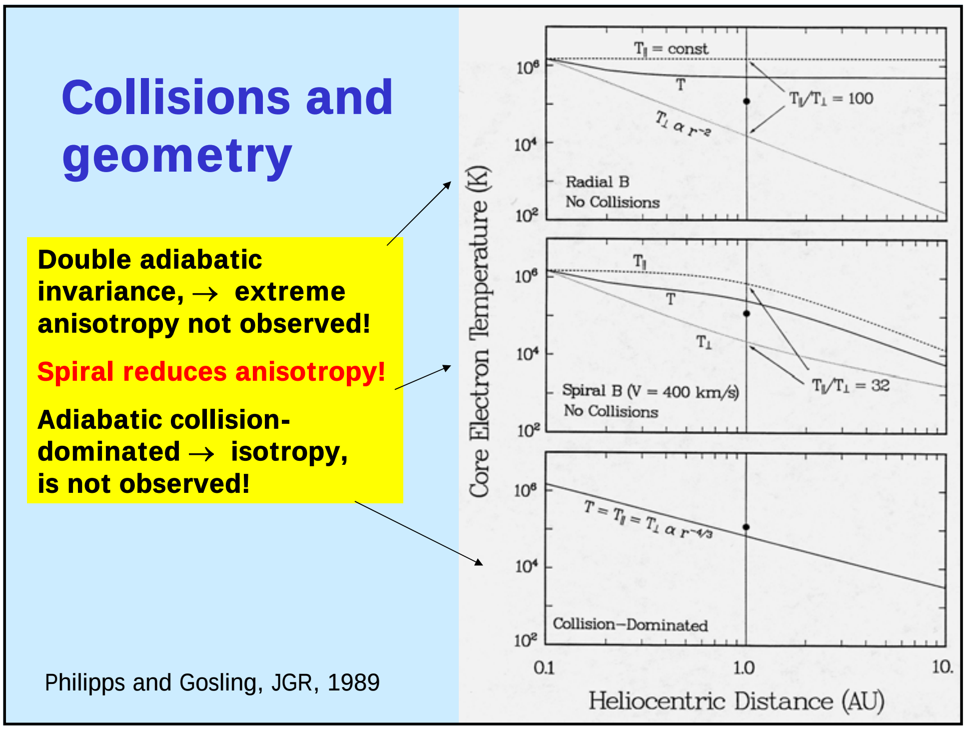
Heat flux by run-away protons



N=0.7

Beam

Marsch and Livi, JGR, **92**, 7255, 1987



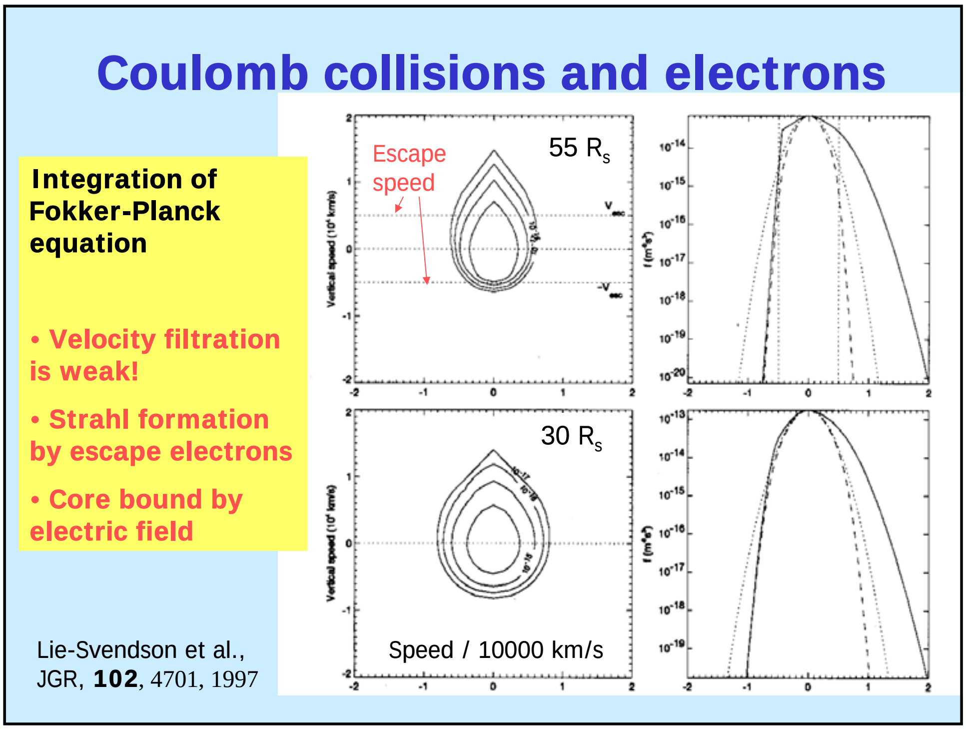
Collisions and geometry

Double adiabatic invariance, → extreme anisotropy not observed!

Spiral reduces anisotropy!

Adiabatic collision-dominated → isotropy, is not observed!

Philipps and Gosling, JGR, 1989



Coulomb collisions and electrons

Integration of 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

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 tenuous and turbulent

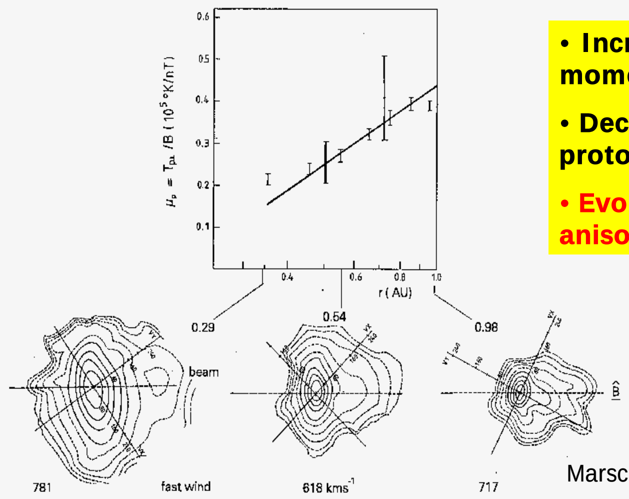
→ **free energy for micro-instabilities**

→ **resonant wave-particle interactions**

→ **collisions by Fokker-Planck operator**

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

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, 1982

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:

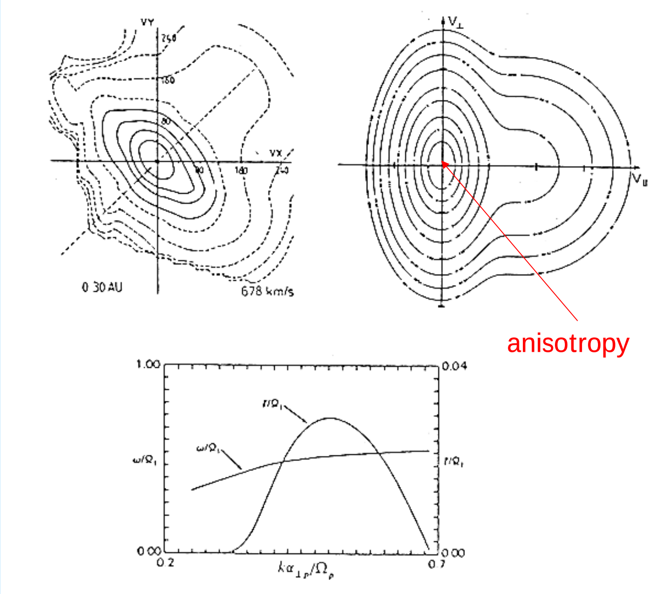
$\omega(\underline{k}) - \underline{k}\cdot\underline{v} = 0$ (Landau resonance)

$\omega(\underline{k}) - \underline{k}\cdot\underline{v} = \pm\,\Omega_j$ (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 perpendicular $T_\perp$



anisotropy

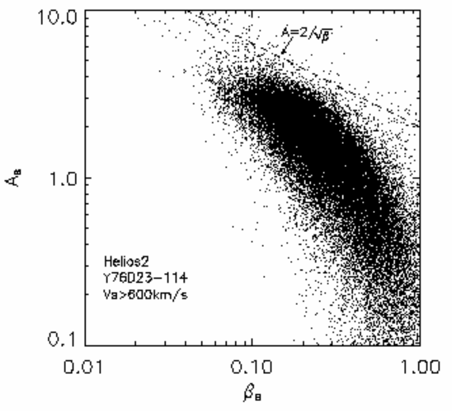
$\omega \approx 0.5\Omega_p$

$\gamma \approx 0.05\Omega_p$

Marsch, 1991

Temperature anisotropy versus plasma beta

$A_B = T_\perp / T_{||} - 1$



- Fast solar wind
- V > 600 km/s
- 36297 proton spectra
- Days 23 -114 in 1976

Dashed line refers to plateau:

$$A_B = 2\ \beta_B^{-1/2}$$

$\beta_B = 2\ (W_{||}/V_A)^2\ 1.92$

β_B is the core plasma beta, for VDF values > 20 % of max.

Marsch et al., JGR, **109**, 2004

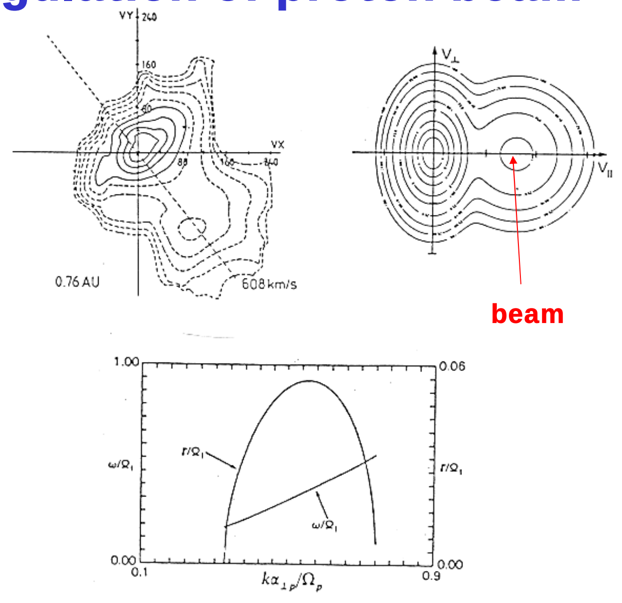
Wave regulation of proton beam

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

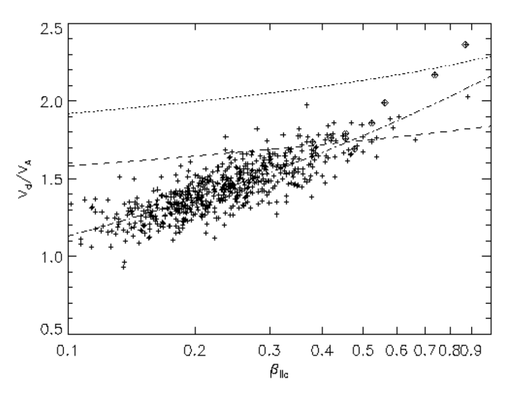
$\omega \approx 0.4\Omega_p$

$\gamma \approx 0.06\Omega_p$

Marsch, 1991



Beam drift versus core plasma beta



- Origin of the beam not yet explained (mirror force in corona, Coulomb collisions)
- Quasilinear resonant pitch-angle diffusion determines the kinetics (thermodynamics) of solar wind protons.
- Proton beam drift speed is regulated by wave-particle interactions and depends on the plasma beta.

- The dotted (dashed) line corresponds to a relative beam density of 0.05 (0.2).

$$V_d/V_A = (2.16 \pm 0.03)\ \beta_{\|c}^{(0.28 \pm 0.01)}$$

(empirical fit to data given by the dot-dash line)

Tu, Marsch and Qin, JGR, **109**, 2004

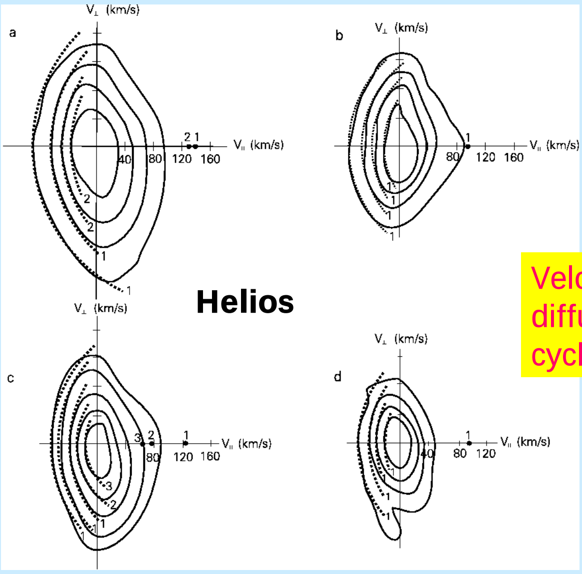
Kinetic plasma instabilities

- 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!

Wave mode	Free energy source
Ion acoustic	**Ion beams, electron heat flux**
Ion cyclotron	**Temperature anisotropy**
Whistler (Lower Hybrid)	**Electron heat flux**
Magnetosonic	**Ion beams, differential streaming**

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

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 **106**, 8357, 2001

Quasi-linear (pitch-angle) diffusion

Diffusion equation

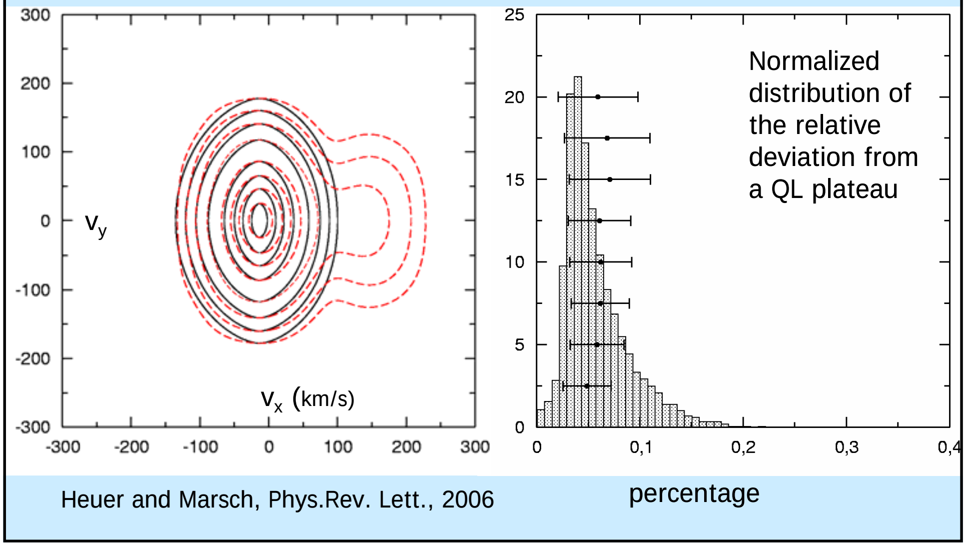
$$\frac{\partial}{\partial t} f_j(V_\perp, V_\parallel, t) = \sum_M \sum_{s=-\infty}^{+\infty} \frac{1}{(2\pi)^3} \int_{-\infty}^{+\infty} d^3k \, \hat{\mathcal{B}}_M(\mathbf{k}) \times \frac{1}{V_\perp} \frac{\partial}{\partial \alpha} \left(V_\perp \, \nu_j(\mathbf{k}, s; V_\parallel, V_\perp) \frac{\partial}{\partial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

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,
Phys. Fluids, **9**, 2377, 1966

Statistics on diffusion plateaus of solar wind protons



Normalized distribution of the relative deviation from a QL plateau

Heuer and Marsch, Phys.Rev. Lett., 2006

Summary

- In-situ ion and electron measurements indicate strong deviations from local (collisional) thermal equilibrium
- Wave-particle interactions and micro-instabilities regulate the kinetic features of particle velocity distributions
- Kinetic models are required to describe the essential features of the plasma in the solar wind
- The non-equilibrium thermodynamics in the tenuous solar wind involve particle interaction with micro-turbulent fields
- Wave energy transport as well as cascading and dissipation in the kinetic domain are still not well understood