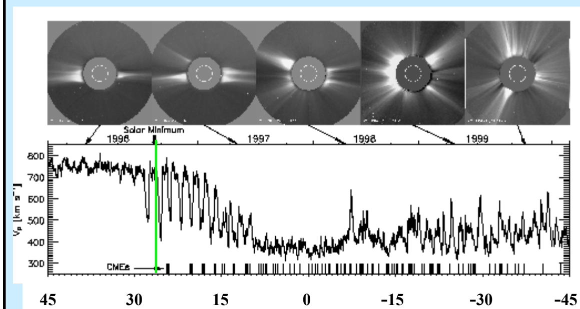
The microstate of the solar wind

- 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 interactions
- Kinetic models of the solar wind

Changing corona and solar wind



McComas et al., GRL, 2000

LASCO/Ulysses

Length scales in the solar wind

Macrostructure - fluid scales

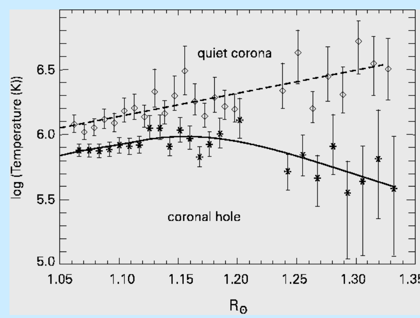
• Heliocentric distance:	r	150 Gm (1AU)
• Solar radius:	R_s	696000 km (215 R_s)
• Alfvén waves:	λ	30 - 100 Mm

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!

Electron temperature in the corona



Streamer belt, closed

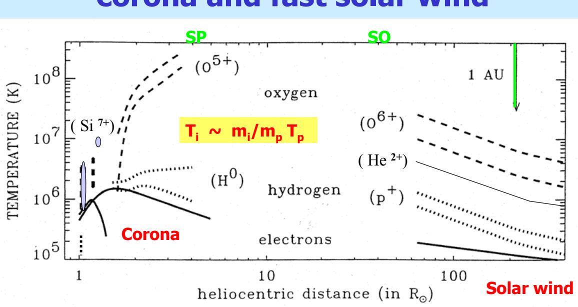
Coronal hole, open magnetically

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

Heliocentric distance

SUMER/CDS SOHO

Temperature profiles in the corona and fast solar wind

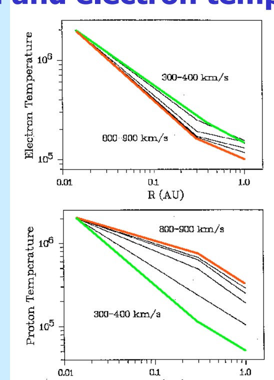


Cranmer et al., Ap.J., 2000; Marsch, 1991

Proton and electron temperatures

Electrons are cool!

Protons are hot!



slow wind ↓ fast wind

fast wind ↓ slow wind

Marsch, 1991

Theoretical description

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

Distribution functions | Moments

Kinetic equations

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

→ **Particle velocity distributions and field power spectra**

Multi-Fluid (MHD) equations

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

→ **Single/multi fluid parameters**

Velocity distribution functions

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

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

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: $T_j = m_j v_j^2/k_B$

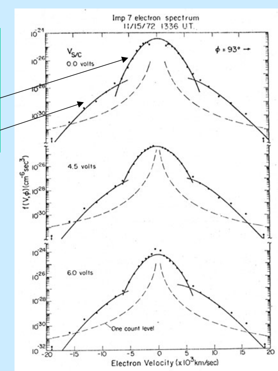
Heat flux: $Q_j = 1/2m_j \int d^3v\, f_j(\mathbf{x},\mathbf{v},t)\, (\mathbf{v}-\mathbf{U}_j)\, (\mathbf{v}-\mathbf{U}_j)^2$

Electron energy spectrum

IMP spacecraft

Two solar wind electron populations:

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



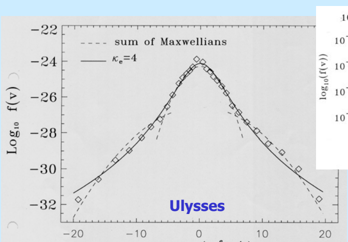
Core: local, collisional, **bound** by electrostatic potential

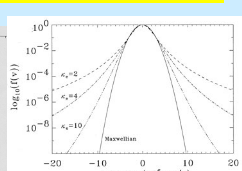
Halo: global, collisionless, **free** to escape (exopsheric)

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

Solar electron exosphere and velocity filtration

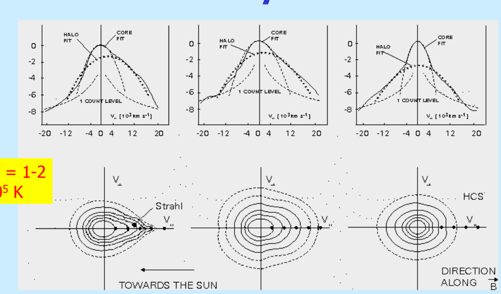
That suprathermal electrons drive solar wind through electric field is not compatible with coronal and in-situ observations!





Maksimovic et al., A&A, 1997

Electron velocity distributions



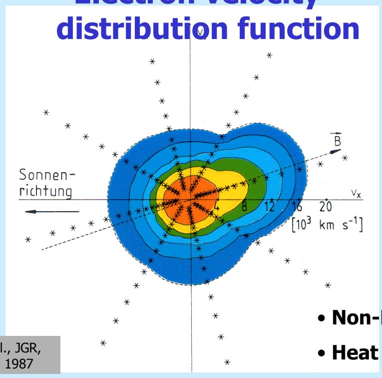
T_e = 1-2 10^5 K

high | intermediate speed | low

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

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

Electron velocity distribution function



Sun

Helios

n_e = 3-10 cm^{-3}

- Non-Maxwellian
- Heat flux tail

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

Electron heat conduction

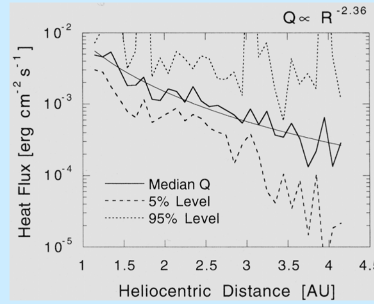
Heat carried by halo electrons!

$T_H = 7\ T_C$

Interplanetary potential:

Φ = 50-100 eV

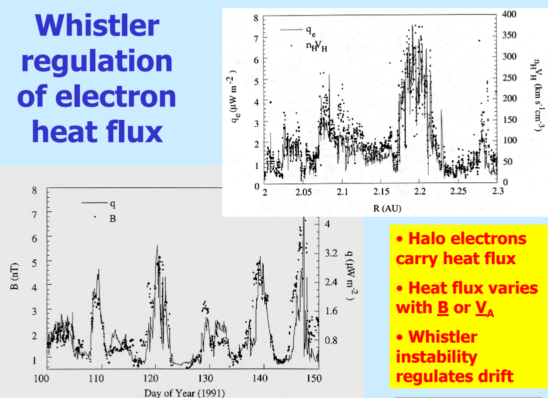
$\underline{E} = -1/n_e \underline{\nabla} p_e$



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

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

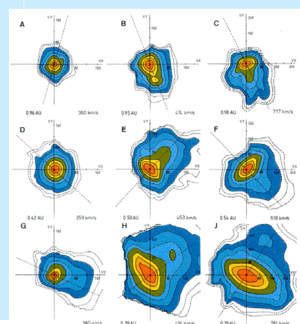
Whistler regulation of electron heat flux



- 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



Helios

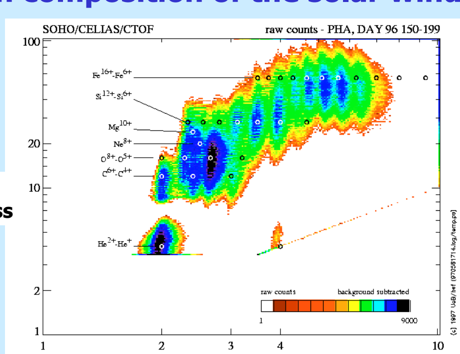
- Temperature anisotropies
- Ion beams
- Plasma instabilities
- Interplanetary heating

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

Ion mass

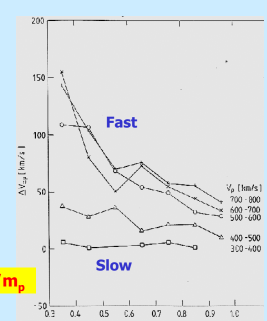


Mass/charge

Grünwaldt et al. (CELIAS on SOHO)

Ion differential streaming

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



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

Distance r /AU

- Helios:

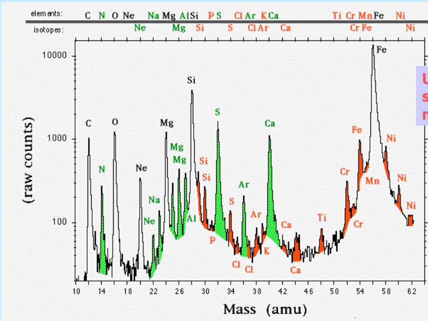
Alpha particles are faster than the protons!

- 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

Elements (isotopes) in the solar wind

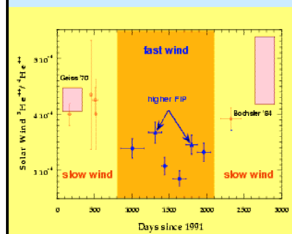


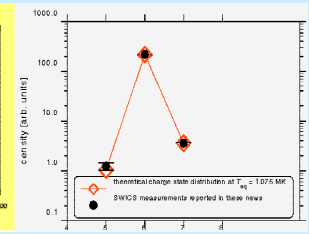
Unfractionated sample of solar material!

SOHO CELIAS/MTOF

Ipavich et al., GRL, 1998

Rare ions of Helium and Oxygen





$^3He^{2+}$ / $^4He^{2+}$ = 3.5-4.5 x 10^{-4}

O^{5+} in the solar wind

Gloeckler et al., GRL, 1998

Ulysses SWICS

Wimmer-Schweingruber et al., JGR, 1999

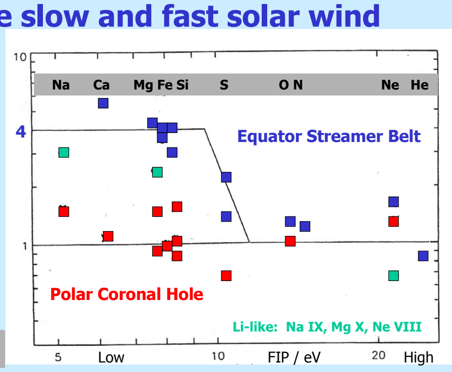
Composition in the corona and the slow and fast solar wind

SUMER

First Ionization Potential (FIP) bias

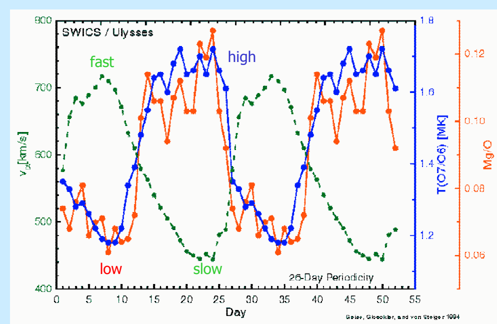
FIP effect from EUV line ratios

1.03 R_S



Feldman et al., Ap. J., **505**, 999, 1998

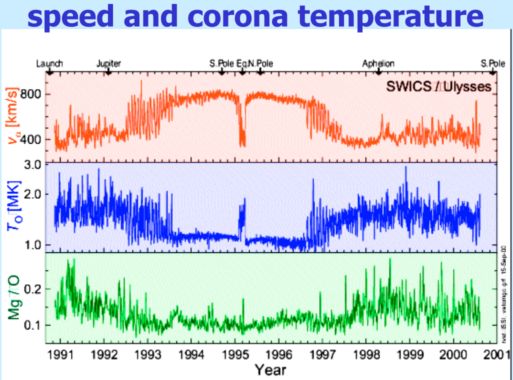
Oxygen freeze-in temperature



Geiss et al., , 1996

Ulysses SWICS

Correlations between wind speed and corona temperature



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**

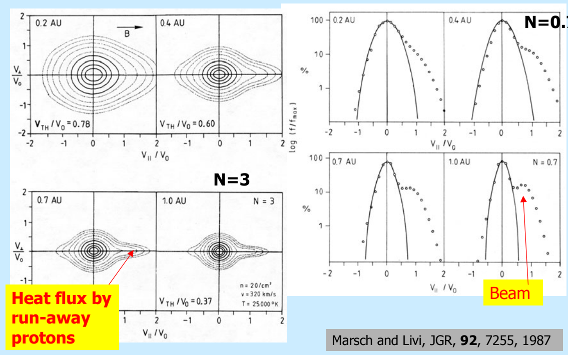
Problem: Thermodynamics of the plasma, which is far from equilibrium.....

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}

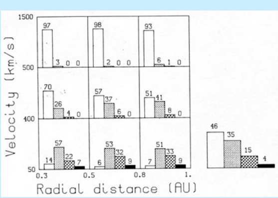
- Since N < 1, Coulomb collisions require kinetic treatment!
- Yet, only a few collisions (N ≥ 1) remove extreme anisotropies!
- Slow wind: N > 5 about 10%, N > 1 about 30-40% of the time.

Coulomb collisions in slow wind



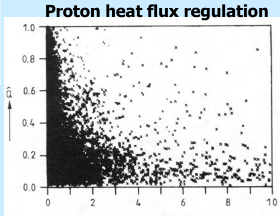
Marsch and Livi, JGR, **92**, 7255, 1987

Proton Coulomb collision statistics



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

Proton heat flux regulation



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

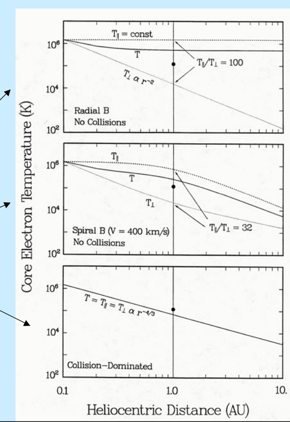
Livi et al., JGR, **91**, 8045, 1986

Collisions and geometry

Double adiabatic invariance, → extreme anisotropy not observed!

Spiral reduces anisotropy!

Adiabatic collision-dominated → isotropy, is not observed!

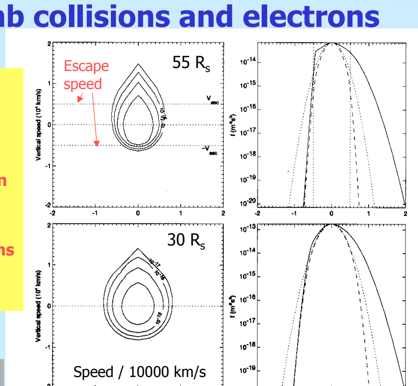


Philipps and Gosling, JGR, 1989

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 dilute and turbulent

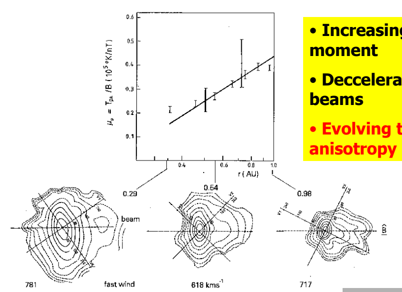
→ **free energy for micro-instabilities**

→ **resonant wave-particle interactions**

→ **collisions by Fokker-Planck operator**

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

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

Wave-particle interactions

Dispersion relation using measured or model distribution functions f(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(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)

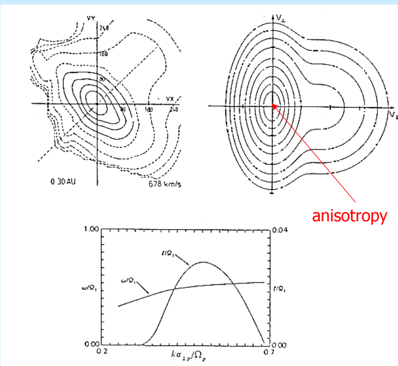
→ Energy and momentum exchange between waves and particles. Quasi-linear or non-linear relaxation.....

Proton temperature anisotropy

- Measured and modelled proton velocity distribution
- Growth of ion-cyclotron waves!
- Anisotropy-driven instability by large perpendicular $T_\perp$

$\omega \approx 0.5\Omega_p$

$\gamma \approx 0.05\Omega_p$



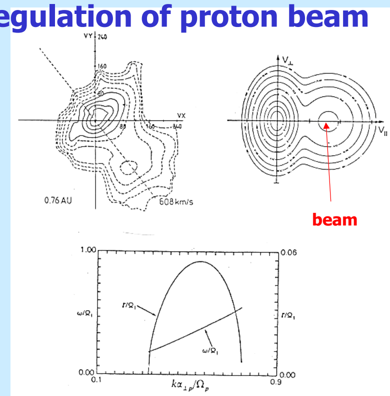
Marsch, 1991

Wave regulation of proton beam

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

$\omega \approx 0.4\Omega_p$

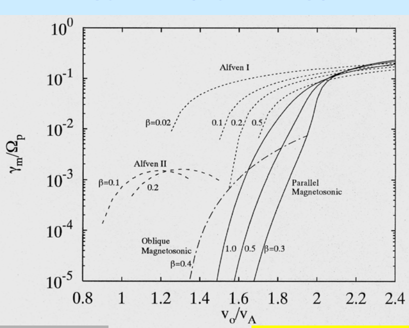
$\gamma \approx 0.06\Omega_p$



Marsch, 1991

Electromagnetic ion beam instabilities

Maximum growth rate

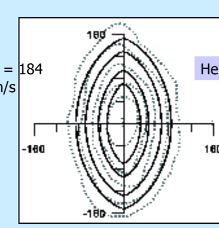


Daughton and Gary, JGR, 1998

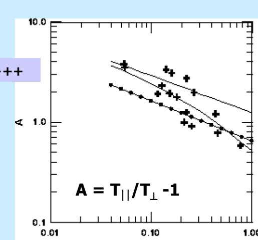
Proton beam drift speed

Core-anistropy regulation by diffusion plateau formation

V_A = 184 km/s



Helios +++



Not bi-Maxwellian but bi-shells!

Tu & Marsch, JGR, 2002

•• A = 0.6 $\beta^{0.4}$ (Gary et al., 2001)

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

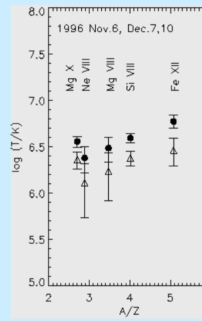
Heavy ion heating proportional to charge/mass by cyclotron resonance

$\Omega \sim Z/A$

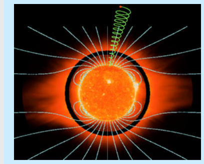
Heavy ion temperature

T=(2-6) MK

r = 1.15 R_S



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



- Magnetic mirror in coronal funnel/hole
- Cyclotron resonance ⇒ increase of μ

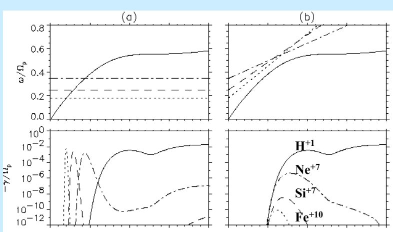
SUMER/SOHO

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: $\omega = \Omega - k \cdot \upsilon$

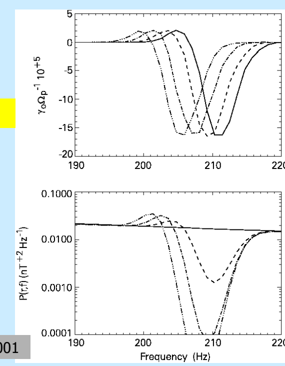
Absorption of cyclotron waves

Oxygen ion damping rate

Frequency sweeping!

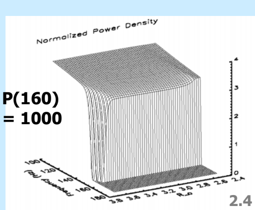
Self-consistent power spectrum

Height / km 0 5000 10000 15000



Tu & Marsch, JGR, **106**, 8233, 2001

Evolution of wave power spectrum

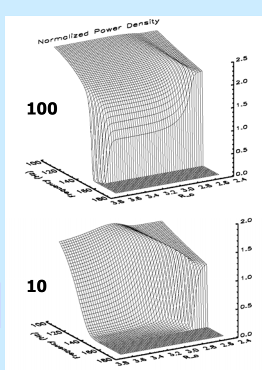


P(160) = 1000

2.4 R_s

3.8 R_s Distance

$\delta b/B \approx 0.01$ at Ω_i



Variable wave spectral density P(f) [nT²/Hz], f = 100-180 Hz

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

Multi-fluid equations

Momentum equation

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

Wave acceleration.....?

Parallel energy equation

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

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 $q_{\perp,\parallel}$ .... ?

Tu and Marsch, JGR, **106**, 8233, 2001

Wave heating and acceleration of protons and oxygen ions

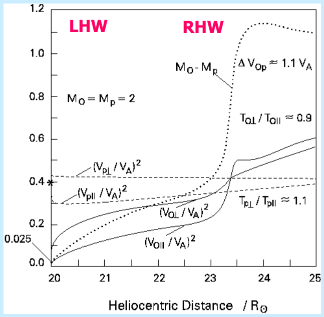
Machnumber ....

Thermal speed squared (plasma beta)

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

O^{6+} ----------

Preferential acceleration and heating of oxygen



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

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

Parallel VDF

$$\frac{\partial F_\parallel}{\partial t} + v_\parallel \frac{\partial F_\parallel}{\partial s} + \left(\frac{q}{m}E_\parallel - g(s)\right)\frac{\partial F_\parallel}{\partial v_\parallel} + \frac{1}{2A(s)}\frac{\partial A(s)}{\partial s} \cdot 2\left(\frac{\partial F_\perp}{\partial v_\parallel} + v_\parallel F_\parallel\right) = \frac{\delta F_\parallel}{\delta t} + \frac{\delta F_\parallel}{\delta t}\Big|_{Coul.}$$

Perpendicular VDF

$$\frac{\partial F_\perp}{\partial t} + v_\parallel \frac{\partial F_\perp}{\partial s} + \left(\frac{q}{m}E_\parallel - g(s)\right)\frac{\partial F_\perp}{\partial v_\parallel} + \frac{1}{2A(s)}\frac{\partial A(s)}{\partial s} \cdot 4\left(v_{j\perp}^2\frac{\partial F_\perp}{\partial v_\parallel} + v_\parallel F_\perp\right) = \frac{\delta F_\perp}{\delta t} + \frac{\delta F_\perp}{\delta t}\Big|_{Coul.}$$

Vocks and Marsch, GRL, **28**, 1917, 2001

Reduced diffusion equations

Number of particles

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

Perpendicular thermal speed

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

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

Diffusive transport coefficients

Diffusion

Acceleration

Heating

$$\begin{pmatrix} D_j(w_\parallel) \\ A_j(w_\parallel) \\ H_j(w_\parallel) \end{pmatrix} = \sum_M \frac{1}{(2\pi)^3}\int_{-\infty}^{\infty} d^3k\,\hat{\mathcal{B}}_M(\mathbf{k}) \times \sum_{s=-\infty}^{\infty} \overline{\nu}_j(\mathbf{k}, s; w_\parallel)\begin{pmatrix} 1 \\ \frac{s\Omega_j}{k_\parallel} \\ (\frac{s\Omega_j}{k_\parallel})^2 \end{pmatrix}$$

Wave-particle relaxation rate and resonance condition

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

Reduced velocity distributions

Number of particles

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

Perpendicular thermal speed

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

Moments

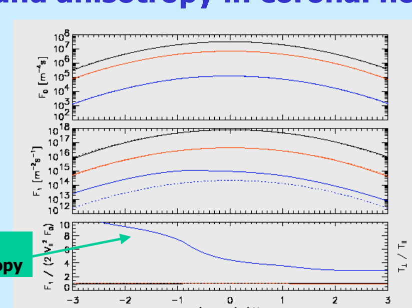
$$\int_{-\infty}^{\infty} dw_\parallel F_{j\parallel}(w_\parallel)\begin{pmatrix} 1 \\ w_\parallel \\ w_\parallel^2 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ V_{j\parallel}^2 \end{pmatrix}$$

Normalisation

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

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

Reduced velocity distributions and anisotropy in coronal hole



H^+

He^{2+}

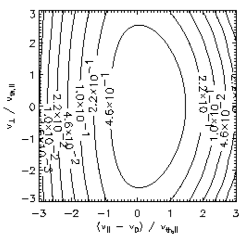
O^{5+}

Strong anisotropy

Vocks and Marsch, GRL, **28**, 1917, 2001

Height = 0.43 R_s

Model ion velocity distribution in coronal hole



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

Waves+collisions+mirror force

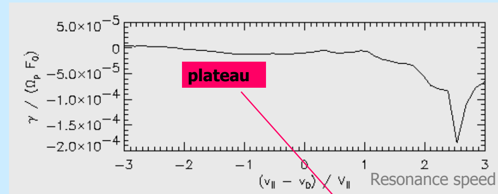
$$W_{j\perp}^2(w_\|) = \frac{F_{j\perp}(w_\|)}{F_{j\|}(w_\|)}$$

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

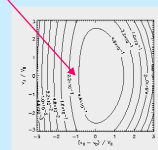
$$f_j(w_\|, w_\perp) = \frac{F_{j\|}(w_\|)}{2\pi W_{j\perp}^2(w_\|)} \exp(-\frac{w_\perp^2}{2W_{j\perp}^2(w_\|)})$$

Vocks and Marsch, ApJ., **568**, 1030, 2002

Plateau at marginal stability



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



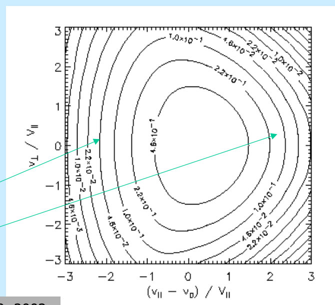
Vocks and Marsch, ApJ, **568**, 1030, 2002

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) cannot be described adequately by polynomial expansion!



Vocks & Marsch, ApJ, **568**, 1030, 2002

MHD turbulence dissipation through absorption of dispersive waves

- **Viscous and Ohmic dissipation in collisionless plasma (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

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

Pitch-angle gradient in wave frame

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

Kennel and Engelmann, Phys. Fluids, **9**, 2377, 1966

Ingredients in the quasi-linear diffusion equation

Normalised wave amplitude (Fourier)

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

Wave-particle relaxation rate

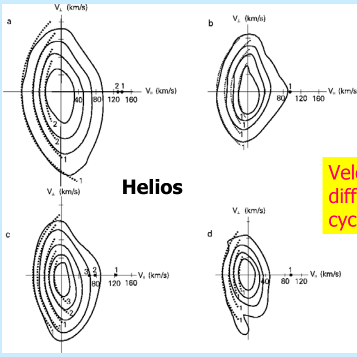
$$\nu_j(\mathbf{k},s;V_\|,V_\perp) = \pi\Omega_j^2\,\delta(\omega_M(\mathbf{k}) - s\Omega_j - k_\|V_\|) \times \left|\frac{1}{2}(J_{s-1}e_M^+ + J_{s+1}e_M^-) + \frac{V_j(\mathbf{k},s)}{V_\perp} J_s e_{Mz}\right|^2$$

Resonant speed; Bessel function of order s

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

Marsch and Tu, J. Geophys. Res., **106** , 227, 2001

Pitch-angle diffusion of protons



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

Plateau formation by wave-particle diffusion

Wave-frame coordinates

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

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

Transformed velocity distribution function

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

Resonant speed (s=1)

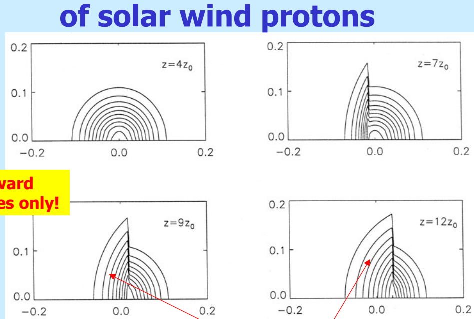
$$U_j(\mathbf{k}) = -\Omega_j/k_\|; \quad \alpha_j(k_\|) = \arccos(-\Omega_j/k_\| U)$$

Marsch and Tu, JGR, in press, 2001

Plateau in pitch-angle gradient

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

Quasilinear diffusion model of solar wind protons



Outward waves only!

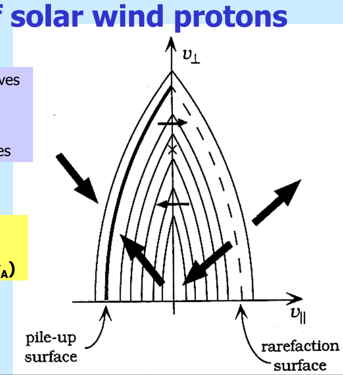
Galinsky and Shevchenko, Phys. Rev. L., **85**, 90, 2000

Pitch angle diffusion!

The kinetic diffusion-shell model of solar wind protons

- Dissipation of outward waves
- Energy flux across $v_{||} = 0$ boundary
- Generation of inward waves

Diffusion in kinetic shells (segments of spheres located at ± v_A)



Isenberg, J. Geophys. Res., **106**, 29249, 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**