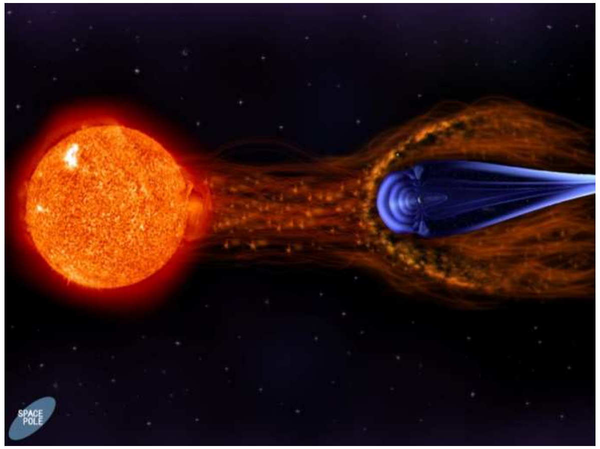
Kinetic models of the solar wind



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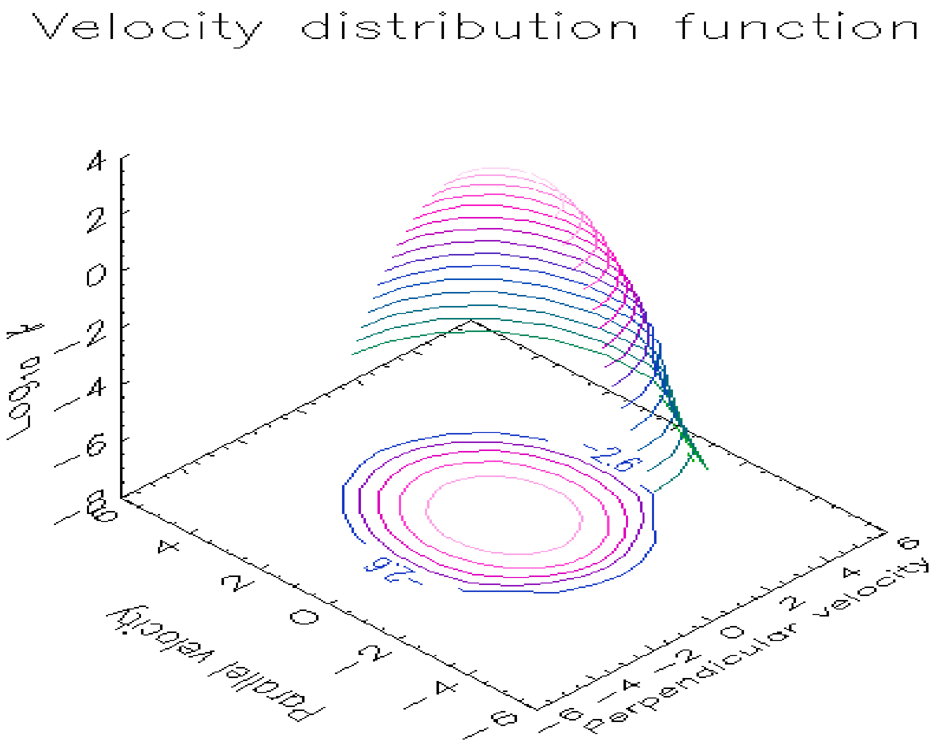
The kinetic approach

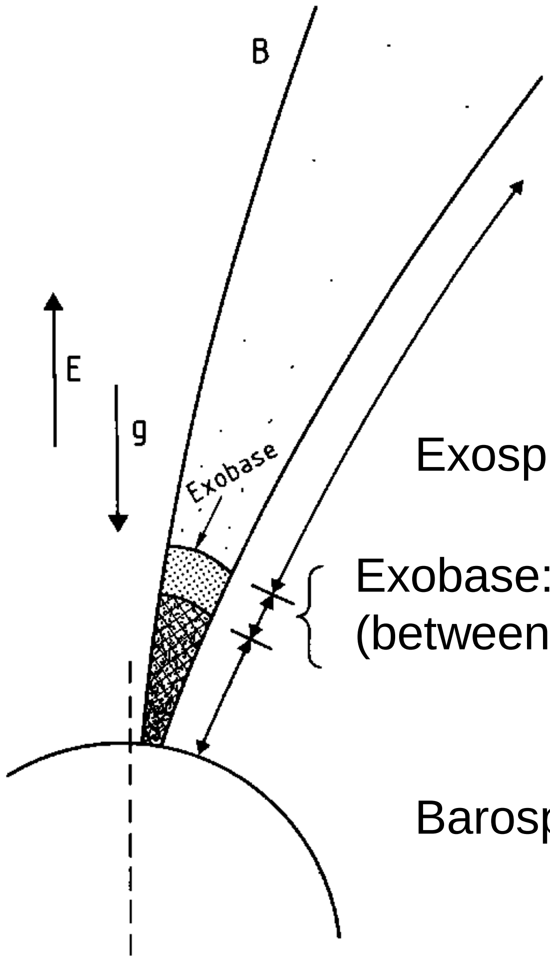
- Based on the velocity distribution function of the particles
- $f(\vec{r}, \vec{v}, t)\, d\vec{r}\, d\vec{v}$
- number of particles with a velocity in [$\vec{v}$, $\vec{v}+d\vec{v}$] and a position in [$\vec{r}$, $\vec{r}+d\vec{r}$] at an instant t
- Non-Maxwellian VDF observed in-situ in the solar wind



Evolution equation

$$\frac{\partial f}{\partial t}+\vec{v}\cdot\frac{\partial f}{\partial \vec{r}}+\vec{a}\cdot\frac{\partial f}{\partial \vec{v}}=-\frac{\partial}{\partial \vec{v}}\cdot\left[\vec{A}f-\frac{1}{2}\frac{\partial}{\partial \vec{v}}\cdot\left(\vec{D}f\right)\right]\quad+(WPI)[1]$$

Friction Diffusion

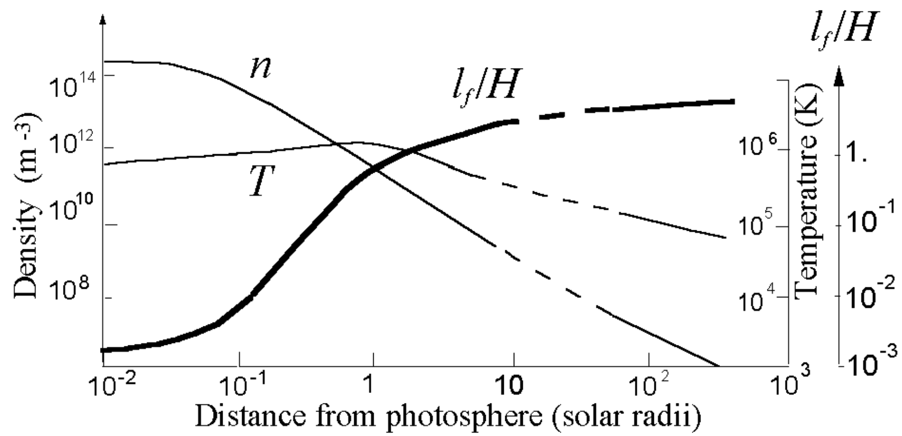


Exosphere: mfp>>H

Exobase: MFP=H
(between 1.1 and 6 Rs)

Barosphere: mfp<<H

Vlasov
Fokker-Planck
WPI Whistler turbulence
WPI Kinetic Alfven waves



$$\frac{\partial f}{\partial t} + \vec{v} \cdot \frac{\partial f}{\partial \vec{r}} + \vec{a} \cdot \frac{\partial f}{\partial \vec{v}} = -\frac{\partial}{\partial \vec{v}} \cdot \left[\vec{A} f - \frac{1}{2} \frac{\partial}{\partial \vec{v}} \cdot \left(\vec{D} f \right) \right] + (WPI)[1]$$

Spectral numerical method of expansion of the solution in orthogonal polynomials

$$f(z, y, \mu) = \exp(-y^2) \sum_{i=1}^{l} \sum_{j=1}^{m} \sum_{k=1}^{n} a_{ijk} P_i(\mu) S_j(y) L_k(z)$$

μ=cos θ

$$y^2 = \frac{mv^2}{2kT}$$

$$Z = -\int_{r}^{r_{top}} \sigma n(r') dr'$$

$$\left(\frac{\partial f}{\partial y} \right)_{y=y_i} \cong \sum_{j=1}^{m} D_{ij} f(y_j)$$

$$\int_a^b W(y) G(y) dy \cong \sum_{i=1}^{n} w_i G(y_i)$$

P(μ): Legendre polynomials
S(y): Speed polynomials
L(z): Modified Legendre polynomials

Advantages: Derivatives are linear function of f calculated at the quadrature points

and integrals (moments) are related to the coefficients.

i = 1,…,10 j=1,…16 k=1,…,10
At each radial distance, f(v,μ) is represented by 2*10*16=320 points.

Pierrard V., Astronum2010, ASP, 444, 166-176, 2011.

The moments of f

Number density [m^{-3}]

$$n(\vec{r}) = \int_{-\infty}^{\infty} f(\vec{r},\vec{v})\, d\vec{v}$$

Particle flux [m^{-2} s^{-1}]

$$\vec{F}(\vec{r}) = \int_{-\infty}^{\infty} f(\vec{r},\vec{v})\,\vec{v}\, d\vec{v}$$

Bulk velocity [m s^{-1}]

$$\vec{u}(\vec{r}) = \frac{\vec{F}(\vec{r})}{n(\vec{r})}$$

Pressure [Pa]

$$\vec{P}(\vec{r}) = m\int_{-\infty}^{\infty} f(\vec{r},\vec{v})(\vec{v}-\vec{u})(\vec{v}-\vec{u})d\vec{v}$$

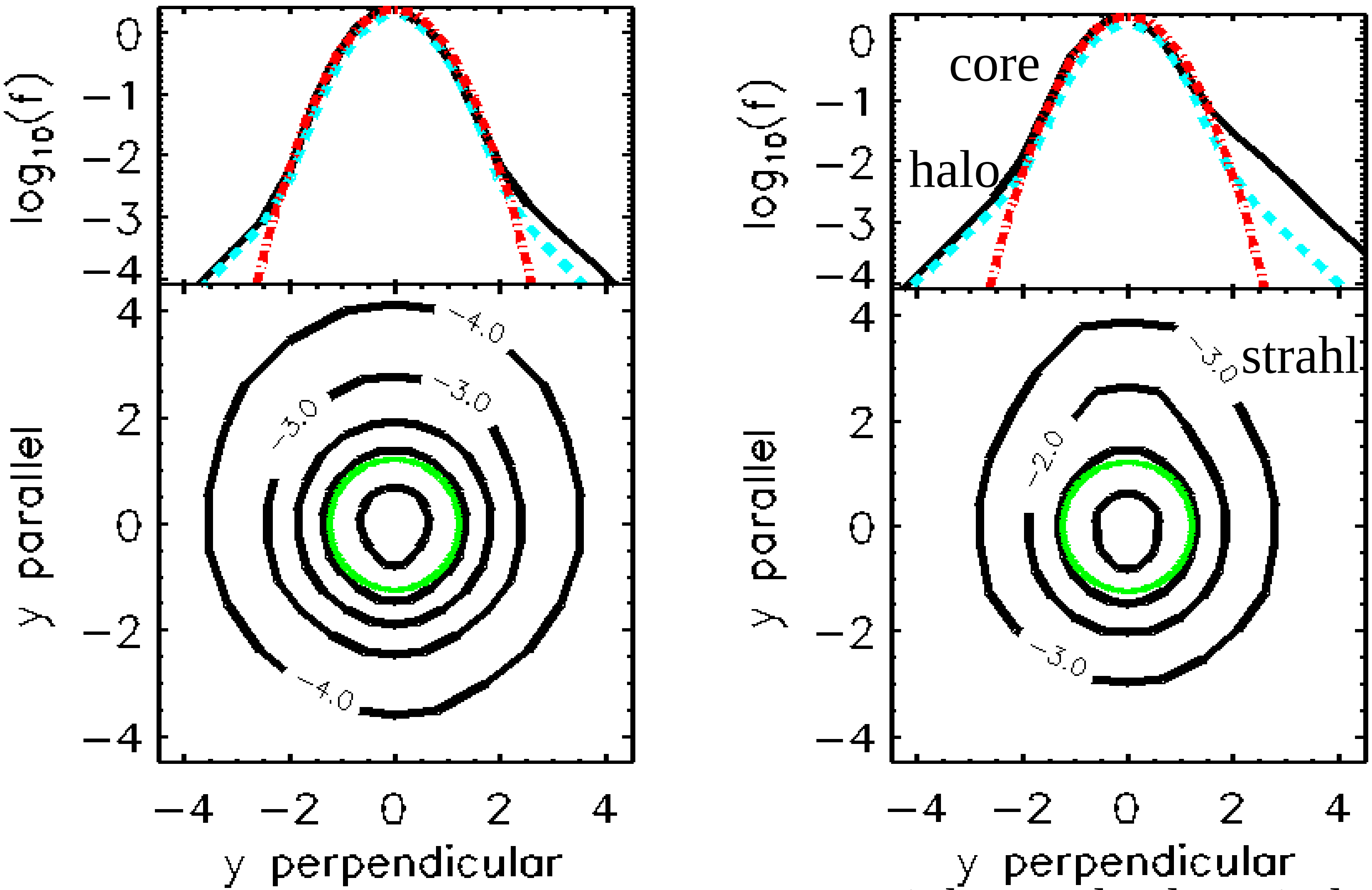
Temperature [K]

$$T(\vec{r}) = \frac{m}{3k\,n(\vec{r})}\int_{-\infty}^{\infty} f(\vec{r},\vec{v})\left|v-u\right|^2 d\vec{v}$$

Energy flux [Jm^{-2} s^{-1}]

$$\vec{E}(\vec{r}) = \frac{m}{2}\int_{-\infty}^{\infty} f(\vec{r},\vec{v})\left|v-u\right|^2(\vec{v}-\vec{u})d\vec{v}$$

Typical electron VDF observed by WIND at 215 Rs

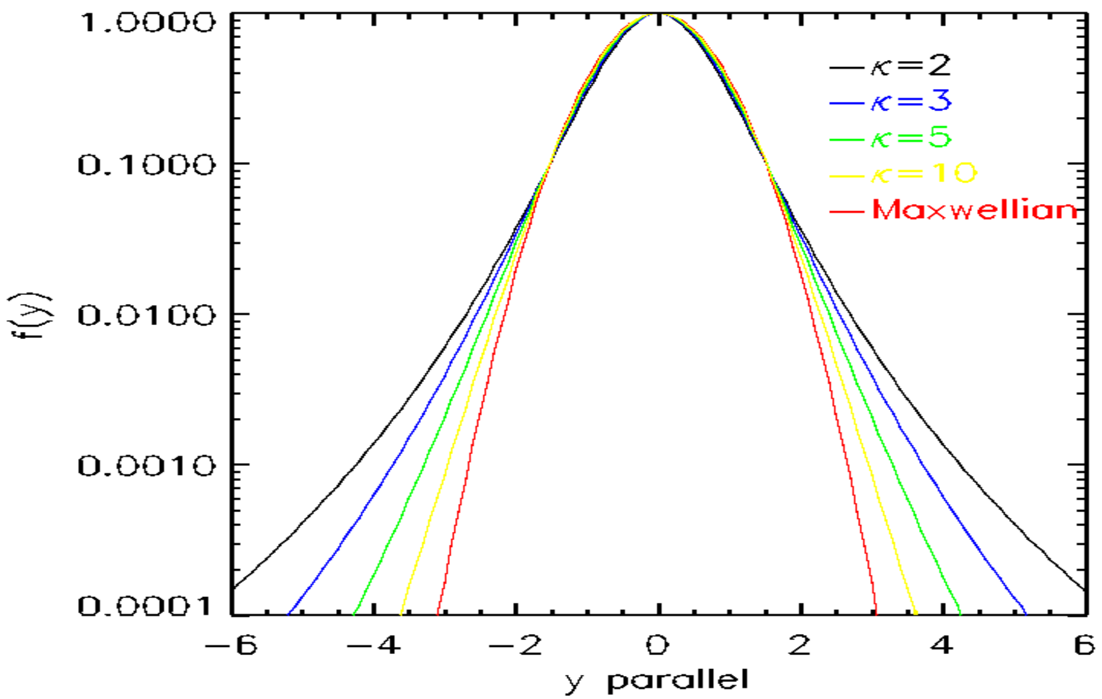


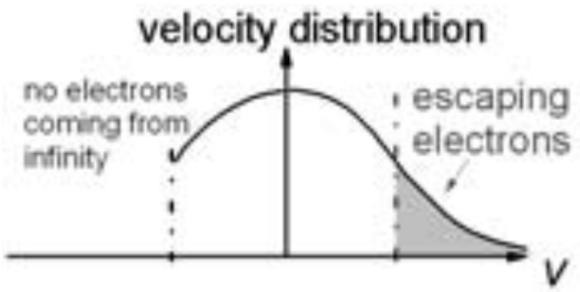
Slow speed solar wind

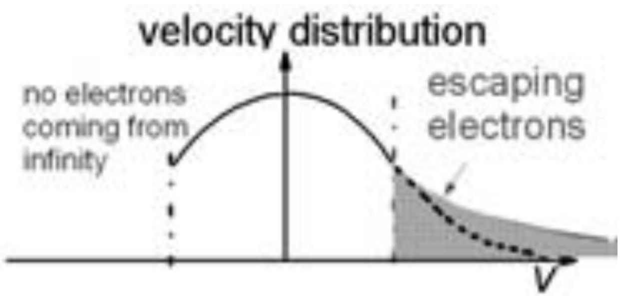
High speed solar wind

Pierrard, Sp. Sci. Rev., 172, 315, 2012

Kappa distributions







Ulysses electron distributions fitted with Kappa functions

Results:

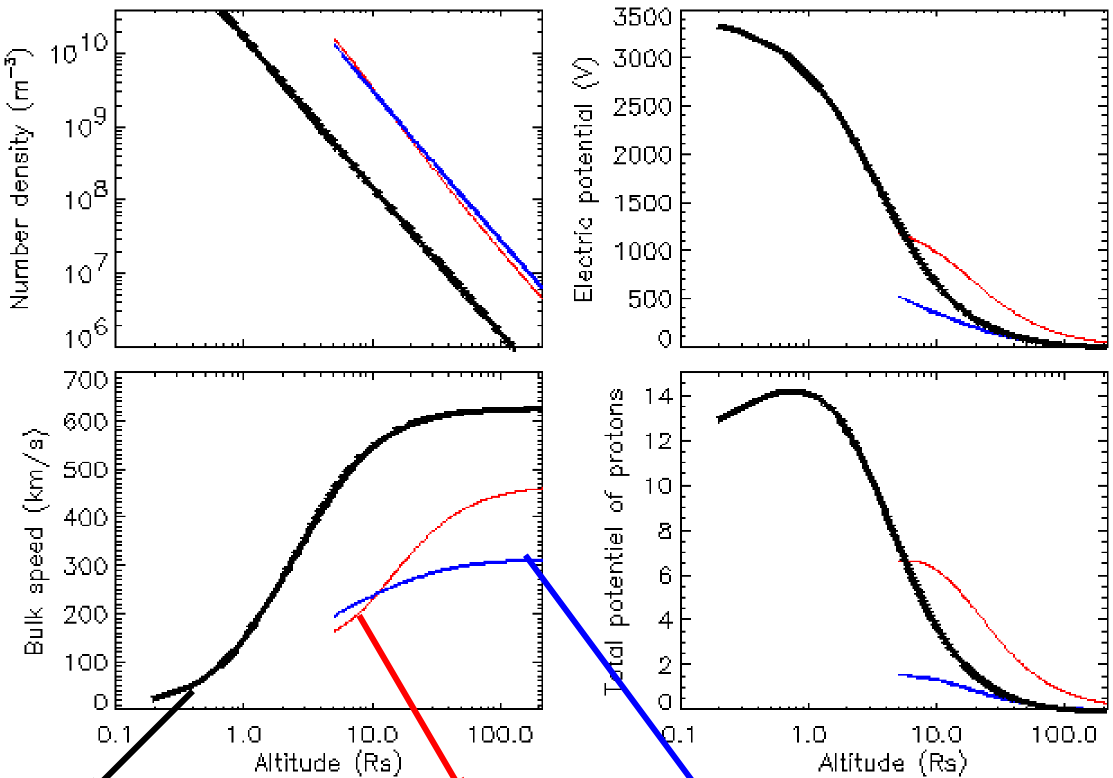
<κ> = 3.8 +/- 0.4 for v > 500 km/s (4878 observ.)

<κ> = 4.5 +/- 0.6 for v < 500 km/s (11479 observ.)

Pierrard and Lazar, Sol. Phys., 287, 153-174, 10.1007/s11207-010-9640-2, 2010.

Vlasov   Influence of halo

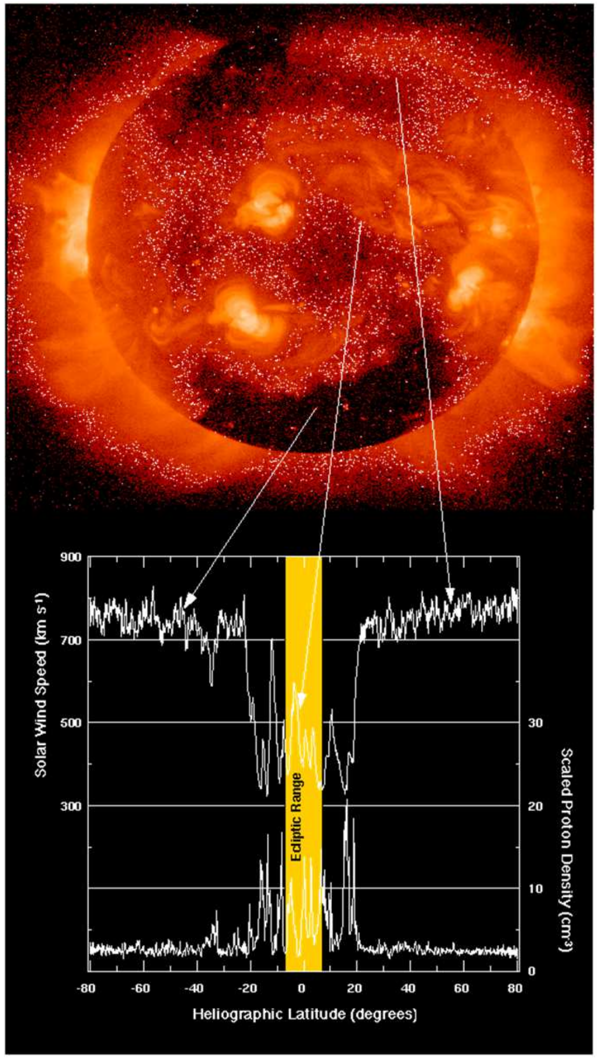
In coronal holes: lower number density
Lower exobase → larger bulk velocity



Lorentzian
(kappa = 3.5)
model r_0= 1.1 Rs

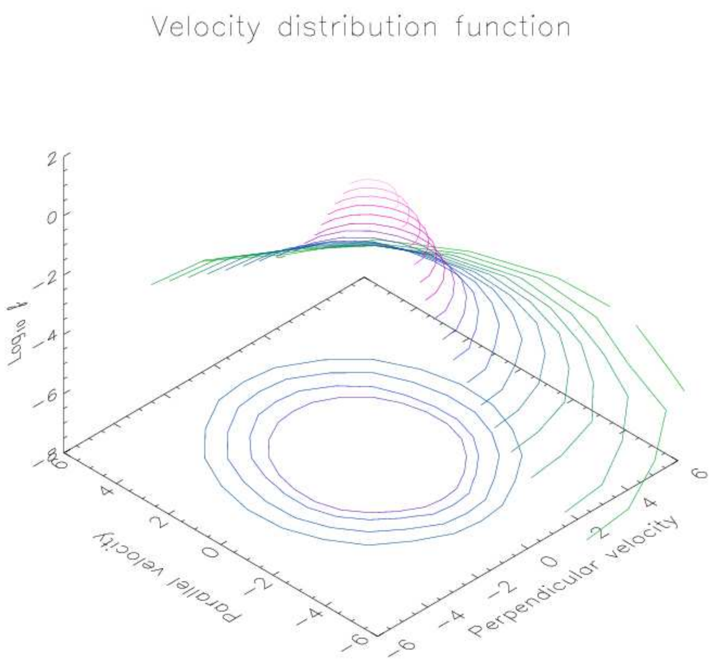
Lorentzian
(kappa=3.5)
model r_0= 6 Rs

Maxwellian
model r_0=6 Rs
$T_0=10^6$ K



Kappa distributions: theory and applications in space plasmas

- Generation of Kappa in space plasmas:
  turbulence and long-range properties of particle interactions in a plasma
  - plasma immersed in suprathermal radiation (Hasegawa et al., 1985)
  - random walk with power law (Collier, 1993)
  - turbulent thermodynamic equilibrium (Treumann, 1999)
  - entropy generalization in nonextensive Tsallis statistics (Leubner, 2002)
  - resonant interactions with whistler waves (Vocks and Mann, 2003)
- Consequences of suprathermal tails :
  - Heating of star's corona (velocity filtration)
  - Solar wind (acceleration)
  - Earth's exosphere
  - Planetary exospheres



Pierrard and Lazar, Sol. Phys., 287, 153-174, 10.1007/s11207-010-9640-2, 2010.

1. Coulomb collisions: Fokker-Planck

$$\frac{\partial f}{\partial t}+\vec{v}\cdot\frac{\partial f}{\partial \vec{r}}+\vec{a}\cdot\frac{\partial f}{\partial \vec{v}}=-\frac{\partial}{\partial \vec{v}}\cdot\left[\vec{A}f-\frac{1}{2}\frac{\partial}{\partial \vec{v}}\cdot\left(\vec{D}f\right)\right]\quad +(WPI)[1]$$

Boundary conditions:

Bottom (collision-dominated):

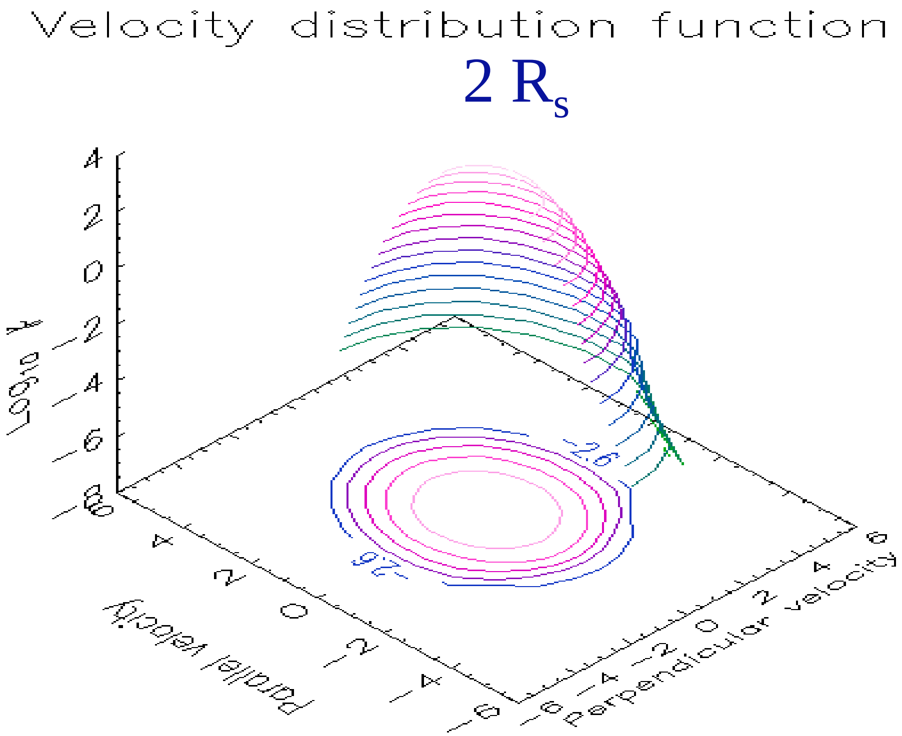
$f(2\ R_s, \mu>0, v)$ = maxwellian

Top (exospheric conditions):

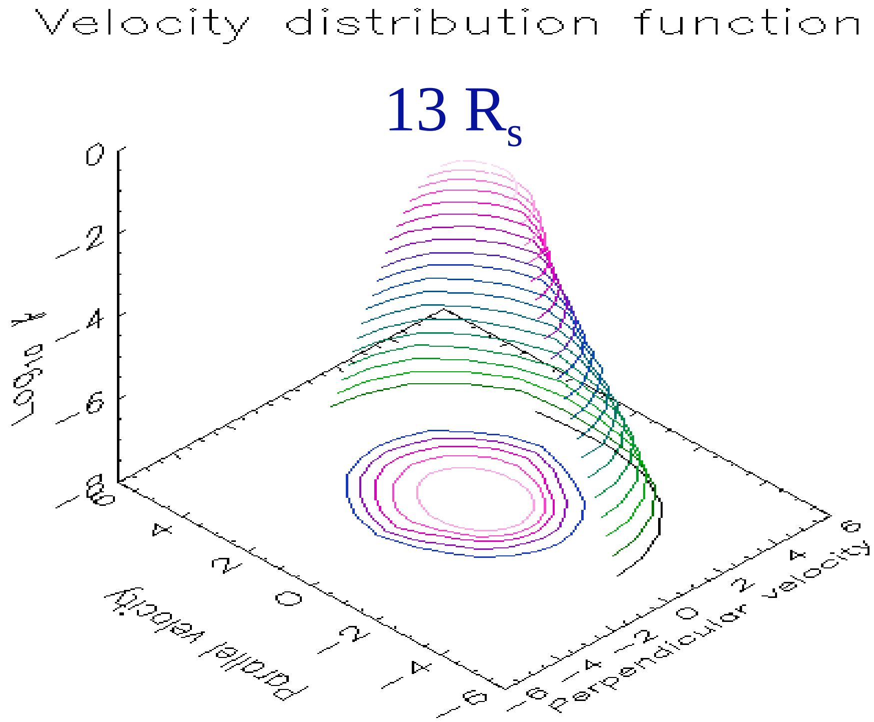
$f(14\ R_s, \mu<0, v<v_e) = f(14\ R_s, \mu>0, v<v_e)$

$f(14\ R_s, \mu<0, v>v_e) = 0$

2 R_s



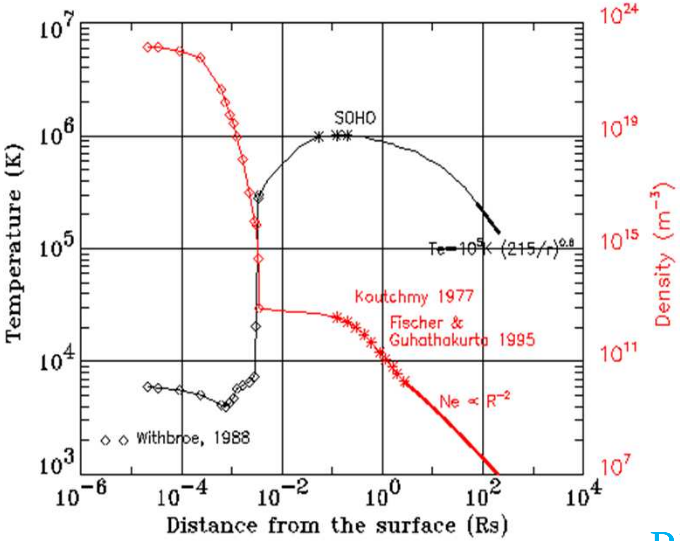
13 R_s

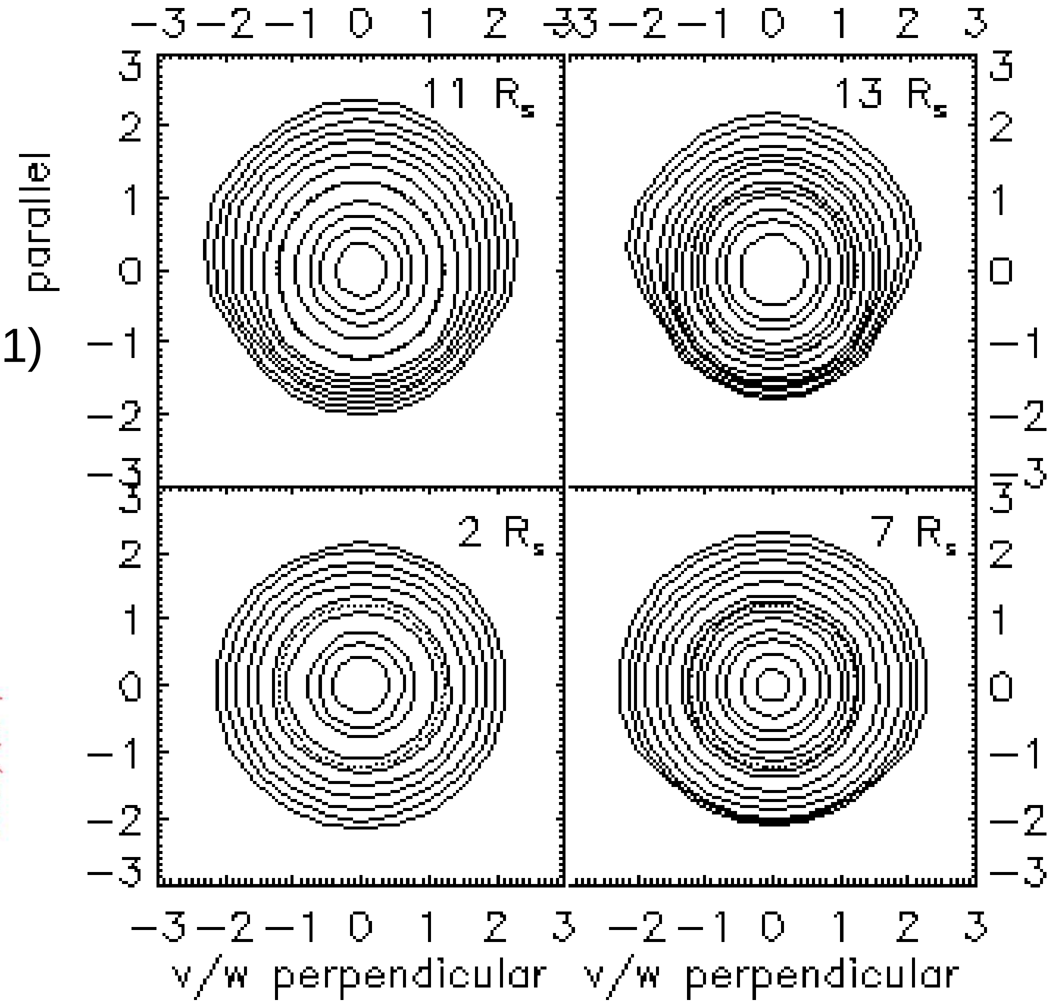


Pierrard, Maksimovic and Lemaire, JGR, 107, 29305, 2001

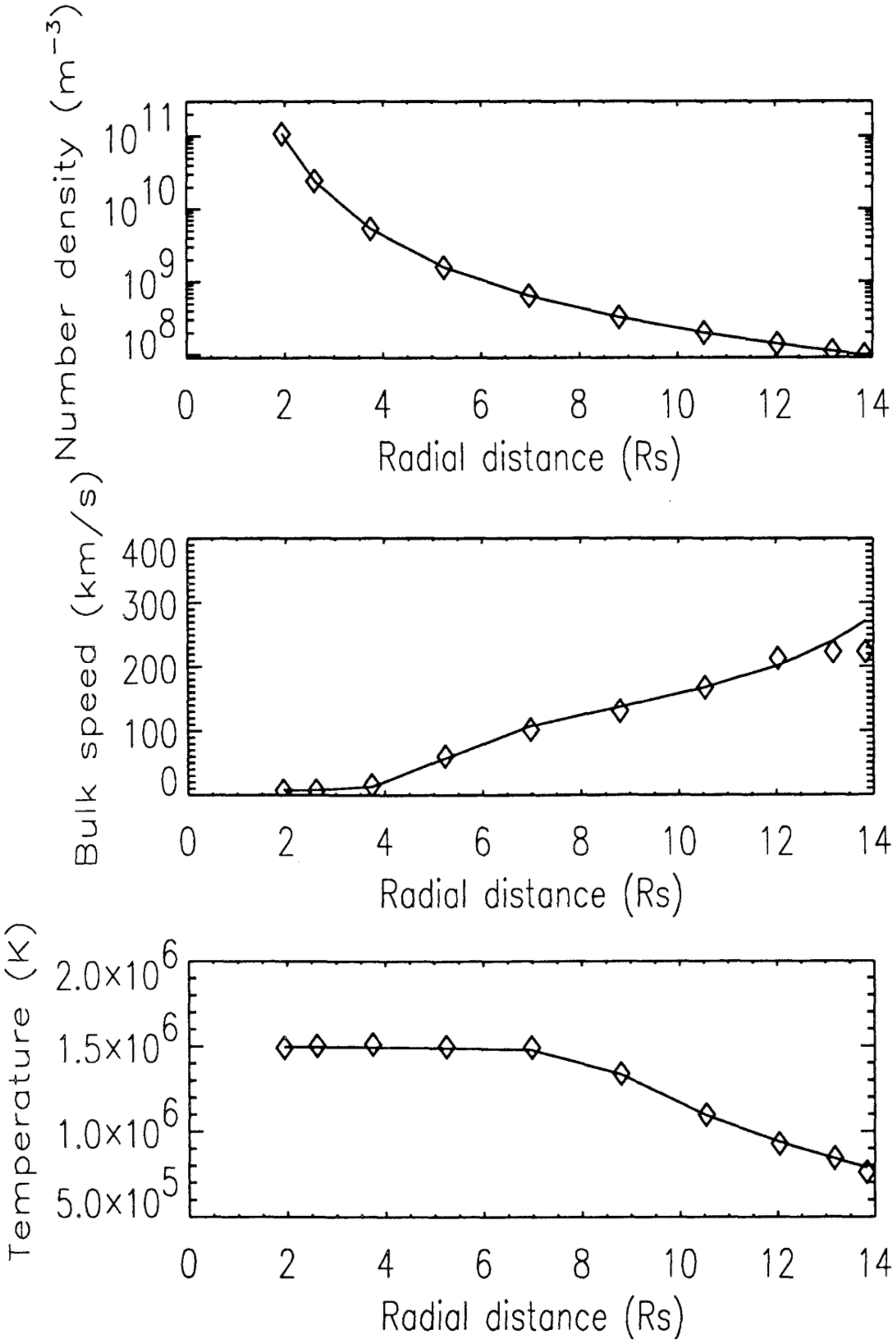
In the transition region, the electron velocity distribution function becomes anisotropic

Cb collisions
mean free path in v^4
Not efficient at large v
Not efficient at large r
(low density):
anisotropy at 2 R_s (Kn=1)
Non-thermal at 1.05 R_s (Kn=0.01)





Pierrard, Maksimovic and Lemaire, JGR, 107, 29305, 2001



Diamonds: with electron self collisions only
Solid line: with proton and electron collisions

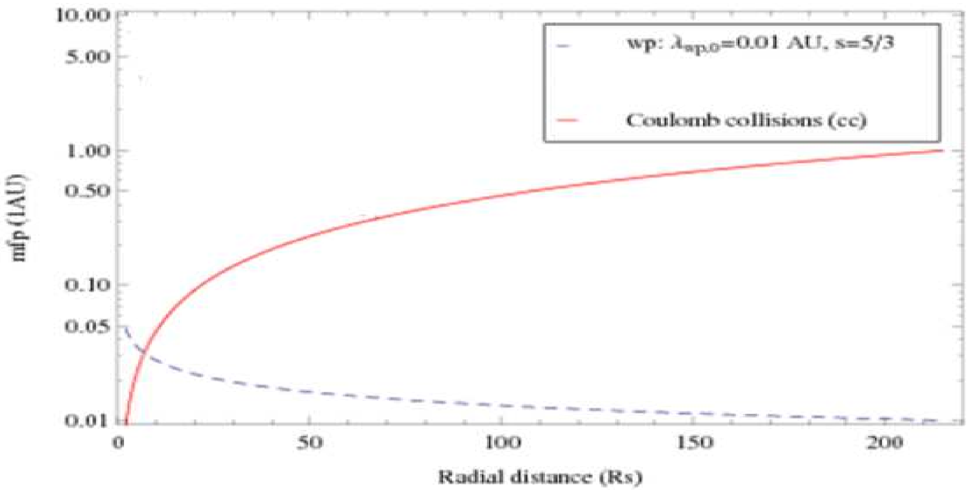
Pierrard, Maksimovic and Lemaire, JGR, 107, 29305, 2001

$$\frac{\partial f}{\partial t}+\vec{v}\cdot\frac{\partial f}{\partial \vec{r}}+\vec{a}\cdot\frac{\partial f}{\partial \vec{v}}=-\frac{\partial}{\partial \vec{v}}\cdot\left[\vec{A}f-\frac{1}{2}\frac{\partial}{\partial \vec{v}}\cdot\left(\vec{D}f\right)\right] \quad +(WPI)[1]$$

2. Whistler wave turbulence

$$\left(\frac{\partial f}{\partial t}\right)_{wp}=\frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}+D_{\mu p}\frac{\partial f}{\partial p}\right)+\frac{1}{p^2}\frac{\partial}{\partial p}p^2\left(D_{p\mu}\frac{\partial f}{\partial \mu}+D_{pp}\frac{\partial f}{\partial p}\right)$$

Scattering mfp compared to Cb mfp



$D_{\mu p} = D_{p\mu}$

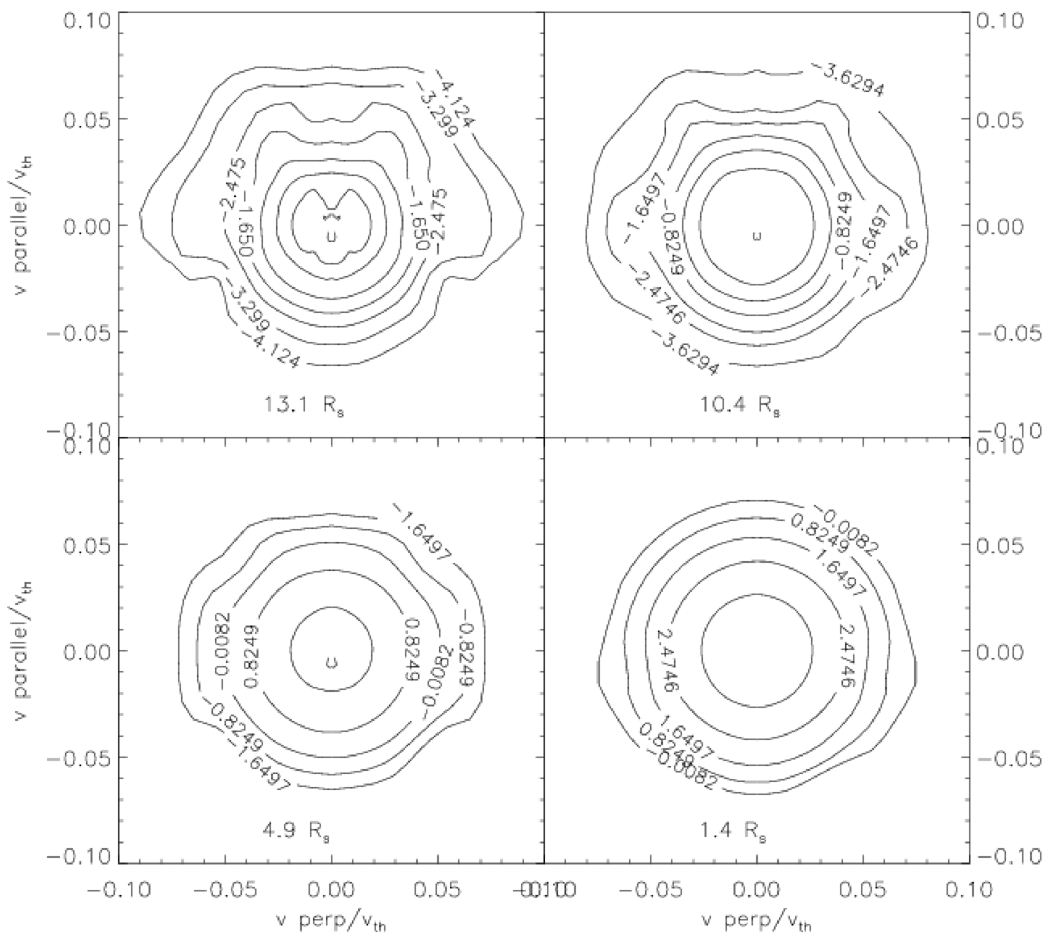
Expressions of Steinacker and Miller (1992) for non relativistic electrons

Resonant with the electron gyrofrequency $\Omega=|e|B_0/(mc)$

For // waves, only cyclotron resonance appears (no transit-time damping)

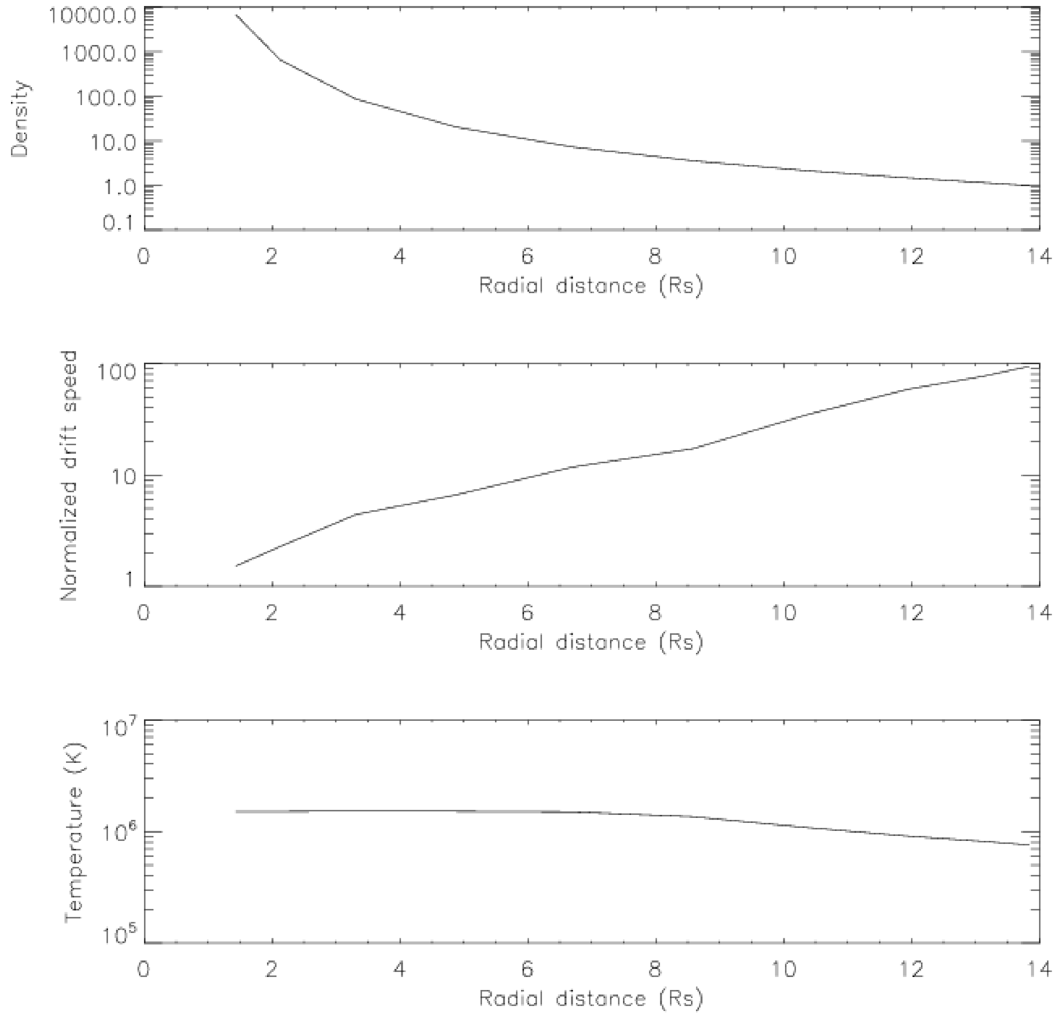
Pierrard, Lazar and Schlickeiser, Sol. Phys., 10.1007/s11207-010-9700-7, 2011

Right-handed polarized wave in the whistler regime.
Wave turbulence determines electron pitch-angle diffusion.
At low radial distances, whistlers may explain suprathermal tails in all directions
Pierrard, Lazar and Schlickeiser, Sol. Phys., 269, 421, 2011



Pierrard, Lazar and Schlickeiser, Sol. Phys., 10.1007/s11207-010-9700-7, 2011

The VDF anisotropy is modified.
The odd moments are modified by whistlers.



Pierrard, Lazar and Schlickeiser, Solar Phys. 269, 421,
DOI 10.1007/s11207-010-9700-7, 2011

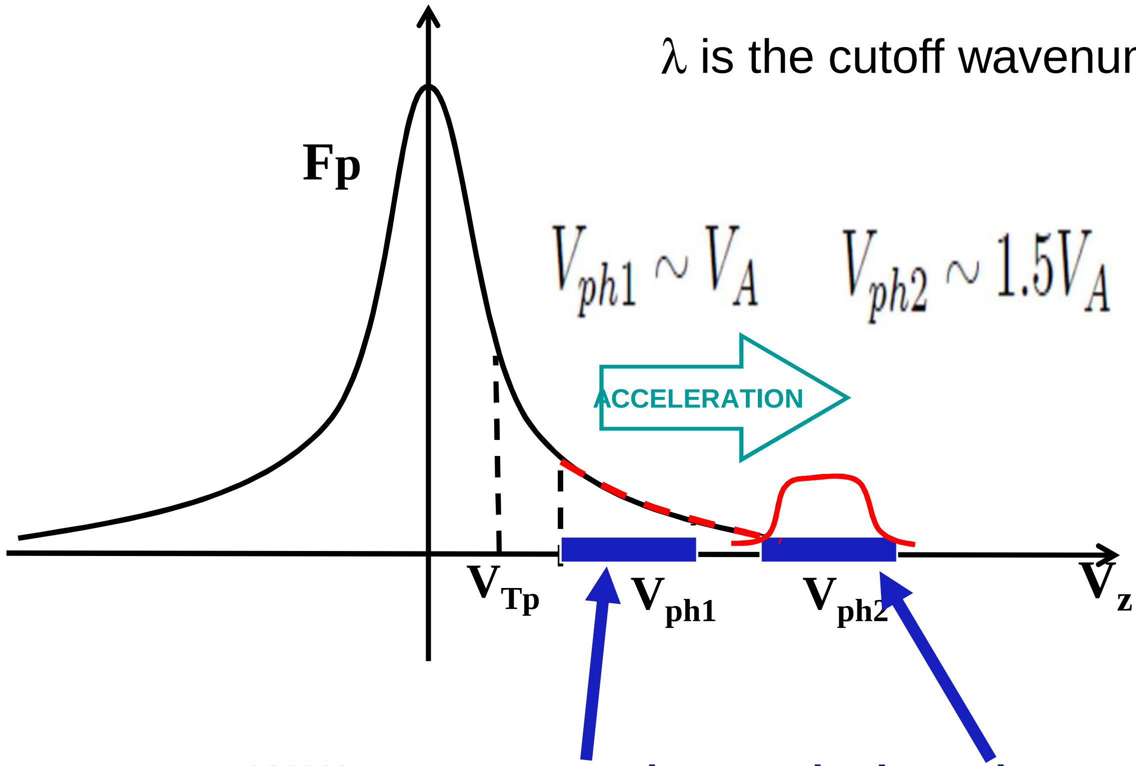
3. Kinetic Alfven waves

$$\left(\frac{\partial f}{\partial t}\right)_A = \left(\mu\frac{\partial}{\partial v} + \frac{1-\mu^2}{v}\frac{\partial}{\partial \mu}\right) D_A \left(\mu\frac{\partial}{\partial v} + \frac{1-\mu^2}{v}\frac{\partial}{\partial \mu}\right) f$$

- **due to increasing wave dispersion, the KAWs' propagation velocity increases;**
- **the protons trapped by the parallel electric potential of KAWs are accelerated by the KAW propagation**

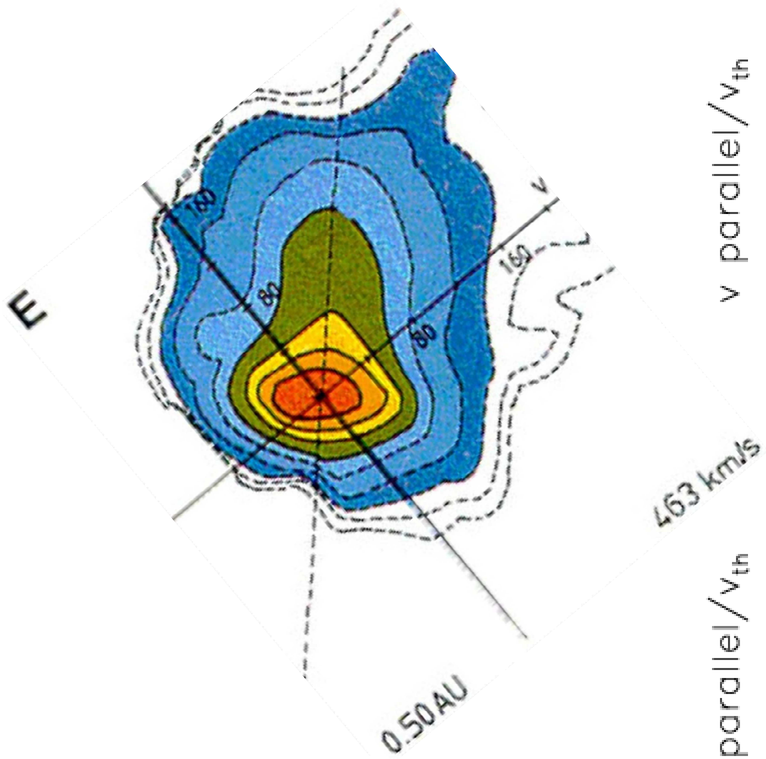
$D_A=0$ except for $1<\mu v/V_A<(1+2\lambda^2)^{1/2}$

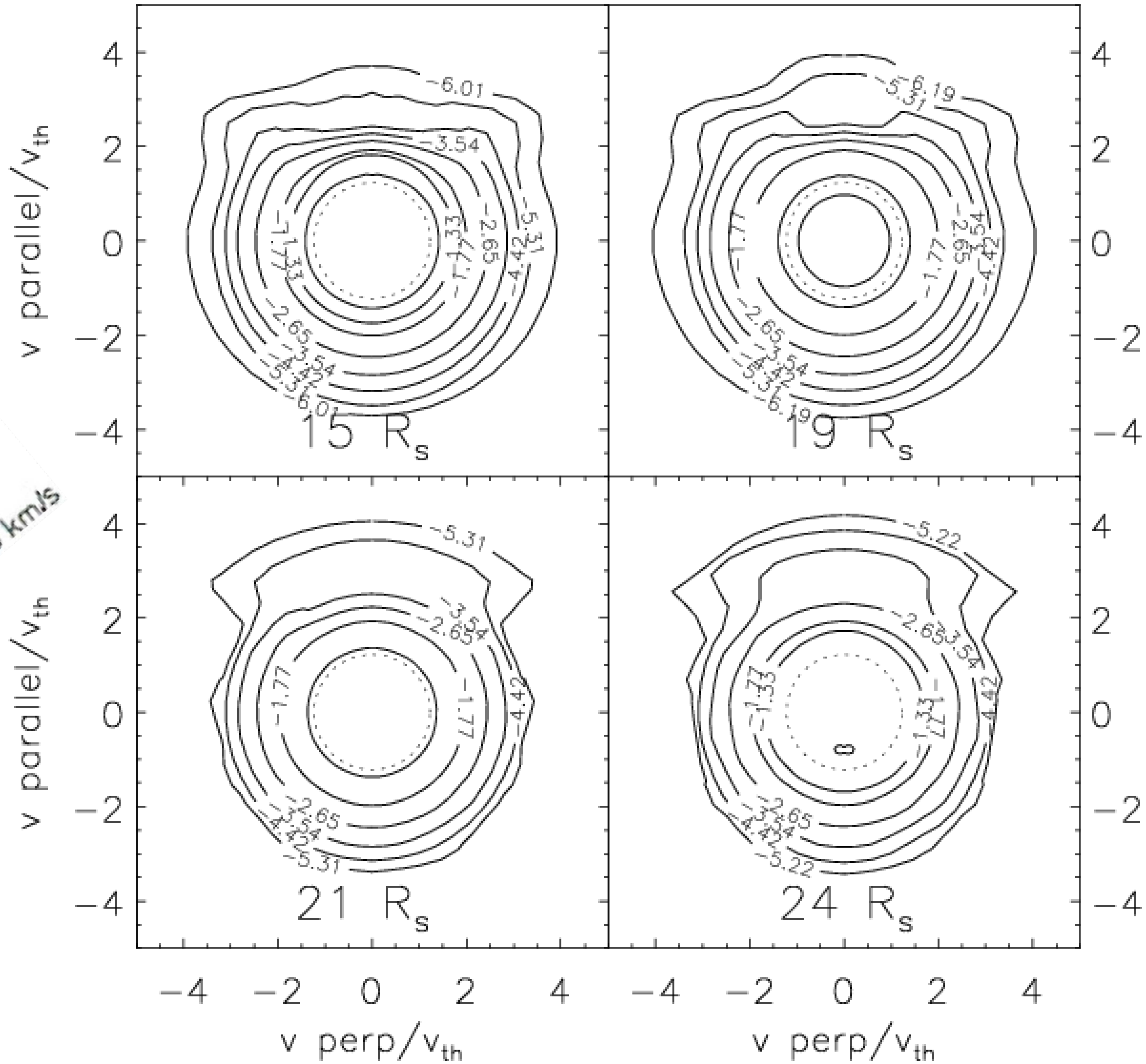
λ is the cutoff wavenumber



KAWs trap protons here and release here

Pierrard and Voitenko, SW12 AIP, 102, 2010.

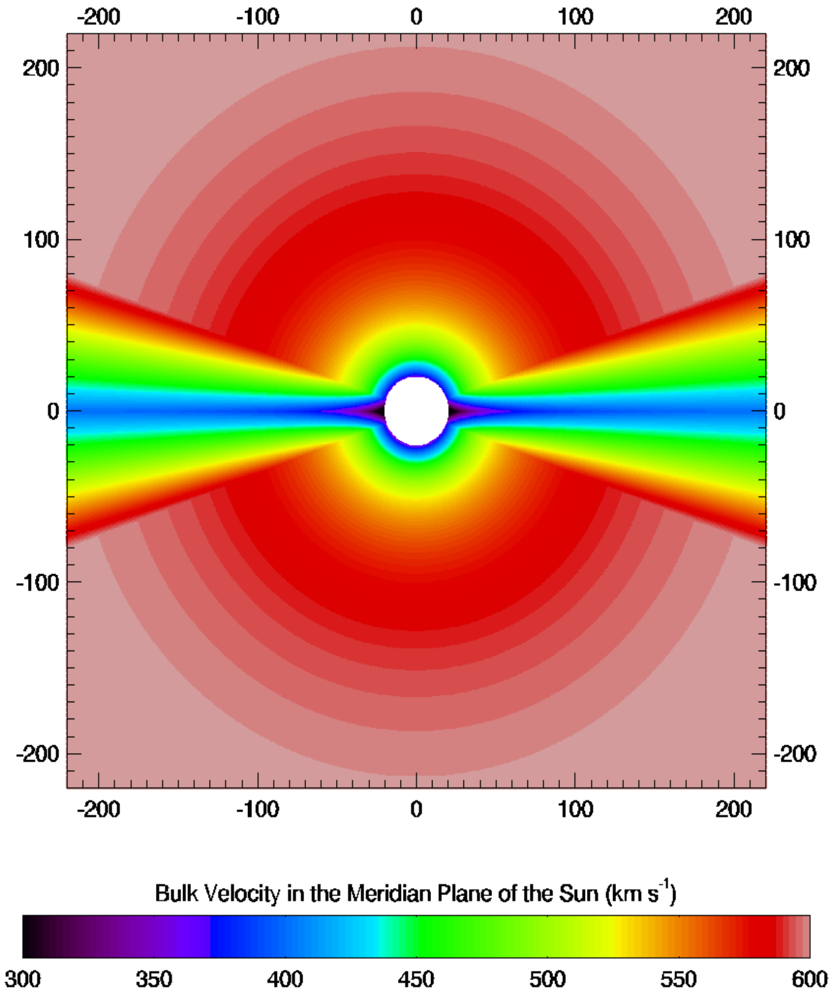


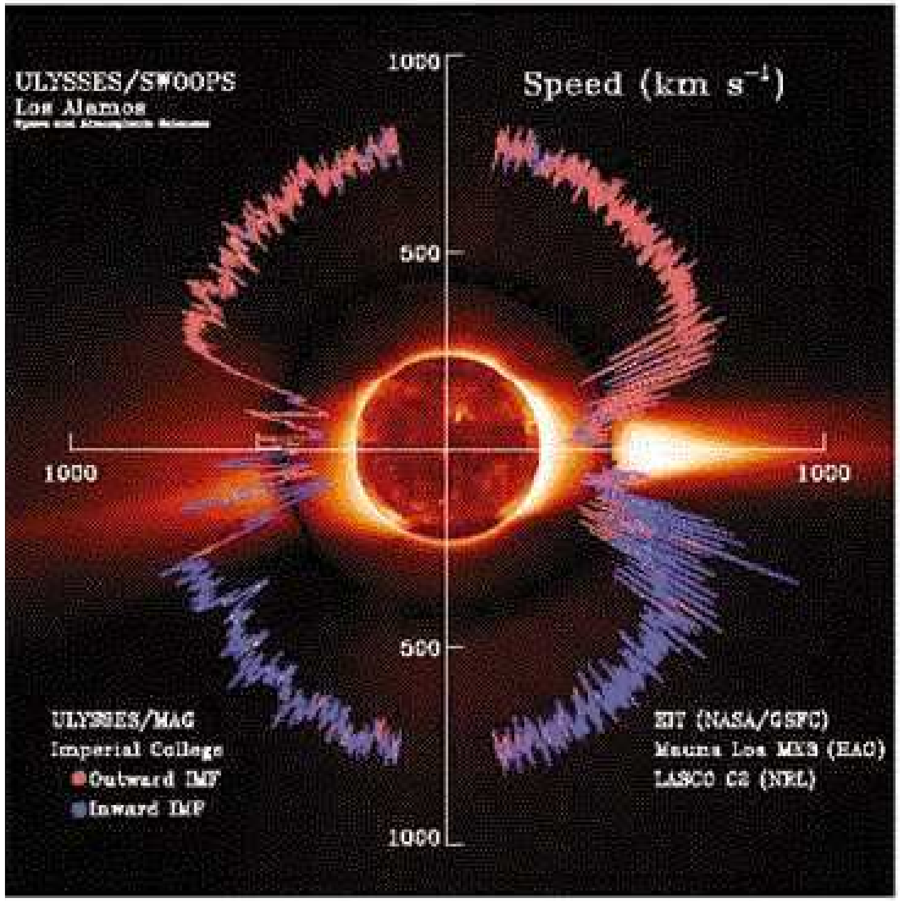


Pierrard V. and Y. Voitenko, Solar Phys., doi: 10.1007/s11207-013-0294-8, 2013

Kinetic solar wind

Assuming different boundary conditions (kappa, n) depending on the heliographic latitude based on Ulysses observations during minimum solar activity.



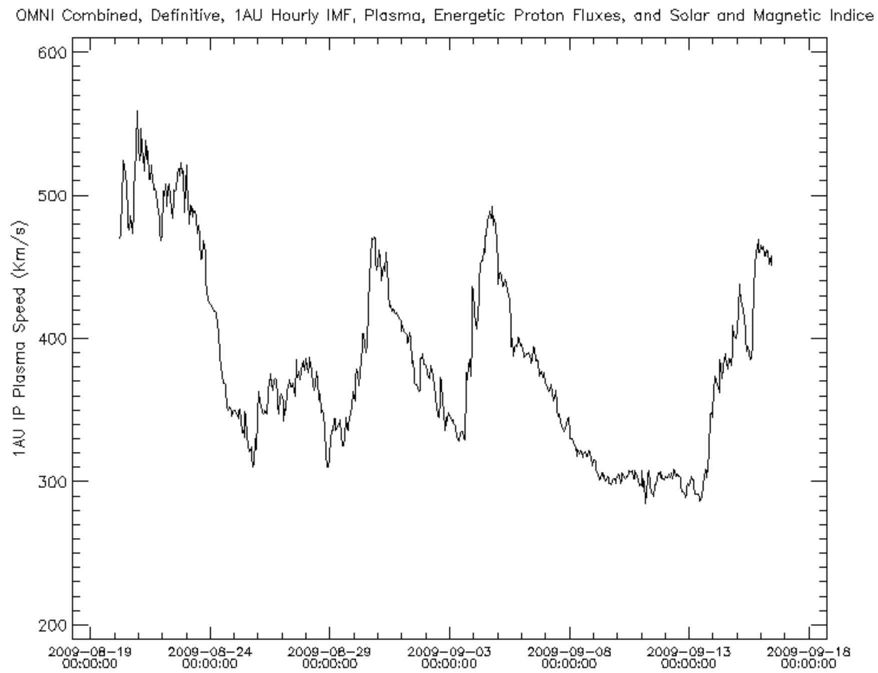


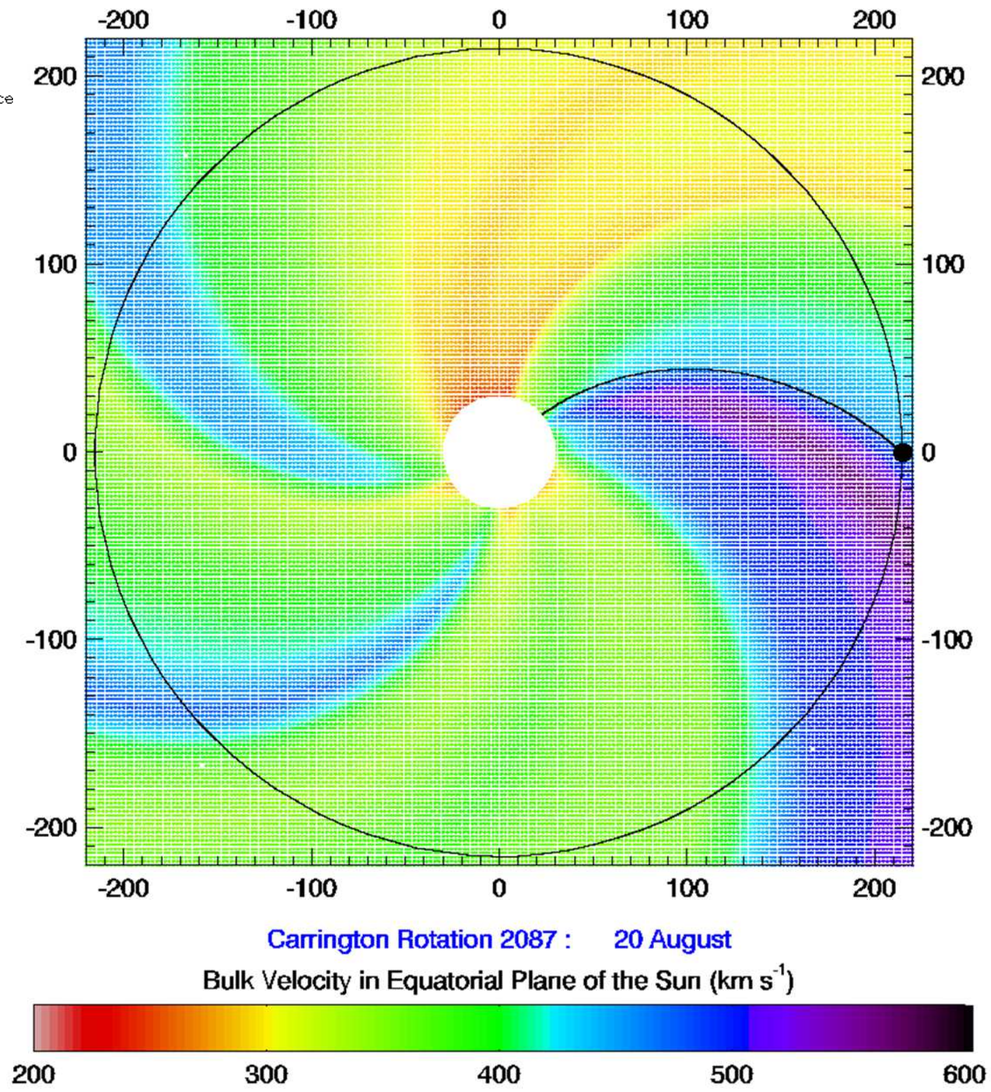
McComas, D.J., et al., Geophys. Res. Lett., 25, 1-4, 1998

Pierrard V.and M. Pieters, ICNS Proc., 2013

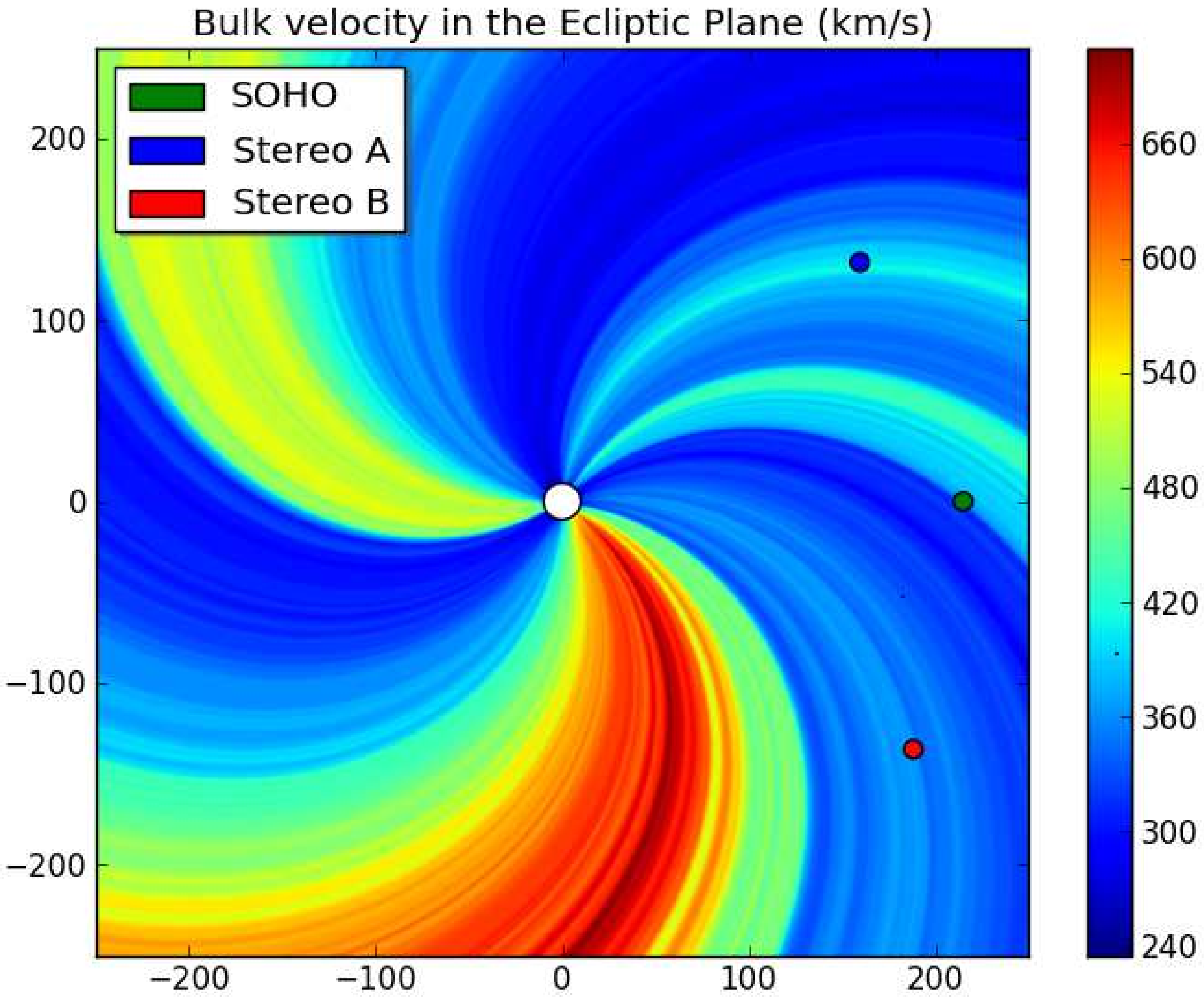
Kinetic model of solar wind including the solar rotation:
Reconstruction obtained from ACE observations

20 August 2009 - 16 September 2009





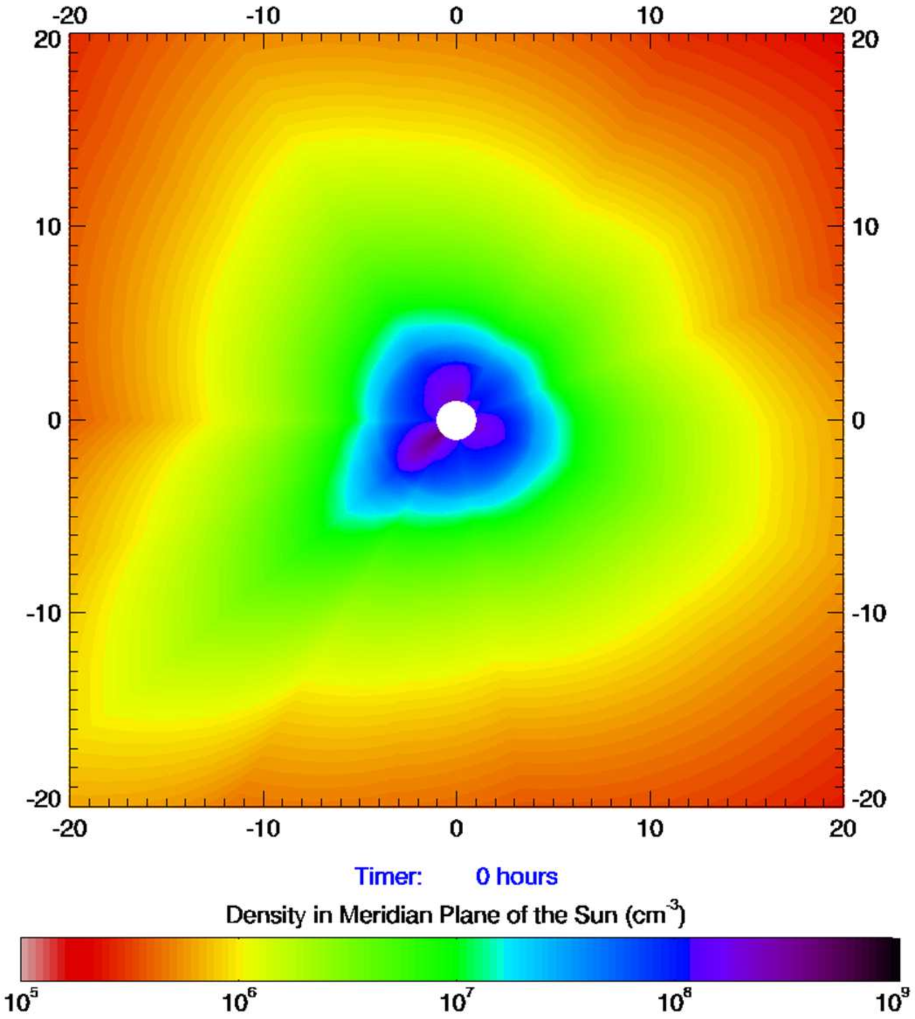
based on Pierrard et al., GRL 28, 223, 2001



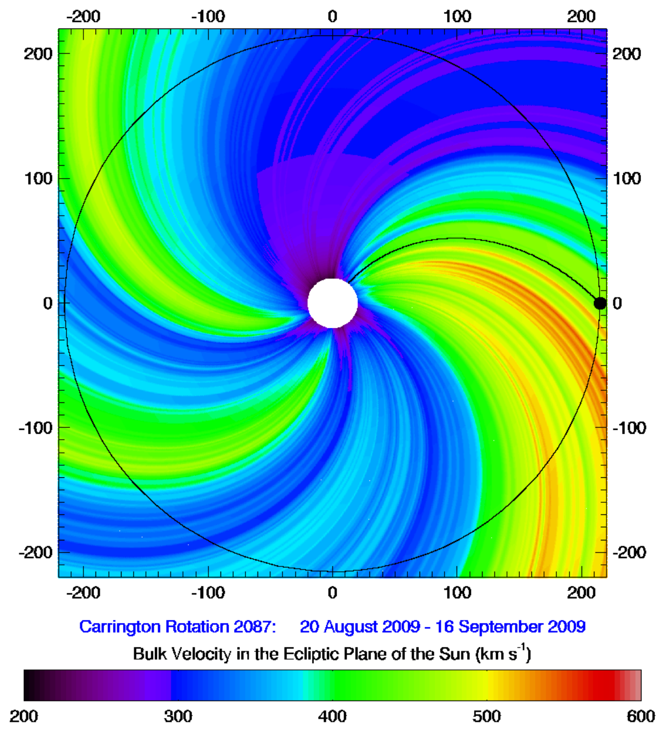
Bulk velocity in the Ecliptic Plane (km/s)
SOHO
Stereo A
Stereo B
200
100
0
−100
−200
−200
−100
0
100
200
660
600
540
480
420
360
300
240

Time dependence

Preliminary results using sudden change of boundary conditions and new stationary solution.



Summary



Kinetic processes in the solar wind plasma

- Kinetic processes prevail in space plasmas
- Importance to be non-Maxwellian
- Kinetic models can study the effects of each term separately on the VDF

Turbulence

- Whistler wave turbulence dominates for energetic electrons. Can contribute to suprathermal tails formation.
- Kinetic Alfvén waves modify the VDF of the protons. Can contribute to the proton beam formation.

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