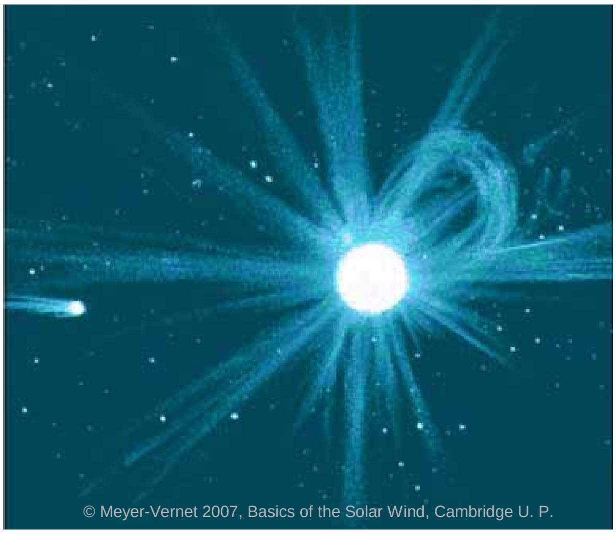
Le vent solaire et l'héliosphère



- *Quelques propriétés générales*
- *Problème fondamental de l'accélération du vent*
- *Aspects de physique de base*

PNST Obernai Mars 2008

Nicole Meyer-Vernet
http://lesia.obspm.fr/~meyer

L'origine du vent : le soleil

Quand le soleil a la langue blanche :
signe de mauvais temps
(Cham)

Mesures à distance

Mesures à distance

< 1600

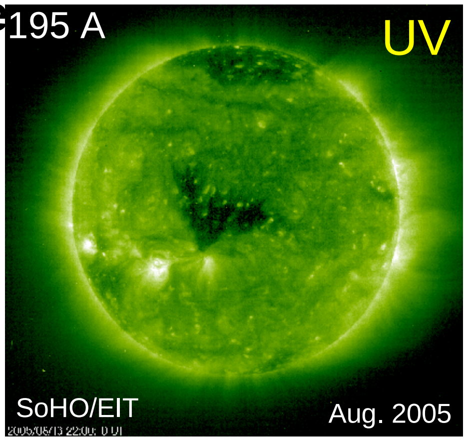
L'oeil : images lumière blanche
Résolution ~ 1 min. d'arc

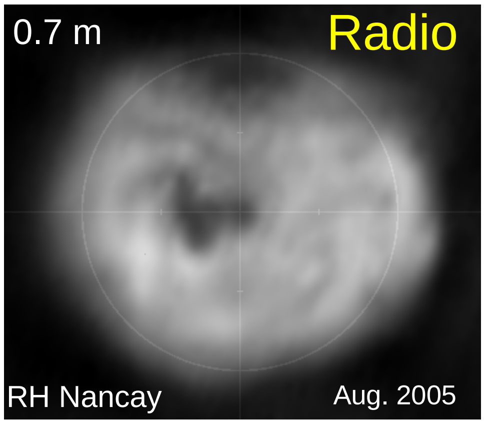
Le plus ancien dessin connu de taches solaires (Chronicle of John of Worcester) (Darlington et al. 1995) **1128 Dec. 8** "qua si due nigre pile infra solis orbitam"

Description d'aurore boréale **1128 Dec. 13**, Corée (Yau et al. 1995)

2000 AD **Images (2-D+) à différentes longueurs d'onde d'un milieu 3-D inhomogène**

- différents atomes
- avec différents états d'ionisation
- à des "températures" différentes
- hors équilibre local pour chaque espèce





Mercier & Chambe 2008

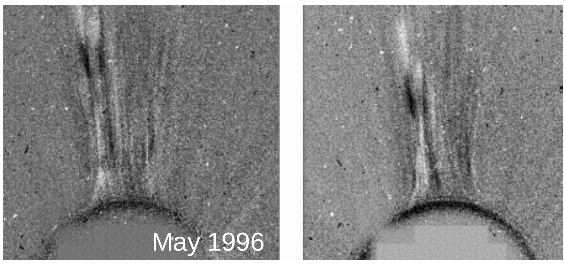
Résolution max ~ 0.1 sec. d'arc

Mesures à distance

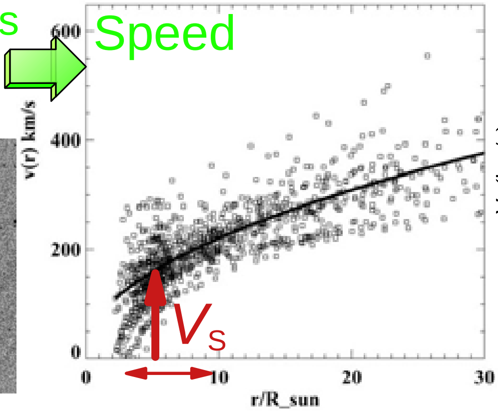
Equatorial

Flow of material in streamers

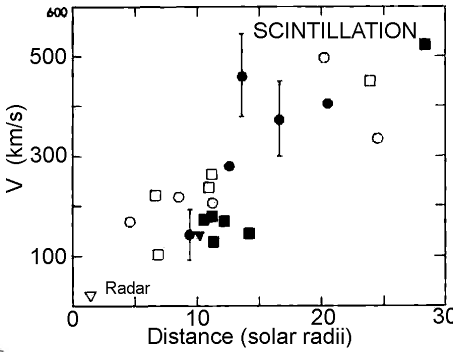
SoHO/LASCO Time diff. images (Sheeley et al. 1997)



Minimum solaire



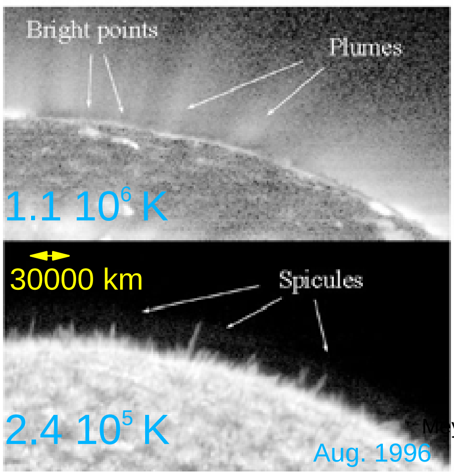
c.f. Interplanetary scintillations (adapted from Armstrong & Woo 1981)

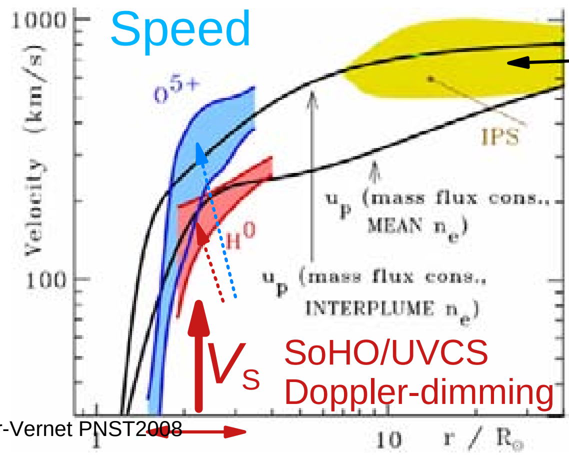


Polar

SoHO/SUMER Wilhelm 2000

0.2 $R_\odot$





Scintillations

From *n* with assumption on flow tube

adapted from Cranmer 2002

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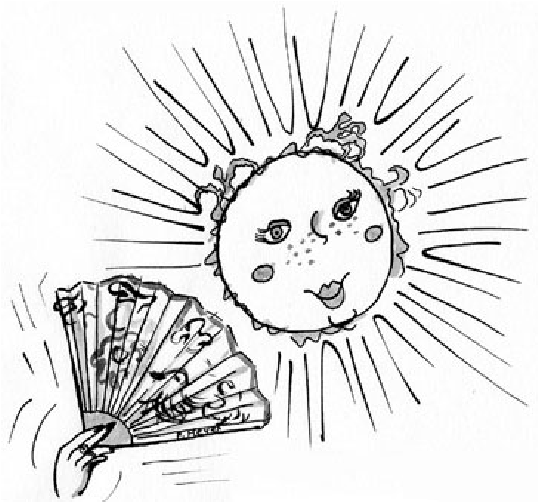
Le vent

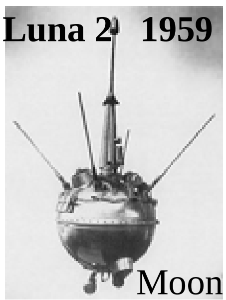


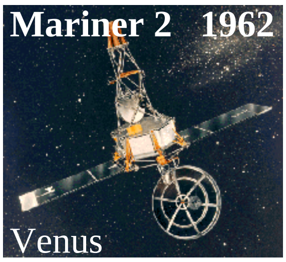
(F. Meyer)

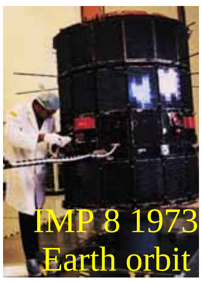
Mesures in situ

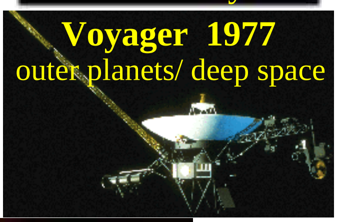
Mesures in situ
Quelques sondes

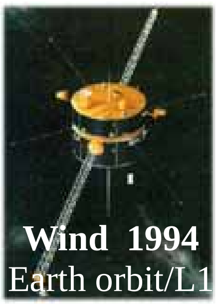
"We had data! Lots of it! There was no longer any uncertainty about the existence and general properties of the solar wind." *(M. Neugebauer)*

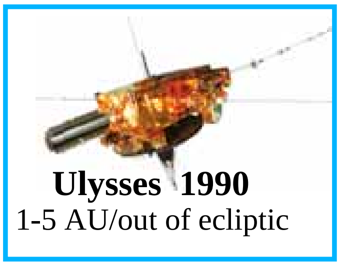












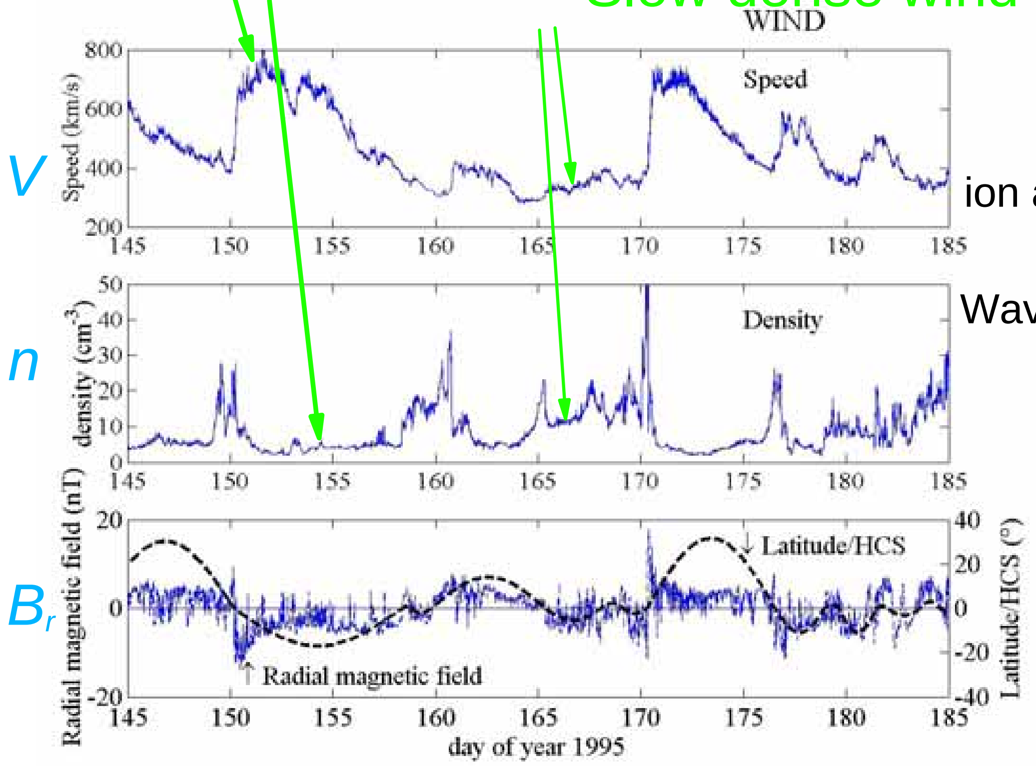
"I should like to ask whether there is a particular importance in performing experiments out of the plane of the ecliptic" *(Mr Hibbs, 1959)*

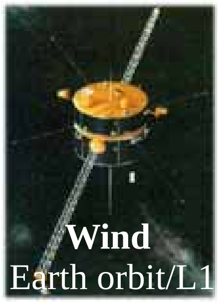
Mesures in situ

Ecliptic (< 8° heliolatitude)

1 month of data near solar activity minimum (June 1995)

- Fast dilute wind
- Slow dense wind





ion analyser

Waves (QTN)

variable

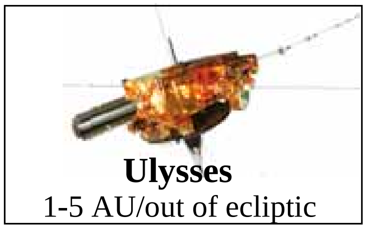
10 min. averages

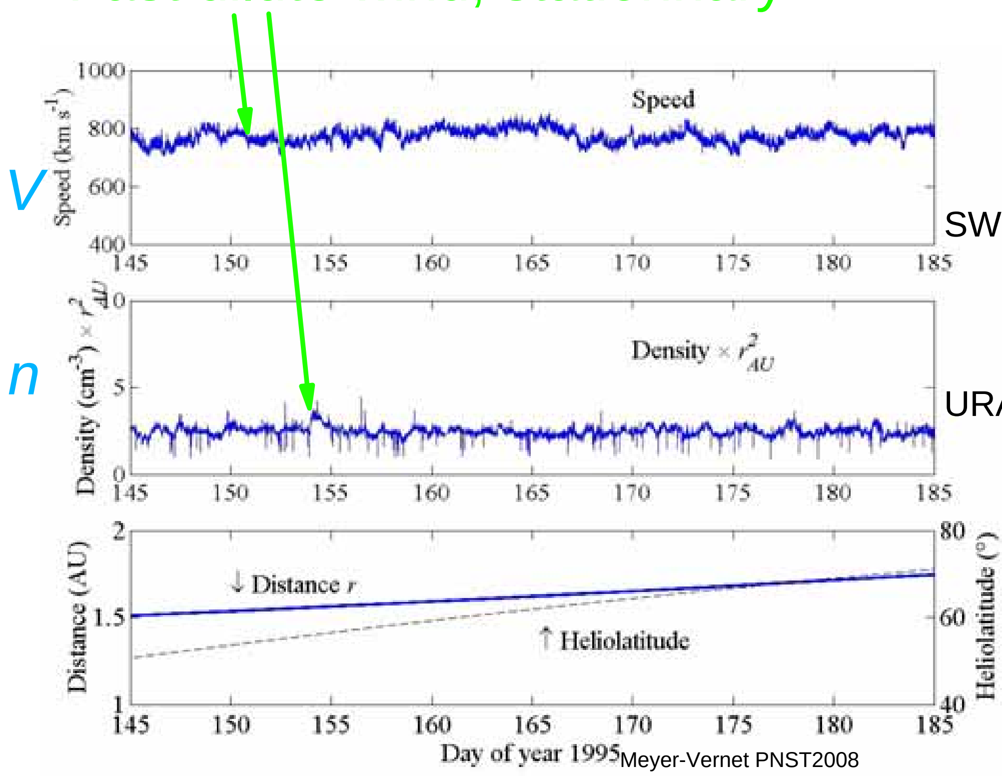
Mesures in situ

High latitude

1 month of data near solar activity minimum (June 1995)

- Fast dilute wind, stationnary





SWOOPS (rate 4 min.)

URAP/QTN (rate 2 min.)

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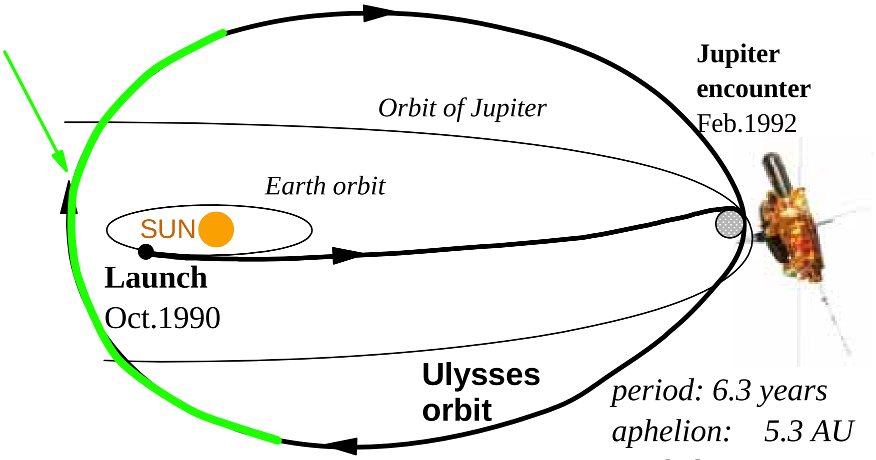
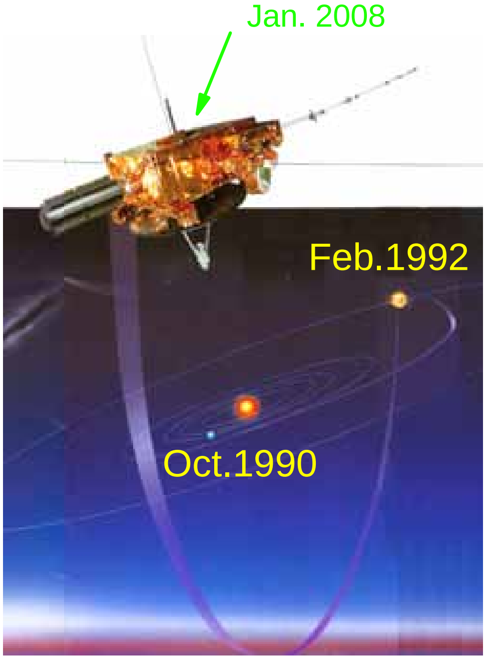
no averages

Ulysses fast latitude scans

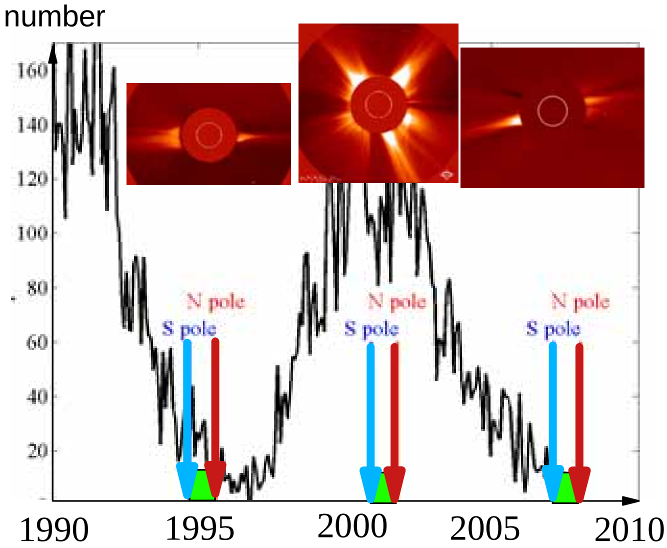


period: 6.3 years
aphelion: 5.3 AU
perihelion: 1.3 AU
inclination: 80°

Pole Nord : Jul.1995 Oct.2001 Jan. 2008



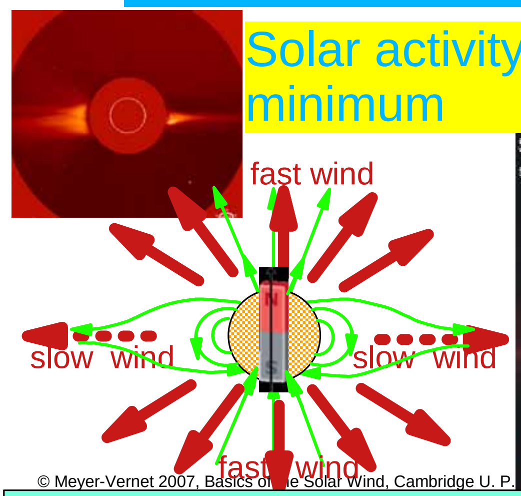
Pole Sud : Sep.1994 Nov.2000 Feb. 2007



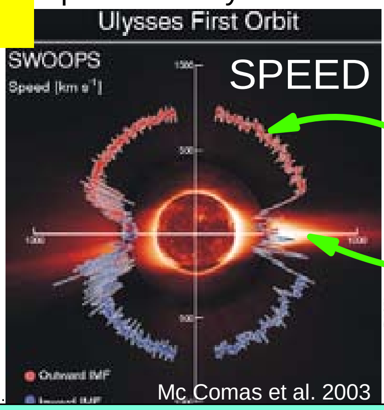
Feb. 2008:
- Short of power supply (radioactive isotope)
- Transmitter off
- Fuel pipes about to freeze

Solar wind structure

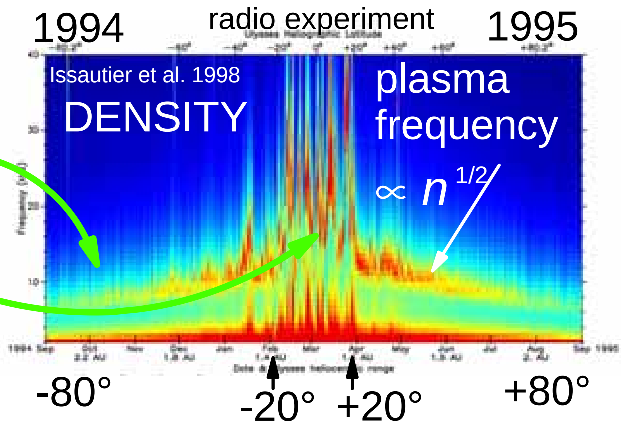
Solar activity minimum



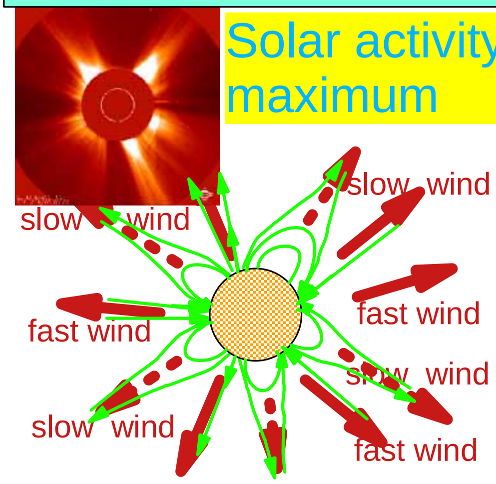
Ulysses/SWOOPS particle analyzer

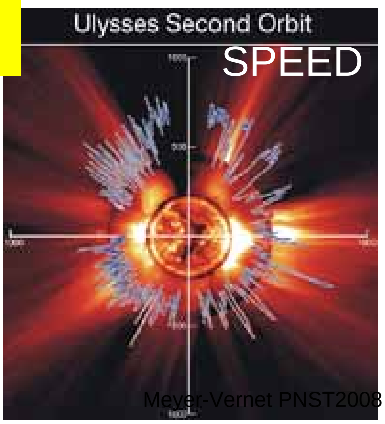


Ulysses/URAP radio experiment



Solar activity maximum





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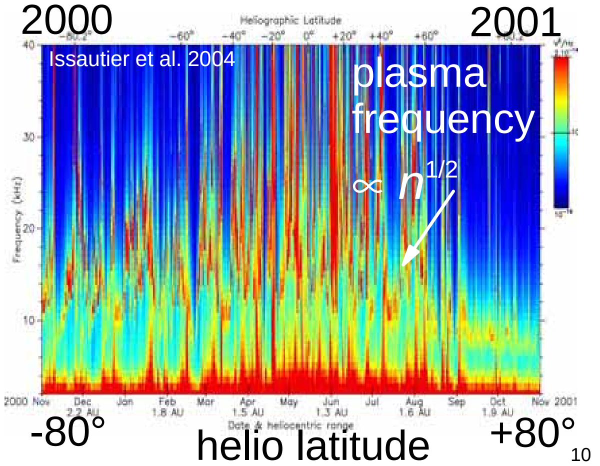
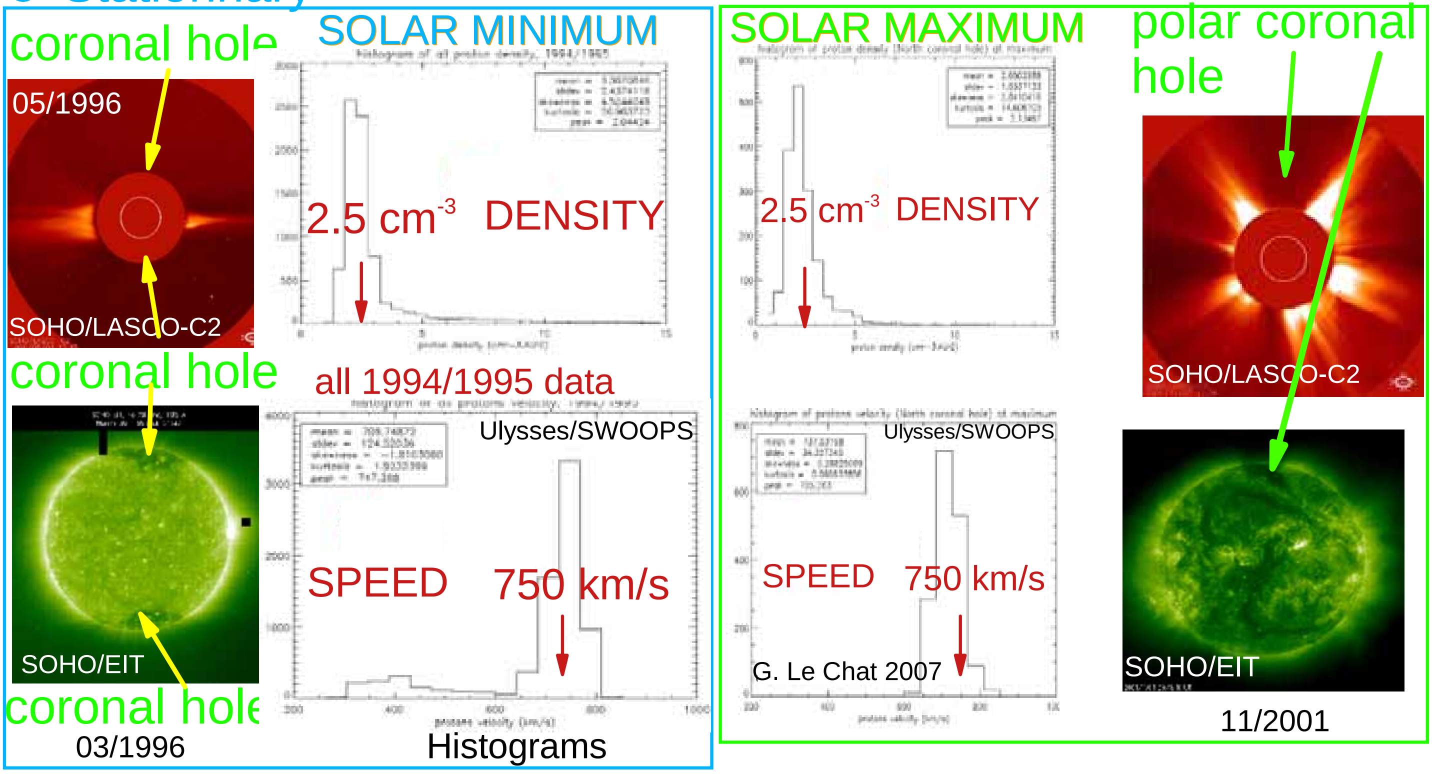


Basic state of the solar wind: fast wind from coronal holes

- Fills most of heliosphere near solar activity minimum
- Stationnary



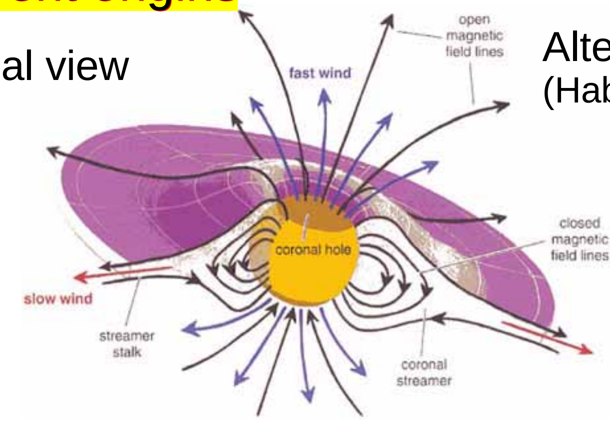
- Similar properties at minimum and maximum activity

Basic properties

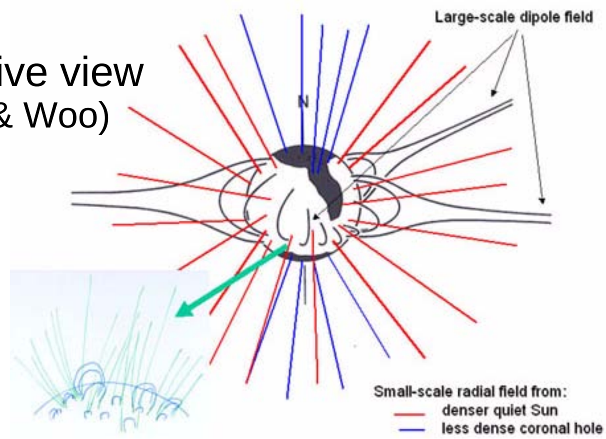
Fast and slow wind have :

- different origins

Traditional view



Alternative view (Habbal & Woo)



- different structures, densities, and speeds
- BUT nearly same flux of total energy!

$$\rho V \times \boxed{(V^2/2 + M_\odot G/R_\odot)} \simeq 1.5\ 10^{-3}\ \mathrm{W/m^2} \text{ at 1 AU}$$

kinetic + potential (enthalpy negligible)

$$\simeq 70 \times (R_\odot / r)^2\ \mathrm{W/m^2}$$

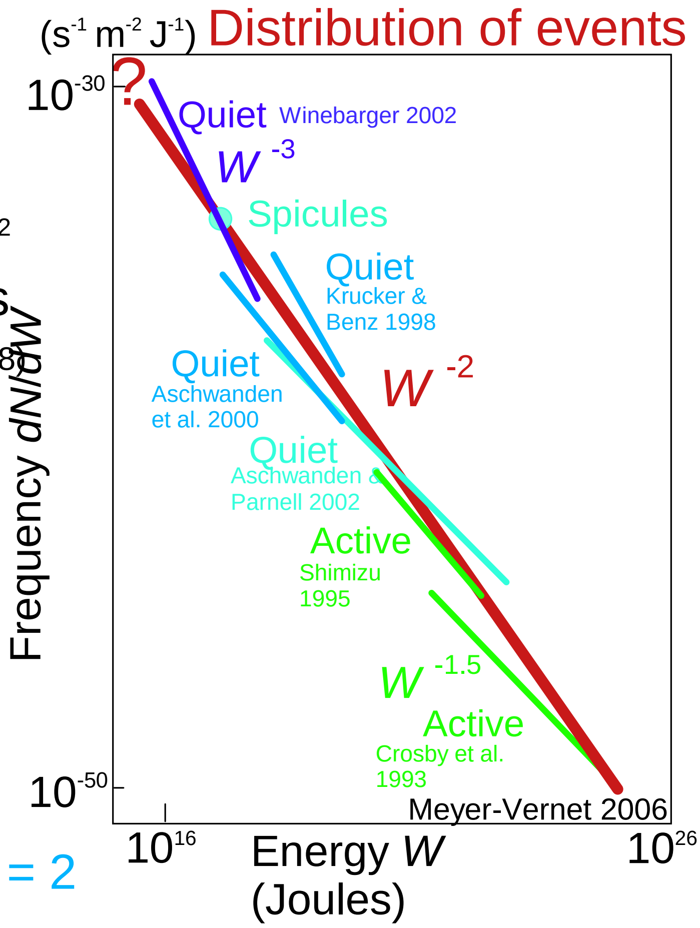
same as Helios (Schwenn 1983)

$$\simeq 10^{-6} \times \text{solar luminosity}$$

Energy flux Compare with :

- winds of stars with reliable wind studies

$M_{\circledast}$ '$[V^2/2+M_{\circledast}G/R_{\circledast}]/4\pi R_{\circledast}^2 \simeq 10^2$ W/m^2 for many giants stars over 10 orders of magnitude in mass loss (Reimers 1988)



- solar activity

Total energy flux:

$\int_{\min}^{\max} W \, dW/W^{a} = \mathrm{Ln}(W_{\max}/W_{\min})$ if $a = 2$

$\simeq 3\,\mathrm{Ln}(W_{min}/W_{max}) \simeq 70$ W/m^2

Energy flux Wind energy balance

In absence of ad-hoc heating and radiation loss

Energy per unit mass at distance r

$V^2/2 + 5k_BT/\mu - MG/r + Q/(\rho V) =$ constant

heat flux (Q); mass flux (ρV)

$5k_BT/\mu$: negligible compared to terminal kinetic energy

$Q/(\rho V)$: negligible at large r

$[Q]_0 \simeq \rho V\,(V^2/2 + MG/R_{\odot}) \times S/S_0$ (base)

same for slow & fast wind

average heat flux required at wind base $Q_0 \simeq 70$ W/m^2

$\geq 10 \times$ collisional heat flux ($\propto \nabla T$) (Spitzer-Härm)

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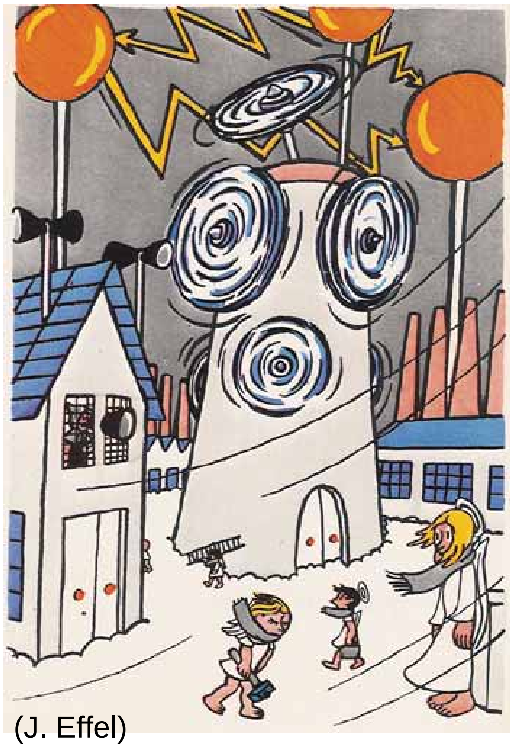
Basic problem:

- Heat flux >> collisional value
- or mechanical energy ... waves

"If I learned anything in my long reign, it is that heat rises"
(Harris) © 1986 The New Yorker Magazine, Inc.

?



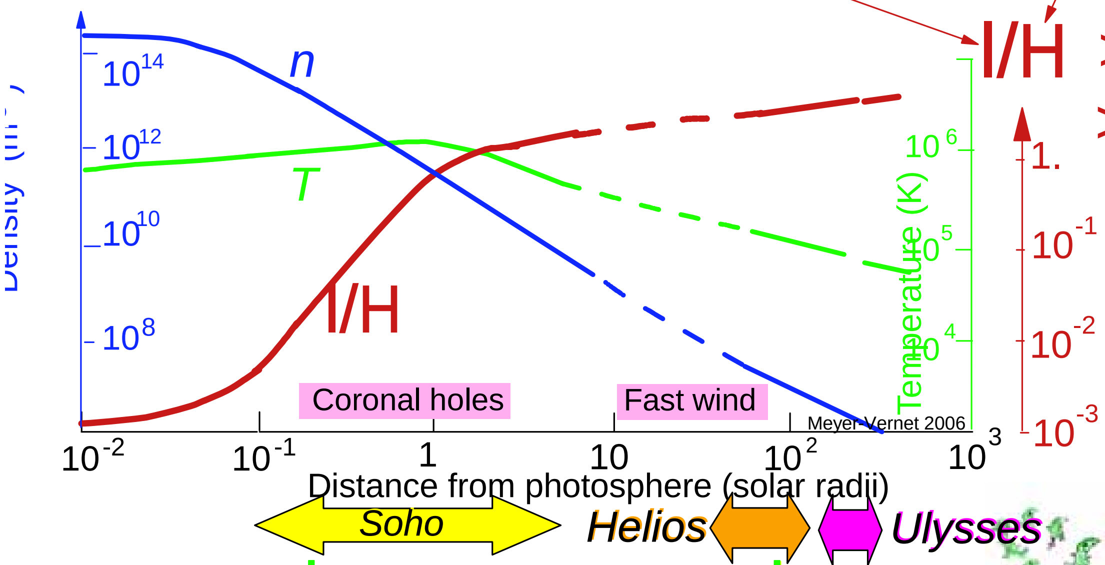
(J. Effel)

☛ Plasma is weakly collisional ⇒ Q ≠ collisional value

Non classical heat flux

- mean collisional free path → l/H ← scale height

l/H >1 in wind
>10^{-3} in corona



Classical transport theory invalid

Free path $l \propto v^4 \Rightarrow$ if v x 3 then l x100 !

☛ *fast particules are collisionless*

☛ *various acceleration processes*

⇒ distribution ≠ Maxwellian

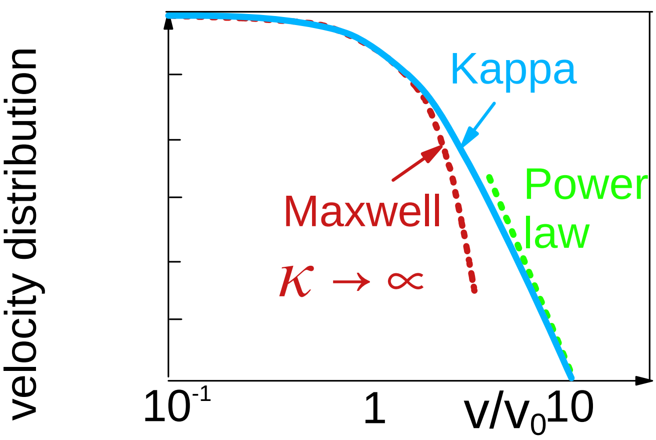
⇒ Heat flux ≠ classical value

N. M-V PSS 2001

Fonctions de distribution observées ≠ Maxwellian

Kappa

$$f_\kappa(v) \propto \left(1 + \frac{v^2}{\kappa v_e^2}\right)^{-(\kappa+1)}$$



- solar wind
  - ✓ electrons: Maksimovic & al 1997, 2006, Nieves-Chinchilla & Vinas, 2008
  - ✓ ions: Gloeckler & al 1992, Collier & al 1996

- magnetospheres
  - ✓ Earth: Bame et al 1967, Vasyliunas 1968, Gloeckler&Hamilton 1987, Christon&al 1989
  - ✓ Jupiter ions: Krimigis & al 1981, Hamilton & al; 1981, Kane 1991, Kane & al 1992, Collier & al 1995
    electrons: Meyer-Vernet & al 1995, Steffl & al 2004
  - ✓ Saturn: protons: Krimigis & al; 1983
  - ✓ Uranus: Krimigis & al 1986, Neptune: Mauk & al1991

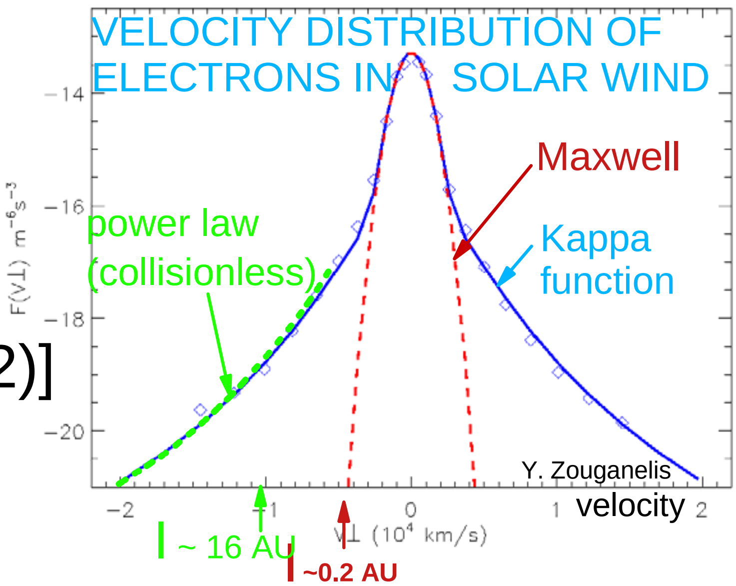
- solar corona ?
  - Solar wind suprathermal electrons remnants of coronal ones? Olbert 1981
  - Production of suprathermal particles (temperature grad., waves, turbulence) Roussel-Dupré 1980, Owocki & Scudder 1983, Vinas & al 2000, Leubner 2000, Vocks 2002, Vocks & Mann 2003
  - Observational inferences: Dufton et al. 1984, Owocki & Ko 1999, Pinfield et al. 1999, Esser & Edgar 2000, Chiuderi & Chiuderi-Drago 2004, Doyle et al. 2004, Ko 2005 and claims to the contrary Ko et al. 1996

Fonctions de distribution observées ≠ Maxwellian

Température hors équilibre local ?

- Température cinétique :

  $3k_BT/2 = < mv^2/2 >$



- ou : $k_BT = - f/[df/ d(mv^2/2)]$

  $v \to 0 : T \simeq T_c$

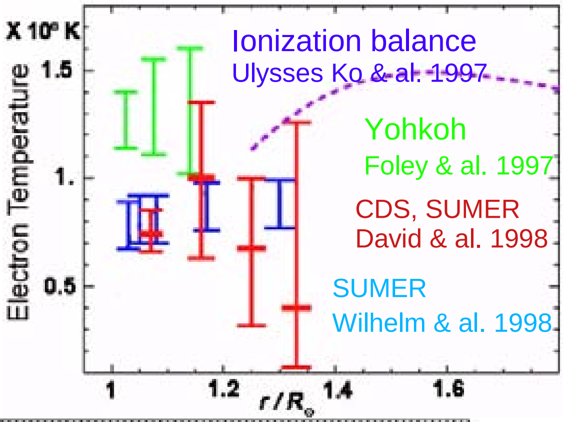
  $v \to \infty : T \propto v^2$

Lois classiques de la thermodynamique pas valables

Ex: ~~loi 0~~: *T* dépend du "thermomètre" (échelle spatiale, temporelle, degrés de liberté, temps de relaxation différents..)

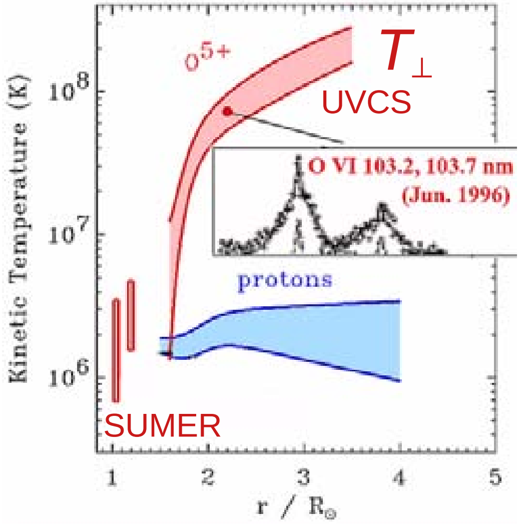
☛ Température hors équilibre local ?

Electrons   Coronal hole

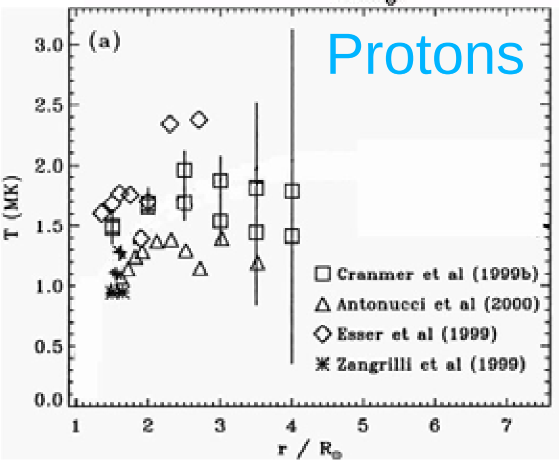


Temperature depends on thermometer

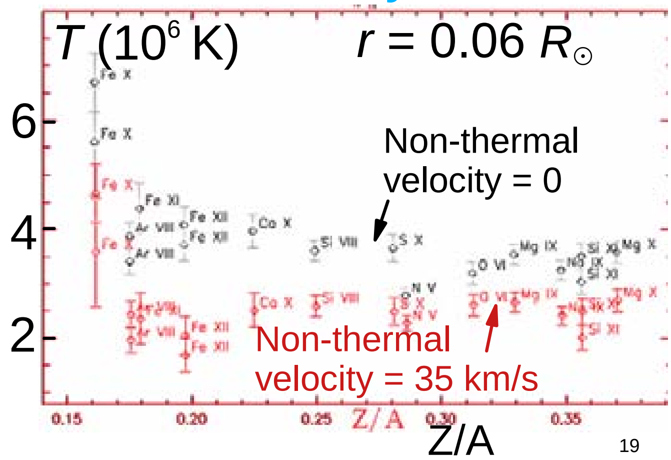
adapted from
Cranmer 2002



Heavy ions

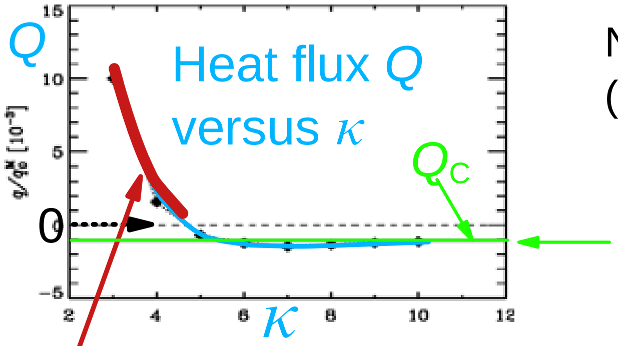


Line width SUMER
Dolla & al. 2004



Non classical heat flux

Weakly collisional plasma with Kappa distribution



Numerical simulation with collisions
(Pantellini & Landi 2001)

classical heat flux (Maxwellian)

large $\kappa \Rightarrow$ distribution ~ Maxwellian

smaller $\kappa \Rightarrow$ more suprathermal electrons

$Q \simeq -10 \times Q_c$ (opposite sign!)

If $\kappa < 4$

heat flows from cold to hot!

- ☛ Kappa ⇒ more fast electrons ⇒ more heat flux
- ☛ in attractive force, faster particles escape more easily

Might contribute to coronal heating & wind acceleration

Olbert 1981, Shoub 1983,1988, Scudder 1992, Pantellini & Landi 2001, Dorelli & Scudder 1999, 2003

Generating Kappa distributions

● *Particular*

Find a way of producing Kappa distributions in particular cases

- ☛ From turbulence Roberts & Miller (1998), Vinas & al. (2000), Leubner (2000), Vocks (2002), Vocks & Mann (2003)

  Difficulty: Generating *f*(*v*) from given wave spectrum is easy BUT not self-consistent!

  however: Yoon & al. (2006) (beam-plasma with $1/nL_D^3 > 5\ 10^{-3}$)

- ☛ Particles ($l >> T/\nabla T$) propagating down ∇T $\Rightarrow$ suprathermal tail (c.f. Roussel-Dupré (1980))

☛ see also Treumann 1999 (Turbulent quasi-équilibrium)

☛ see also Collier 1993 (Levy flights)

Generating Kappa distributions

● *General*

☛ *Rappel : Maxwell-Boltzmann*

"à la Jaynes" (1957) : théorie de l'information

Distribution $f(\mathbf{v})$ la plus probable sachant que

énergie moyenne $<E> = U$ $\int d^3v\, f(\mathbf{v}) = 1$

On minimise $S = -k \int d^3v\, f(\mathbf{v}) \ln(f)$

"entropie" = "ignorance"

(états également probables)

$\Rightarrow f(\mathbf{v}) \propto \exp[-\beta E]$

$E = mv^2/2 \Rightarrow 1/\beta = 2U/3$

Cimetière de Vienne

Note: $S=k \log(W)$: c'est Planck! (Pais, 1982)

● entropie additive

● énergie constante

Généralisation : Hypothèses à modifier ?

Generating Kappa distributions

● *General*

☛ *Tsallis entropy (non additive)* — Tsallis 1988-1998, 2004

☛ *Super-statistics (variation in "temperature")*

➤ System not isolated
➤ Non-infinite heat bath

● **Temperature fluctuations** $\Longrightarrow$ κ distrib. if $\beta = 1/k_B T$ has χ^2 distrib.

$[1+\beta_0 E/\kappa\,]^{-\kappa} = \int d\beta\, e^{-\beta E} f(\beta)$ $\quad \beta_0 = <\beta> \quad 1/\kappa = <\beta^2>/<\beta>^2 - 1$

statistics (f(β)) of a statistics ($e^{-\beta E}$)

$\Rightarrow \kappa$ determined by temperature fluctuations

Wilk & Wlodarczyk 2000, Beck 2002, Cohen 2004

● "Small heat bath" statistics (Almeida 2001)

➤ implicit in Boltzmann ($\kappa \rightarrow \infty$): infinite heat capacity of heat bath
➤ if heat capacity is finite, κ is finite

☛ *Under progress ...*

Conclusion

✓ Nombreuses modélisations avec nombreux paramètres ad-hoc

- conductivité thermique
- flux d'ondes d'Alfvén
- longueur de "dissipation"
- facteur de chauffage
- facteur d'expansion
- facteur de remplissage

✓ Mais pas de consensus sur la question fondamentale : comment l'énergie (magnétique) est convertie en vent)

- Ondes, turbulence? Cranmer 2002, Hollweg & Isenberg 2002
- Particules suprathermiques ? Olbert 1981, Scudder, Maksimovic et al. 2007, Lamy et al. 2003, Zouganelis et al. 2004, 2005

✓ Développer :

☛ Physique des plasmas faiblement collisionnels

☛ Physique de la mesure (spectroscopie hors équilibre (X ⟷ radio)