Nature and variability of plasmas ejected by the Sun

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I. Some properties of the Sun

II. The Sun and its permanent loss rate : the solar winds

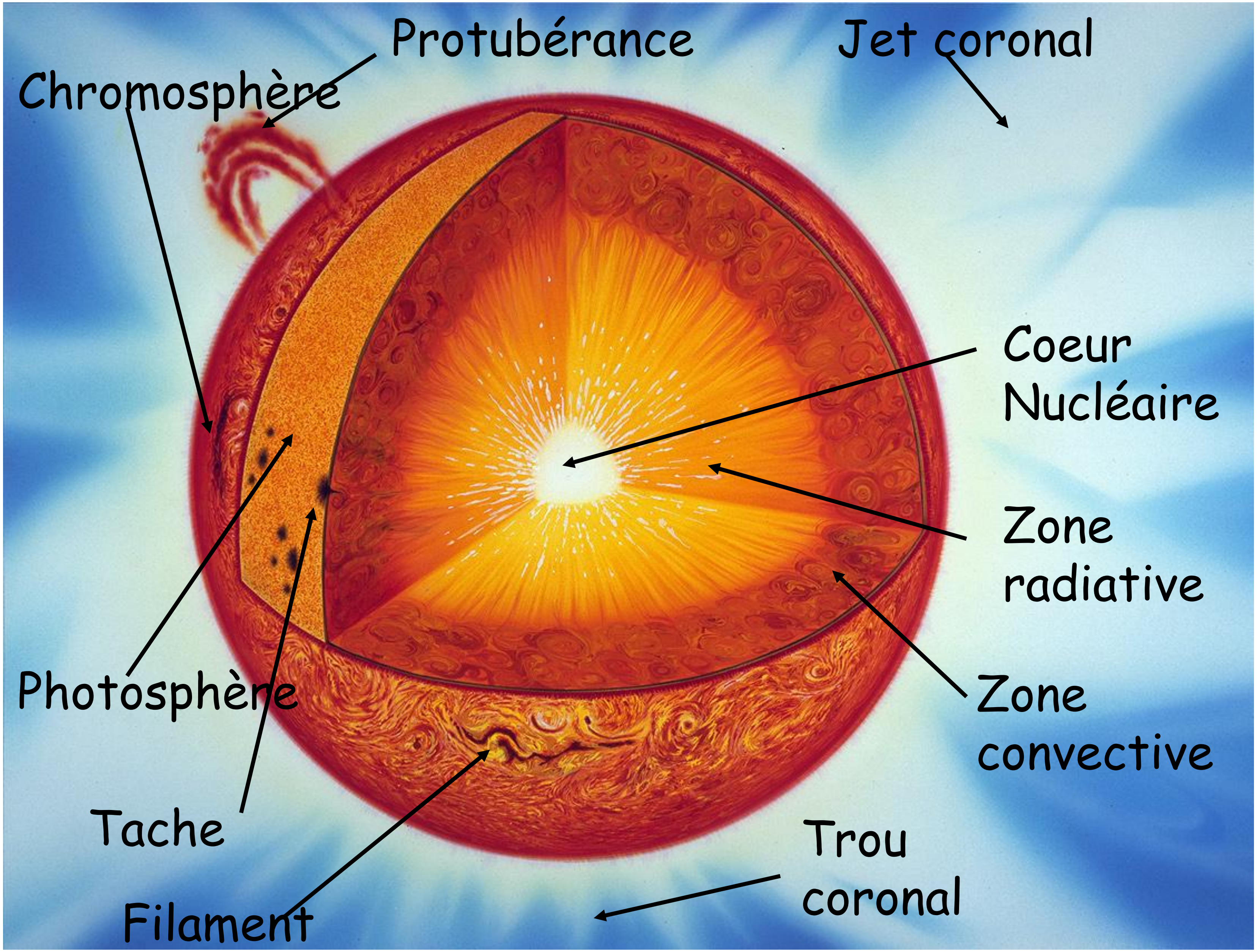
III. Activity-related solar plasma losses

IV. The Heliosphere and a couple of conclusions

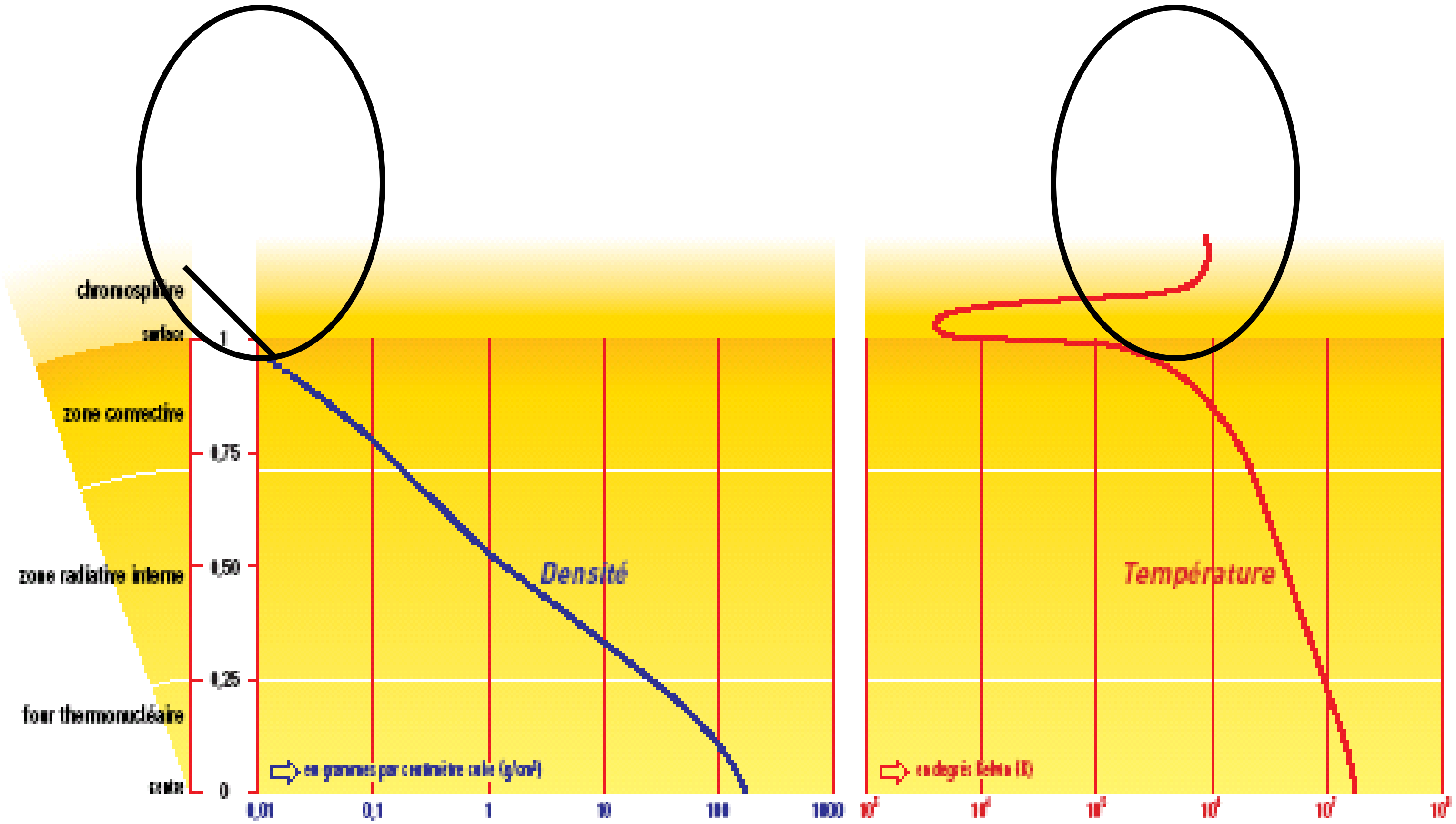
V. A short bibliography

I. Some properties of the Sun
A few figures (a reminder) :

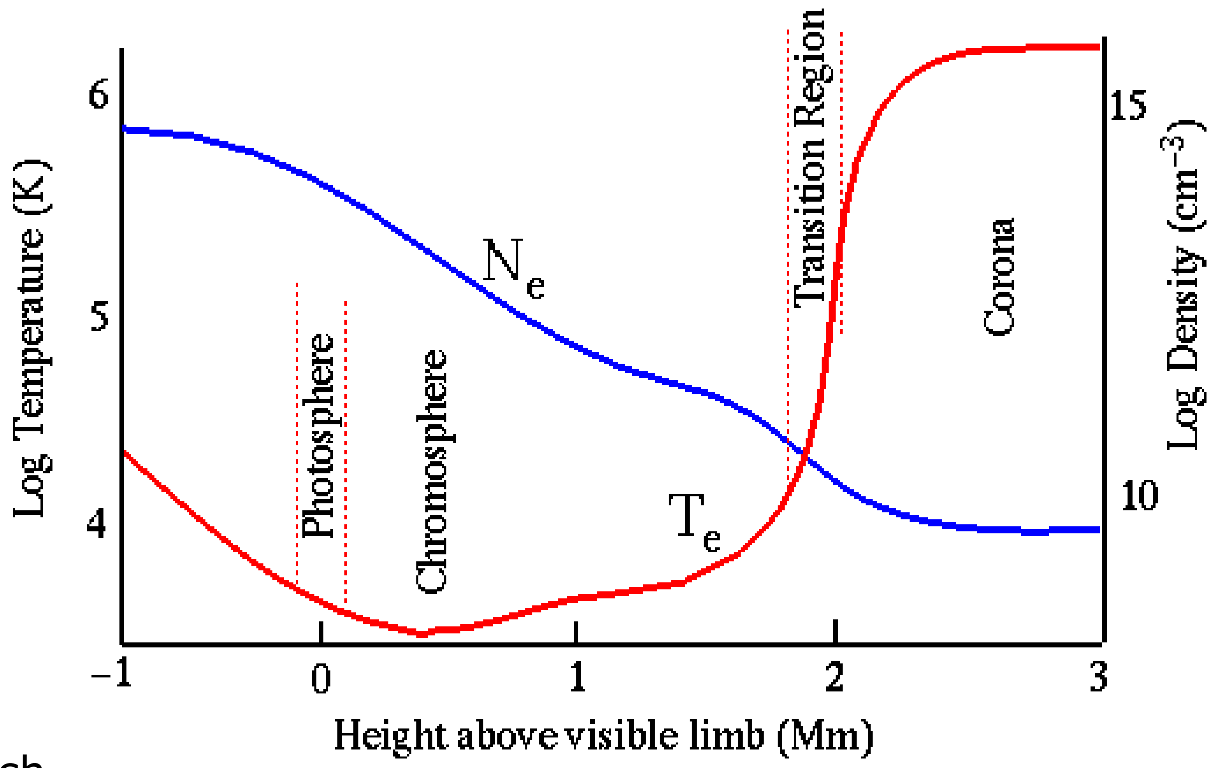
- Age : 4,5 Gy
- Radius : 696 000 km
- Mass : 1,99.10^{30} kg
- Composition : 90 % H et 10 % He
- Average density : 1 410 kg.m^{-3}
- Surface gravity : 274 m s^{-2}
- Escape velocity : 618 km s^{-1}
- Luminosity : 3,9 10^{23} kW
- Surface temperature : 5 780 K
- Color temperature : 6200 K
- Sideral rotation period : 25 days at equator ; 31 days at poles : differential rotation
- Average mass loss : 10^9 kg s^{-1} or 10^{-14} M_s $year^{-1}$


Protubérance
Jet coronal
Chromosphère
Coeur
Nucléaire
Zone
radiative
Zone
convective
Photosphère
Tache
Trou
coronal
Filament

Huge variations from center to surface to outer atmosphere



Close to the surface



Court. E. Marsch

A few spatio-temporal scales

- R = 700 000 km
- Granulation : 1000 km
- Supergranulation : 30 000 km
- Scale heights :
  - Photosphère : 100 km
  - Chromosphère : 300 km
  - Couronne : 50 000 km

Mean free path (mfp) in the corona : from 5 to 500 km depending on the electron density ($10^{16} – 10^{14}$ m^{-3} or $10^{10} – 10^{8}$ cm^{-3})

Knudsen parameter (mfp/H) < 1 in the low corona

A few other physical quantities

- **<u>Corona :</u>**
- Collision frequency e-i : 7 to 700 Hz depending on n
- Cyclotron frequency e : 3 10^6 to 3 10^8 Hz depending on B (1 to 100 G, 10^{-4} to 10^{-2} T)
- Thermal speed e : 3900 km/s
- Sound speed: 166 km/s
- $V_{Alfvén}$: 200 to 2000 km/s depending on B and n

- <u>Photon mean free paths:</u> wavelength dependent !

	Continuum visible	$L\alpha$
– Surface	50 km	1 cm
– Prominence	>> H	10 cm
– Corona	>> H	>> H

(where H is the scale height)

Convective, thermal and magnetic energy densities (at the bottom of the convection zone and) at the photosphere (in J m^{-3})

Location	$0.7\ R_\odot$	$1.0\ R_\odot$
$\rho v^2/2$	5×10^6	1.5×10^2
$\rho k_B T/\mu$	7×10^{12}	1.5×10^4
$B^2/2\mu_0$	4×10^7 (presumed)	$(0.4 - 4) \times 10^4$ (measured)

From N. Meyer-Vernet « Basics of the Solar Wind" (2007)

B more and more heterogeneous in the outer atmosphere :

spatially : open (poles) vs closed (active regions)

temporally : minimum vs maximum activity

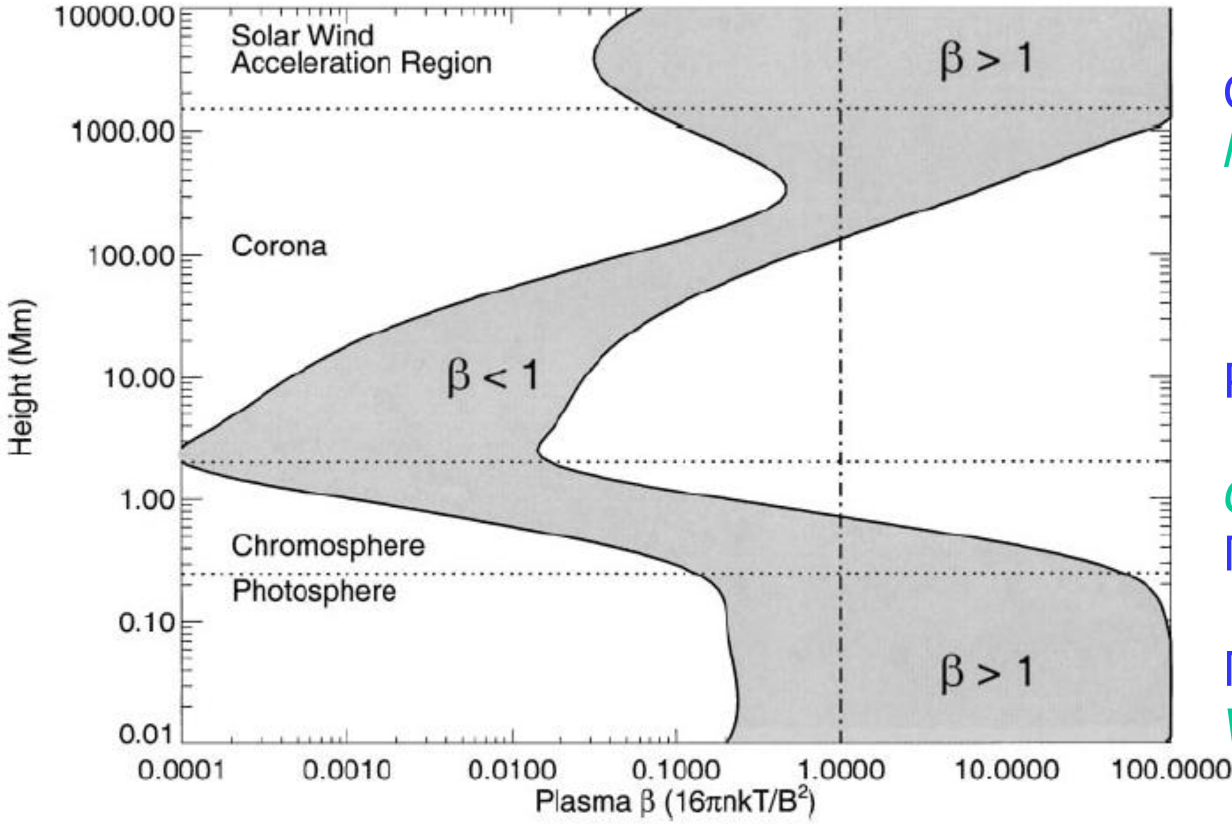
A few parameters in the quiet outer atmosphere

	Photosphere	Upper chromosphere	Lower corona	Corona
Height ($R_\odot$)	0.0	2–5×10^{-3}	10^{-2}–10^{-1}	10^{-1}–1
Temperature T (K)	6×10^3	10^4	10^6	10^6
Scale height $H = k_B T/(\mu g)$ (m)	1.5×10^5	5×10^5	5×10^7	10^8
Sound speed $V_S = (\gamma k_B T/\mu)^{1/2}$ (m/s)	0.8×10^4	1.2×10^4	1.5×10^5	1.5×10^5
Magnetic field amplitude B (T)	0.1 (strong B)	$(2$–$10) \times 10^{-4}$?	$(2$–$10) \times 10^{-4}$?	10^{-4} ?
Ratio of pressure forces to magnetic forces $\beta = 2V_S^2/\gamma V_A^2$	~ 1	~ 1	< 1	< 1

From N. Meyer-Vernet « Basics of the Solar Wind” (2007)

Very large spatial (x,y,r) and temporal variations of the plasma β

$\beta = P_{gas}{}^{*} / P_{magnetic}$ (* or $P_{kinetic}$)



Completely ionised
Non collisionnal

Partially ionised

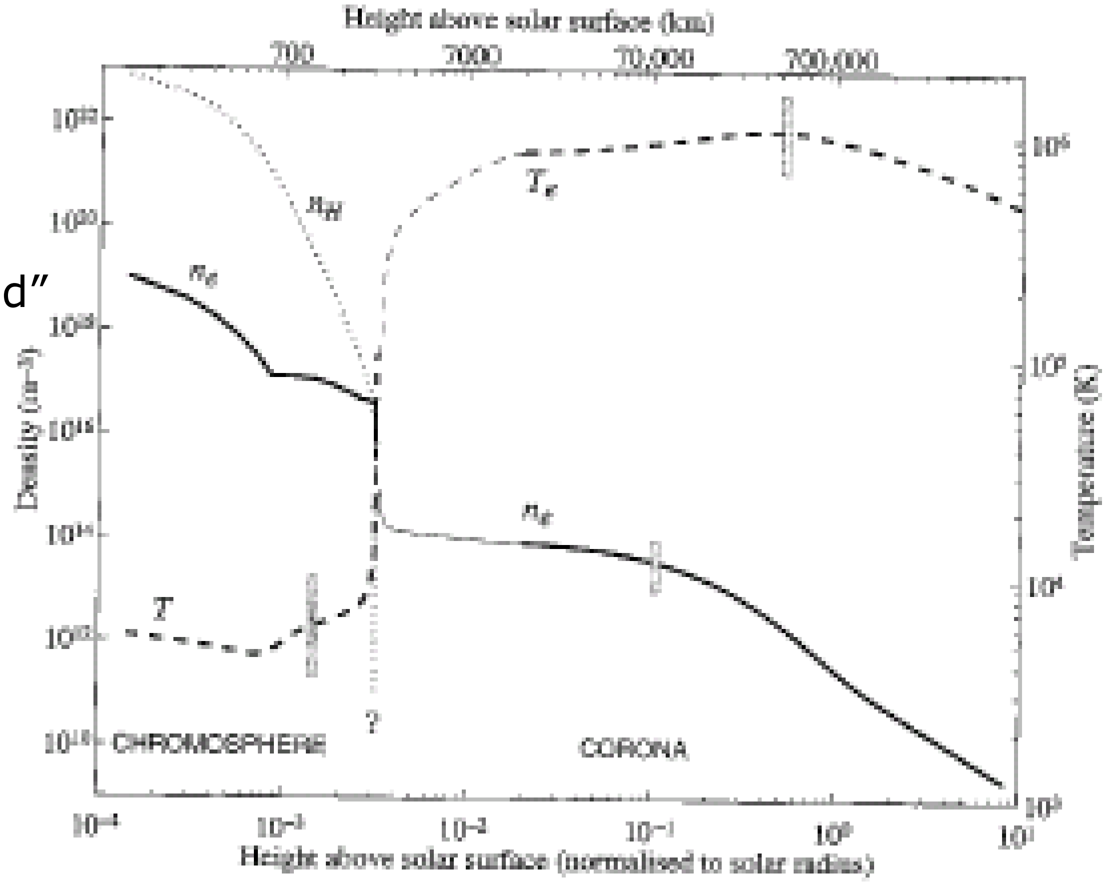
Collisionnal
Neutral

Neutral
Very collisionnal

Aschwanden et al. (2001)

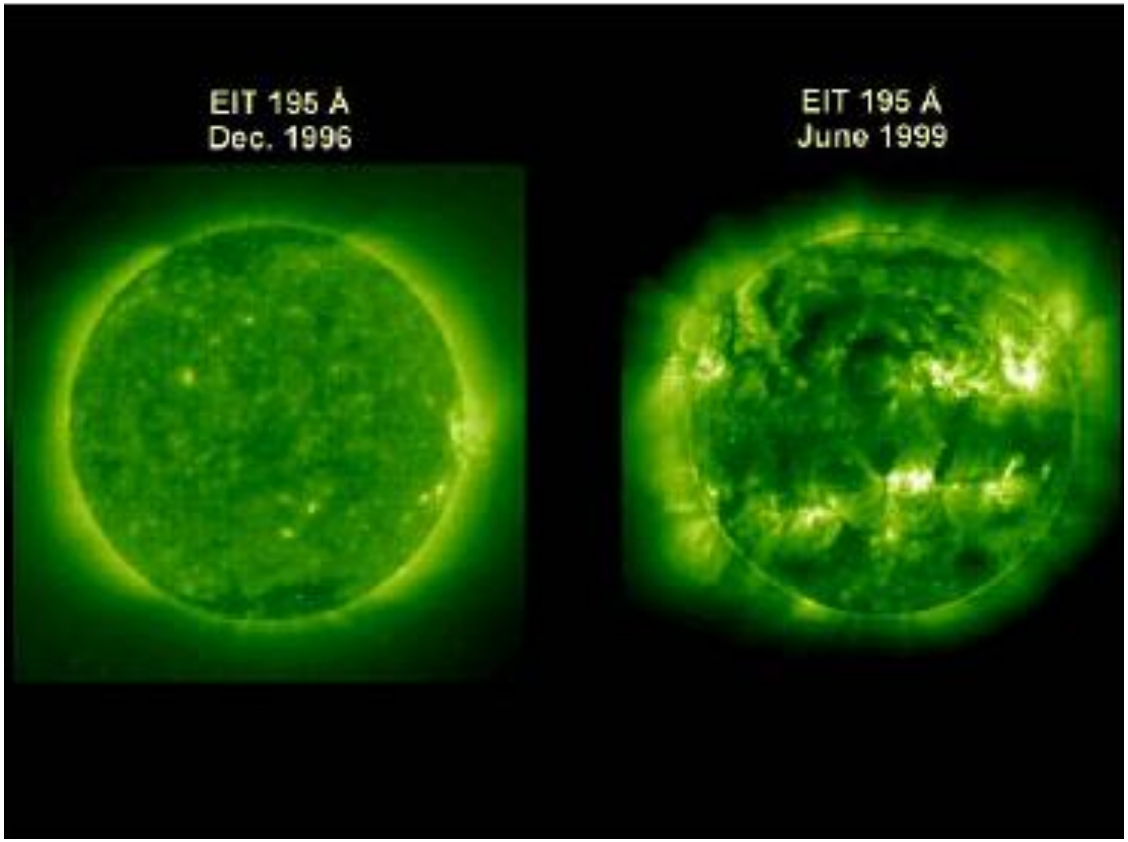
Quiet Sun coronal model

From N. Meyer-Vernet
« Basics of the Solar Wind”
(2007)



The real (quiet and active) low coronae

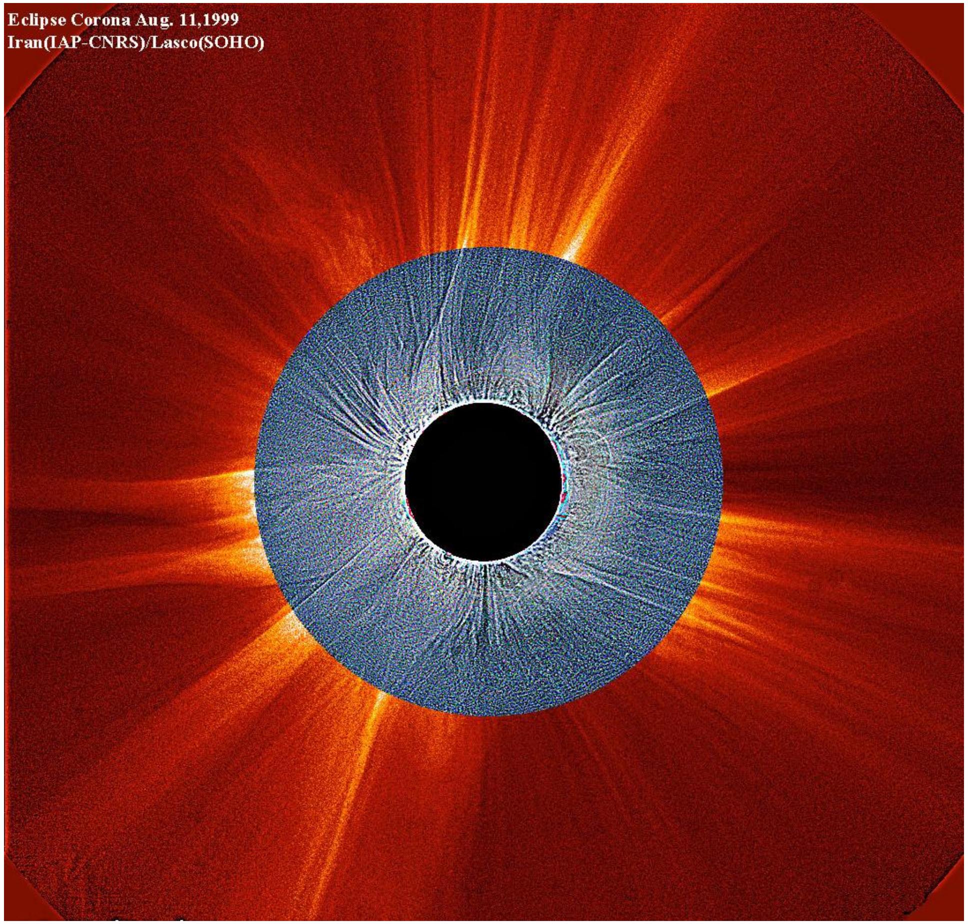
EIT/SOHO



Poloidal field Toroidal fields

The real (active) outer corona

Eclipse+ LASCO/SOHO 1999
Courtesy S. Koutchmy

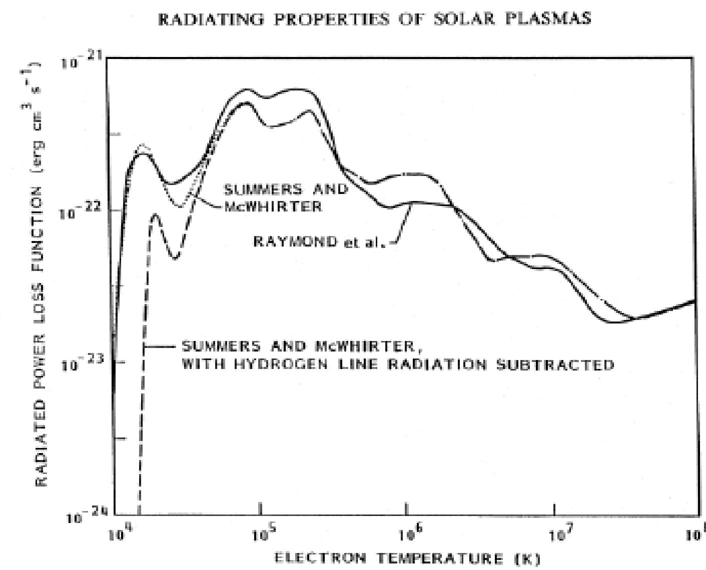


A simple derivation of the T coronal profiles (1)

- Energy balance : $$\frac{\kappa_0}{r^2}\frac{d}{dr}\left(r^2 T^{5/2}\frac{dT}{dr}\right) = W_R$$

where W_R (radiative losses) are given by : $W_R = n^2 F(T) \quad \mathrm{W\,m^{-3}}$

with F(T)



A simple derivation of the T coronal profiles (2)

- W_R (radiative losses) : negligible (n↘ r↗)

$$\frac{d}{dr}\left(r^2 T^{5/2}\frac{dT}{dr}\right) = 0 \qquad\qquad \frac{d}{dr}T^{7/2} = \frac{\text{constant}}{r^2}.$$

T -> 0 at infinity

$$T \propto r^{-2/7}.$$

$T(r) = T_{R_o} (R_o/r)^{2/7}$

Is hydrostatic equilibrium valid ?

Hydrostatic equilibrium

$dp/dr = - G M_0 \rho / r^2$ $\quad\quad$ $p = 2 n k T = \rho k T / \mu$

$T(r) = T_{R\circ} (R_\circ/r)^{2/7}$

$p = p_\circ \exp\{ 7 G M_0 \rho_0 ((R_\circ/r)^{5/7} - 1) / 10 p_\circ R_\circ\}$

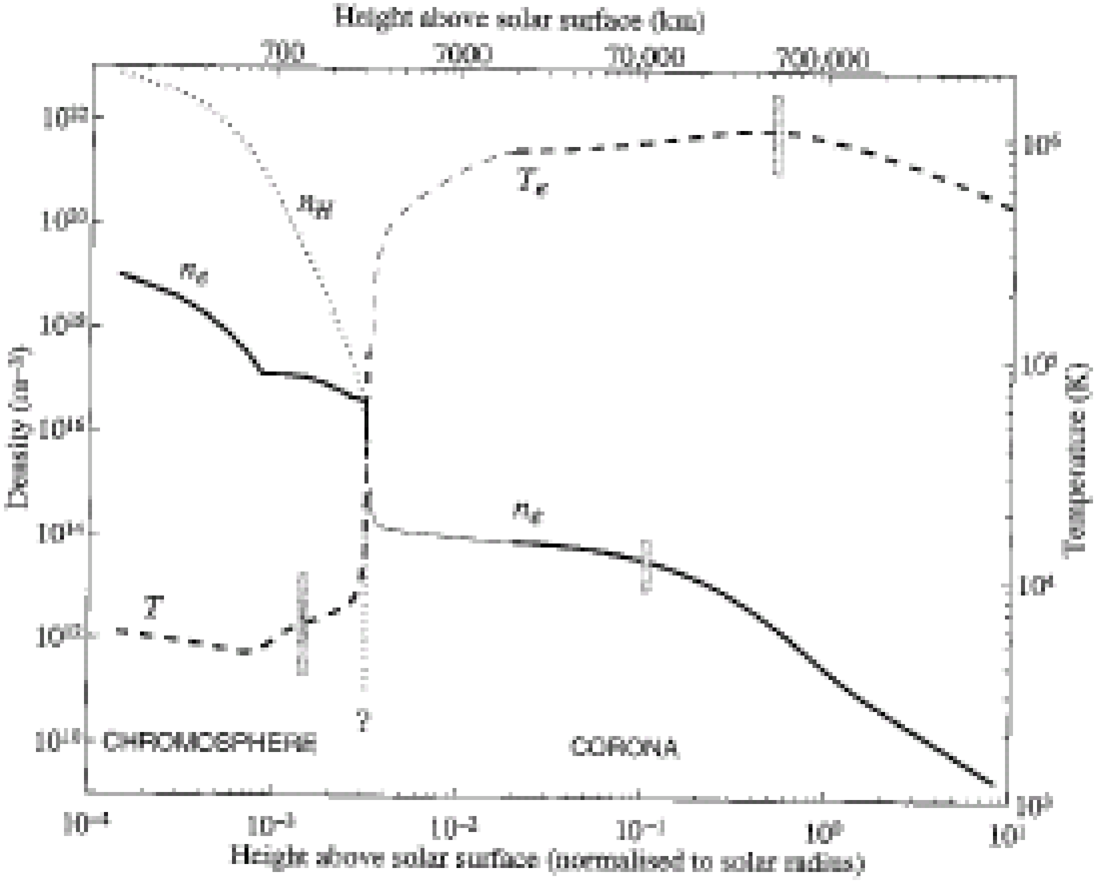
$r \to \infty$ $p \to 10^{-7}$ Pa

But $P_{interstellar} = 10^{-13}$ Pa

$\Rightarrow$Corona cannot be static : **a wind blows ...**

Quiet Sun coronal model

From N. Meyer-Vernet
« Basics of the Solar Wind”
(2007)



Ecole CNRS, Roscoff, 4 Avril 2011, Nature and variability of plasmas ejected by the Sun, jcv

II. The Sun and its permanent loss rate : the solar winds

A wind blows …

Predicted by E. Parker (1958)

Measured with Mariner2 (1962)

Identified as the force acting
on comet tail
(L. Biermann, 1963:
«"solar corpuscular radiation")

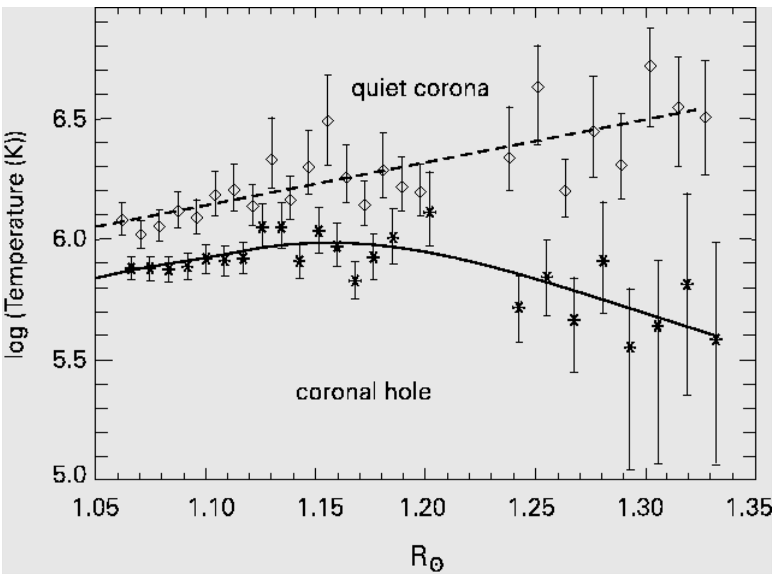
Comet Hale-Bopp

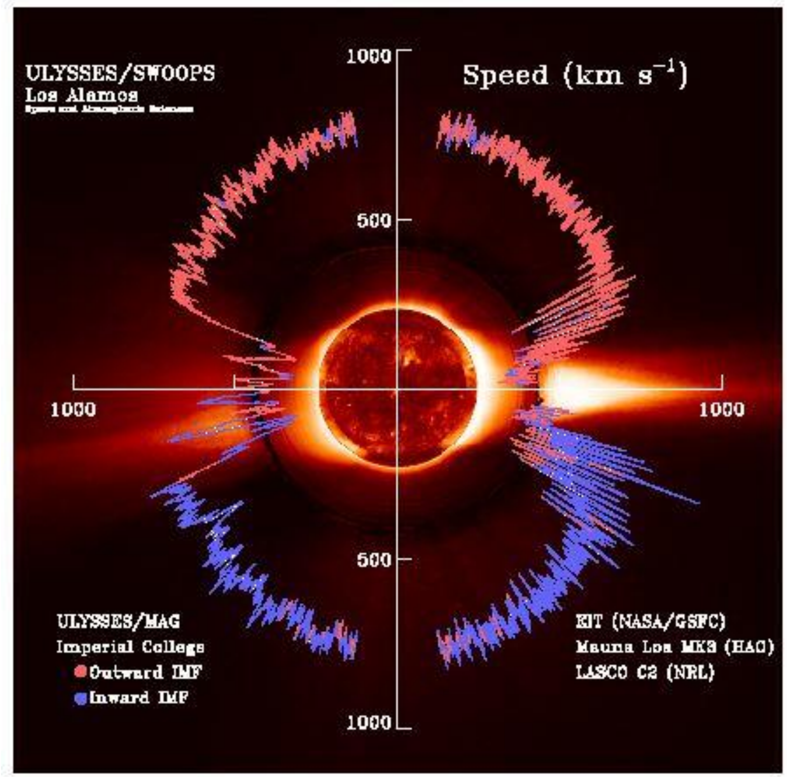
Mass loss : 10^9 kg s^{-1}

The two kinds of solar wind

Slow at the equator : 400 km/s
Fast in Coronal Holes (pôles) : ≈ 800 km/s (up to 1200)
Very variable in time and latitude

The fast wind should come from hottest regions : but CHs are coolest ones (David et al. 1998)!



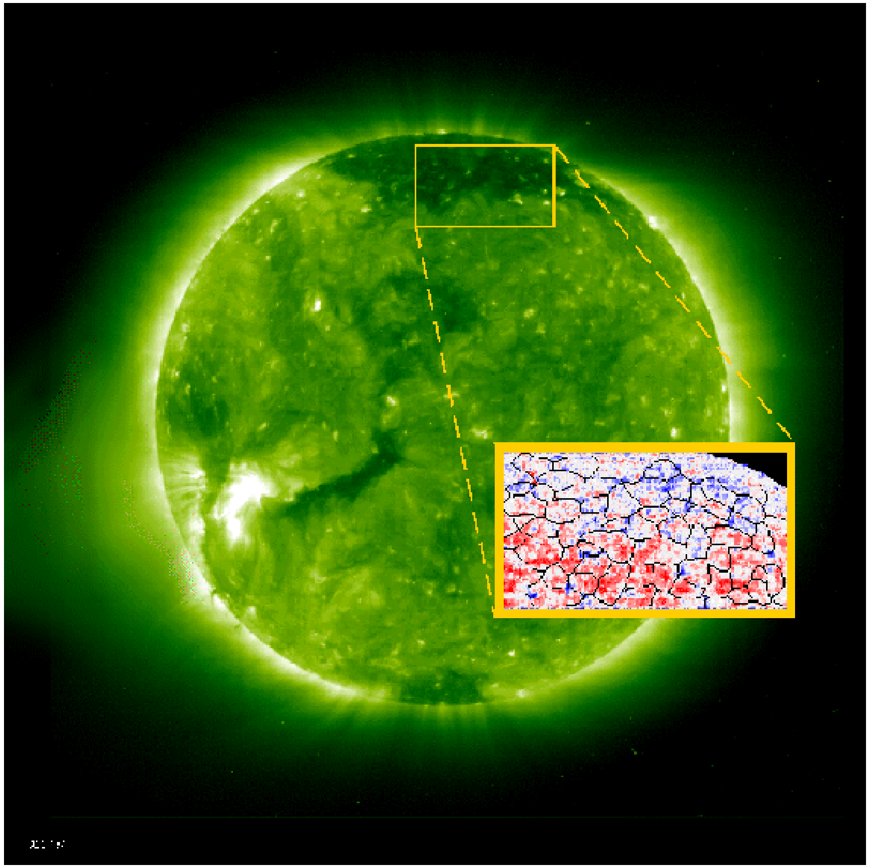


McComas, D.J., et al., Geophys. Res. Lett., 25, 1-4, 1998

The « sources» of the fast wind (1)

Chromospheric
Network i.e. supergranulation
at 6 10^5 K
Doppler shifts
Red: down
Blue: up

Outflow from the network
and network intersections

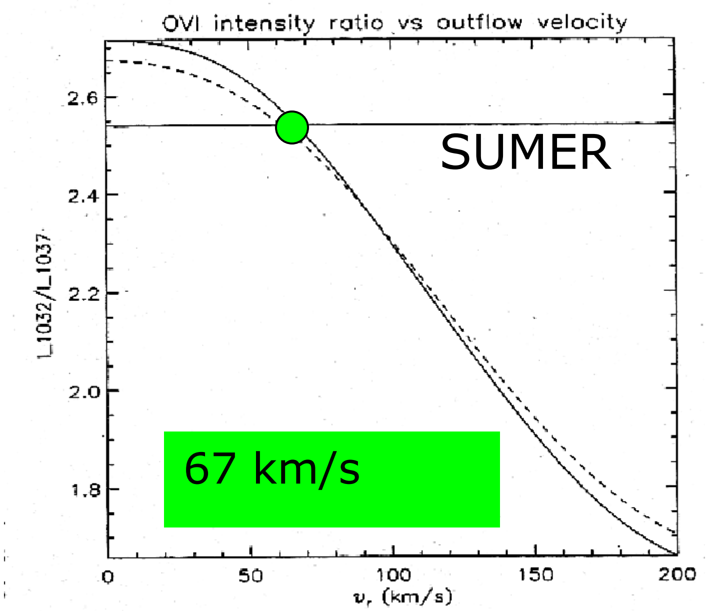


Hassler et al.,
Science 283,
811-813, 1999

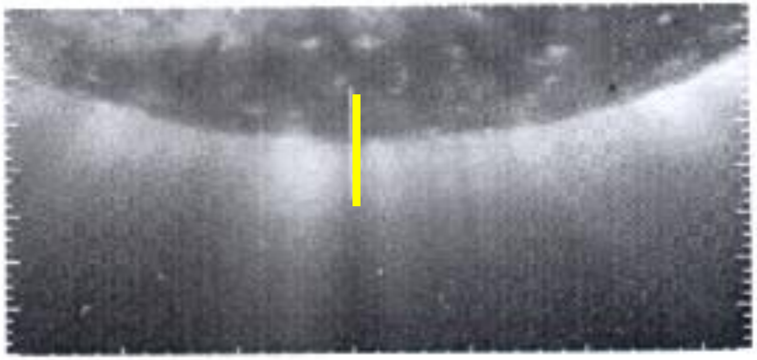
The « sources» of the fast wind (2)

Plumes / interplumes ? (see following viewgraph from E. Marsch)

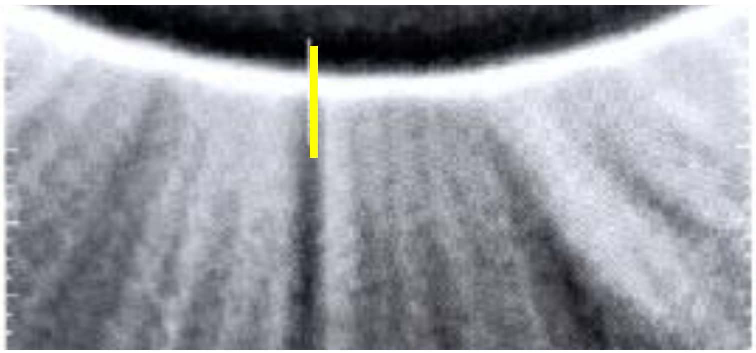
Outflow speed in interplume region at the coronal base



O VI 1031.9 Å / 1037.2 Å
line ratio; Doppler dimming



1.05 R_S
EIT
FeIX/X



Eclipse
26/02
1998
18:33 UT

$T_e = T_i = 0.9$ M K, $n_e = 1.8\ 10^7\ cm^{-3}$

Patsourakos and Vial,
A&A, 359, L1, 2000

The « sources» of the fast wind (3)

Plumes / interplumes?

Small-scales ejecta ? Spicules ??

«(Expanding) Funnels » where high-frequency Alfvén waves (< 10 kHz) in the **chromosphere** could explain the « FIP » effect

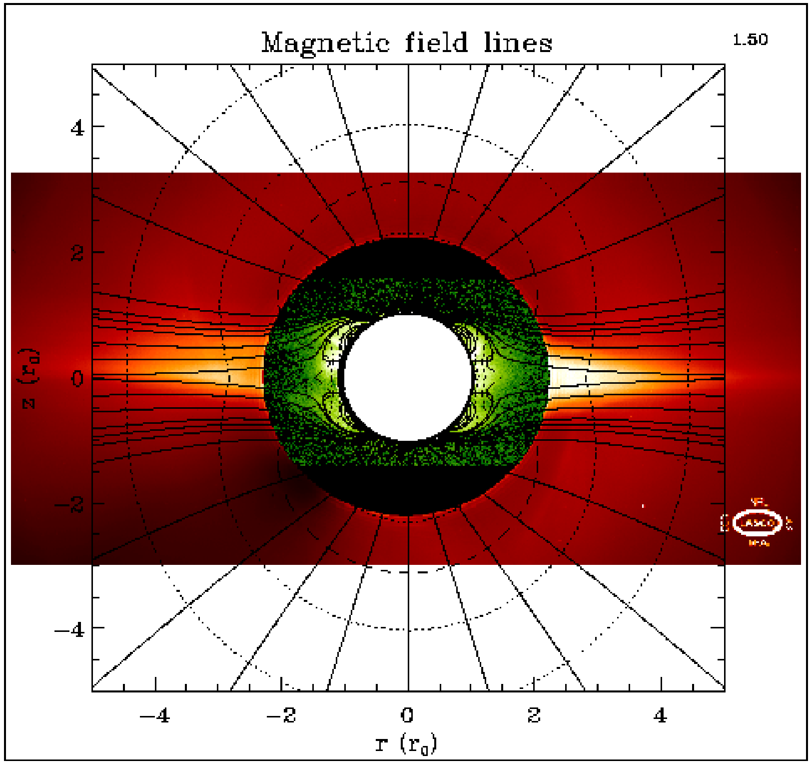
(overabundance of elements with FIP < 10 eV)

The « sources» of the slow wind

Boundary Coronal Hole / current sheet through multipolar magnetic field ?

Banaszkiewicz et al., 1998; Schwenn et al., 1997

Boundary Coronal Hole / Active Region ?
(Sakao et al. 2007, Baker et al. 2009)
but „open" field lines could be long-range closed lines (see following viewgraph)...

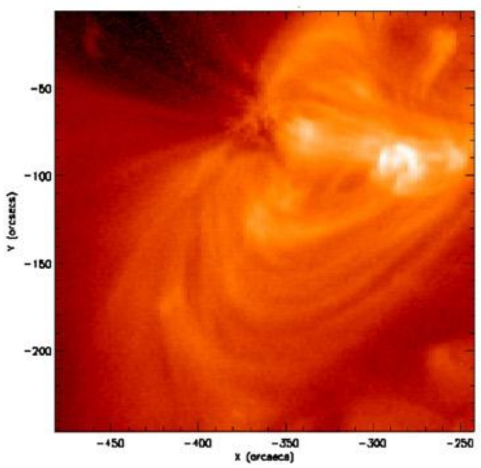


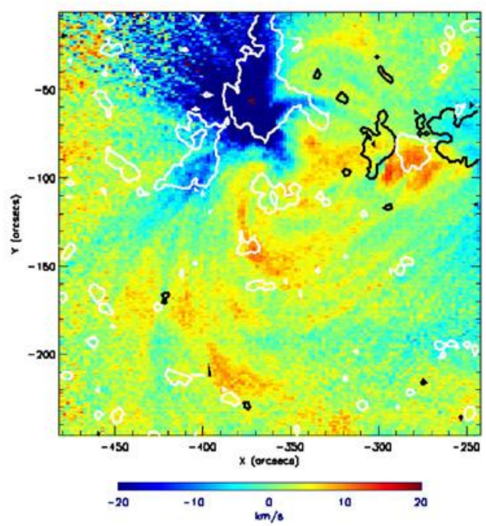
What about Active Region 10942 ?

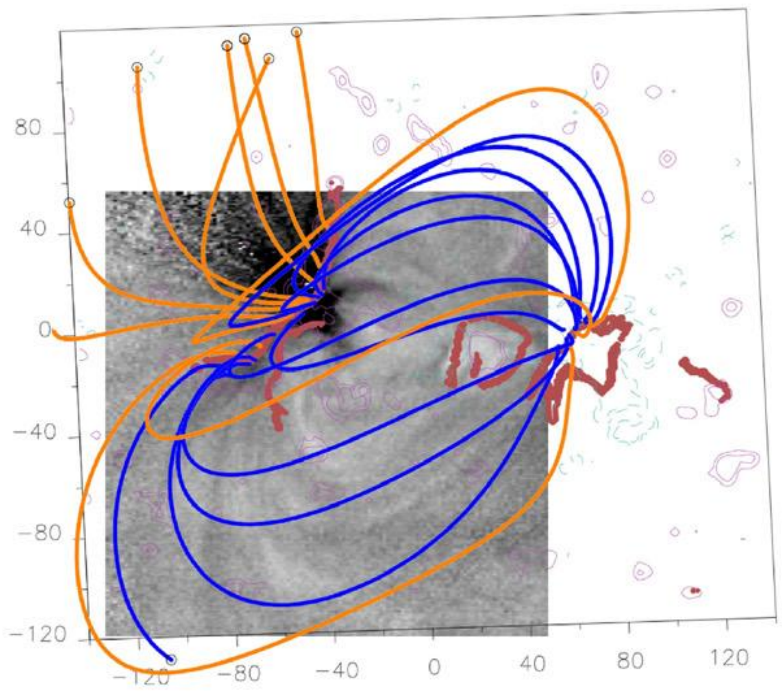
(Baker et al 2009)

Blue outflow to the Solar Wind ?

(Sakao et al 2007)







Intensity from FeXII 195Å (EIS).

Velocities from FeXII Doppler shift (EIS).

Extrapolated magnetic field over velocities field(FeXII Doppler shift).

See also He 2010 et Harra 2008

Fluid models of the wind (1)

Assumes thermal conductivity ($\kappa \sim \frac{3}{2} n k_B v_{th} l_f$)

i.e. $\kappa \sim 10^{-11} \times T^{5/2}\ \mathrm{W\,m^{-1}K^{-1}}$

Assumes the mean free path (l_f) << variation scale

Very low corona : $l_f \approx$ a few 100 km

At 1 A.U. (n ~5 10^6 m^{-3} ; T ~ 10^5 K) : $l_f \approx$ 1 A.U. !

Moreover, l_f varies as v^4 : l_f (3 v) = 100 l_f (v)

Fluid models of the wind (2)

The isothermal Parker model :

Conservation of mass and momentum …

$(V/c_s)^2 - \ln (V/c_s)^2 = 4 (\ln(r/r_c) + r_c/r) + \text{Constant}$

C_s sound speed

r_c critical distance $r_c = G M /(2 C_s^{\,2})$

$dV/dr > 0 \Rightarrow$ $r < r_c$ subsonic

$r > r_c$ supersonic

Sun : $C_s = 140$ km/s

$r_c = 4.5$ R

…. Mass loss = $1.6\ 10^9$ kg/s

Fluid models of the wind (3)

A thorough presentation by M. Velli (1998)

$M = V/c_s$

4 sets of solutions

With the right pressure values,

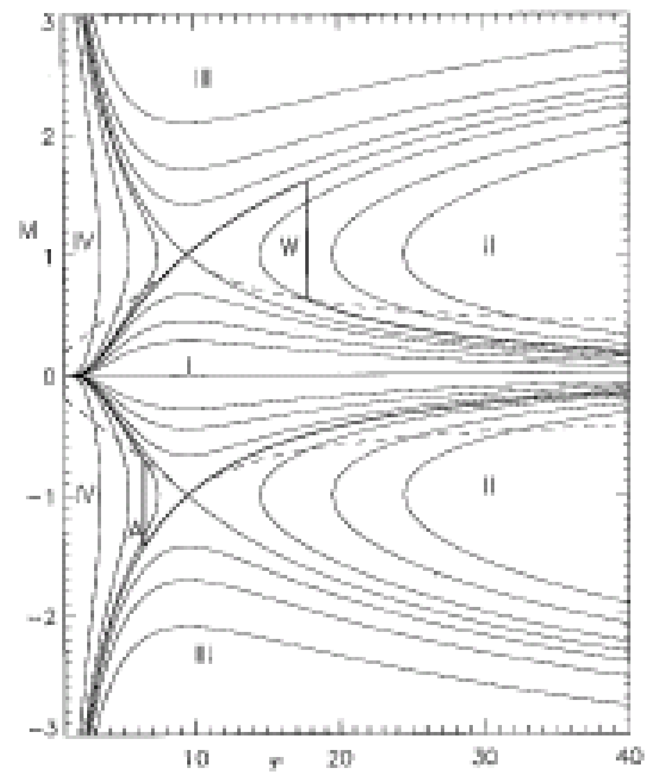
two stationary outflow solutions:

a supersonic shocked wind

(which allows for a low terminal pressure)

and

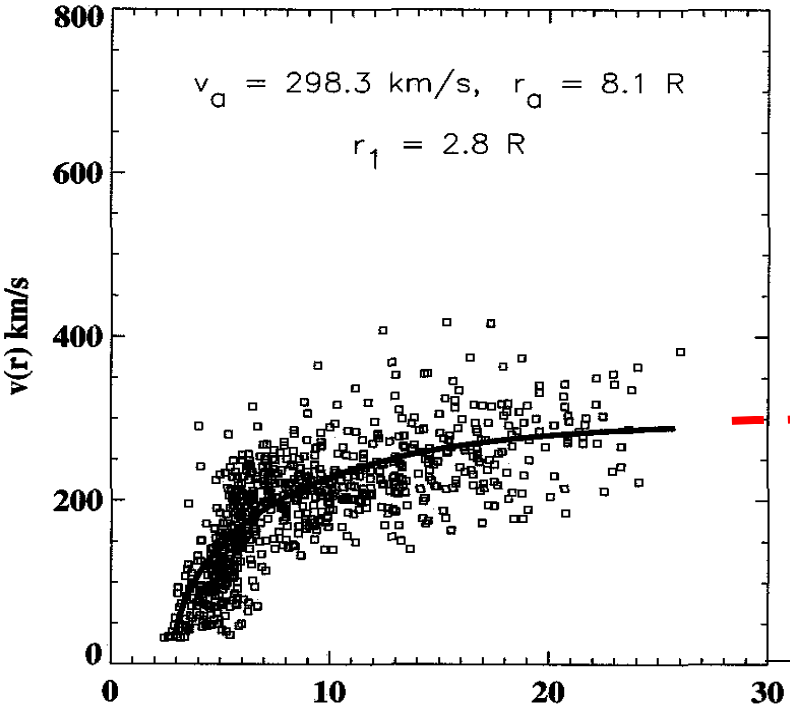
a subsonic breeze (which matches the observed velocity)

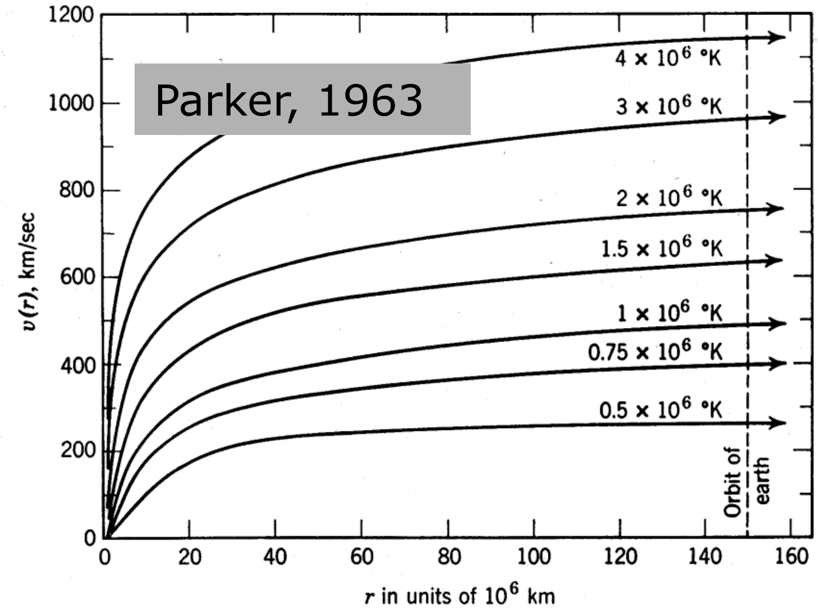


Fluid model for the slow wind : ok ?

« Blob » measurements

Sheeley et al., Ap.J., 484, 472, 1998



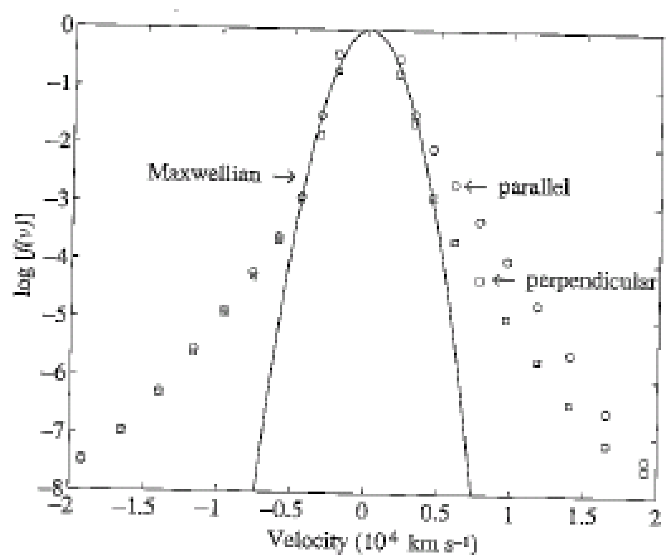


After E. Marsch

The fast wind and the fluid models

Temperature issue : in order to have a fast wind with a 10^6K corona, one needs to deposit additional momentum in the flow :

• Polytropic approximation ? $\gamma < 5/3$ (but why ?)
• Two-fluid (in order to take into account $T_p > T_e$: from UVCS/SOHO to Ulysses)
• Alfvén waves in a **non-radial expansion geometry** : frequencies up to 10 kHz from the chromospheric network; supersonic speeds in the very low corona
…..
« More and more ingenious schemes reminiscent of the Ptolemaic system » (1)
• Main handicap : **observed particles distributions** are far from Maxwellian (or bi-maxwellian) : e.g. electron → (courtesy I. Zouganelis)



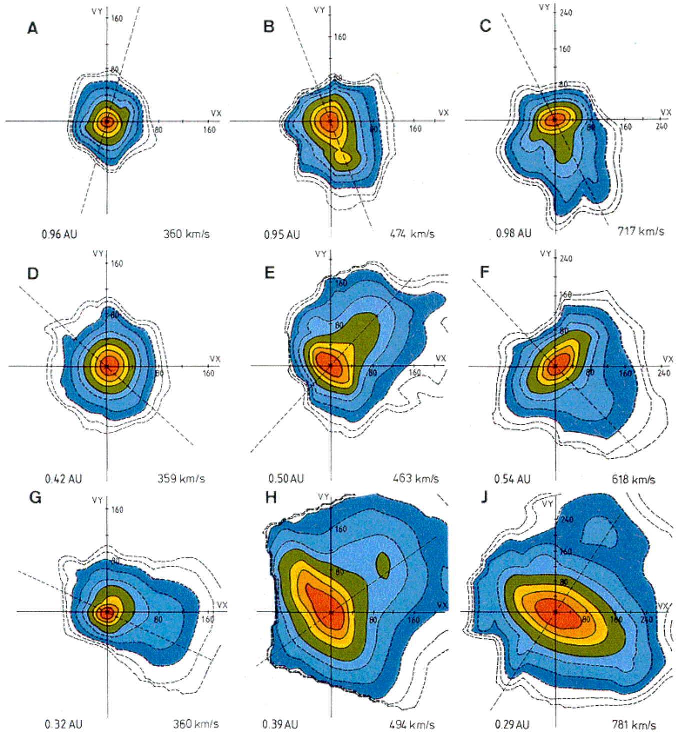
• (1) See N. Meyer-Vernet's book

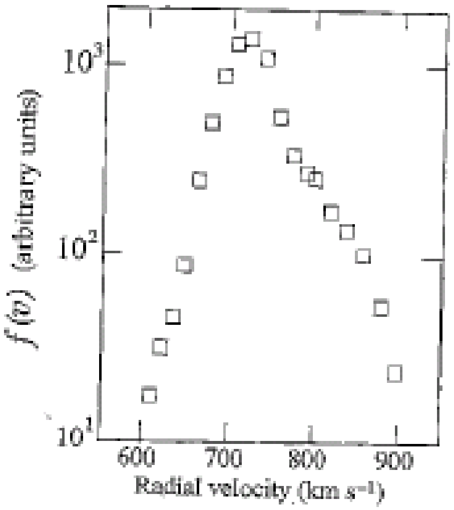
The fast wind and the kinetic/exospheric models (1)

Facts :

Proton distributions in the fast wind

Non-maxwellian at 1 U.A.





Anisotropic (from 1 to 0.3 A.U.)

Helios

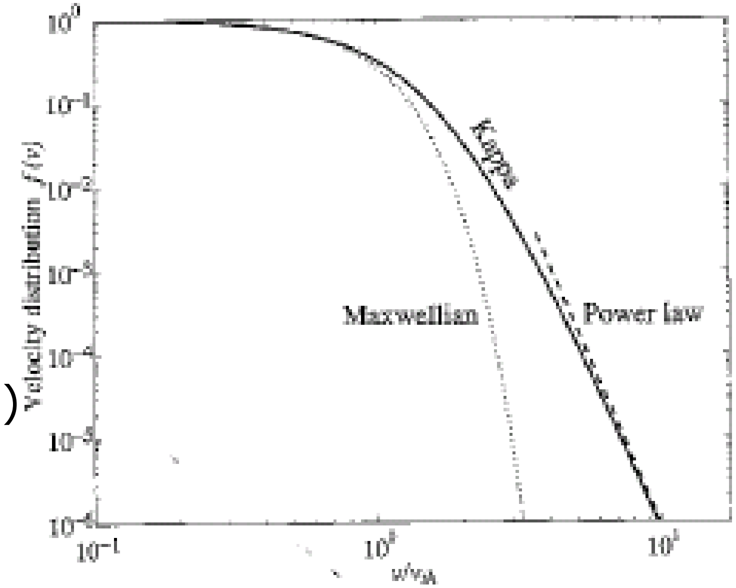
Marsch et al., JGR, 87, 52, 1982

The fast wind and the kinetic/exospheric models (2)

Velocity distributions and their moments : density, mean velocity, ….

The kappa distribution : nearly Maxwellian at low speeds, decreases as a power law at high speed

$$f_\kappa(v) \propto \left[1 + \frac{v^2}{\kappa v_{th}^2}\right]^{-(\kappa+1)}$$



The power law part where energy accumulates at a rate proportional to itself reminds of (flare to nanoflare) energy distribution.

Same « nano-scale » phenomenon ?

The fast wind and the kinetic/exospheric models (3)

Electrons (light) in outer region
Protons (heavy) in inner region
$\Rightarrow$ Electrostatic potential $\Phi_E(r)$

$\Rightarrow$Total electron energy $m_e v^2/2 - e\Phi_E(r) = \text{constant}$

$v_E = (2e\Phi_E/m_e)^{1/2}$

V < v_E Electron trapped

V > v_E Electron moves outward to infinity

An excess of escaping electrons increases the potential which rises the electric field which increases the wind speed etc ….

The fast wind and the kinetic/exospheric models (4)

Improvements :

Invariants of motion => very small cone of escaping electrons

Collisions

Wave-Particle interactions

Building a full model :

Putting the boundary conditions in the chromosphere where …

Radiative losses are important

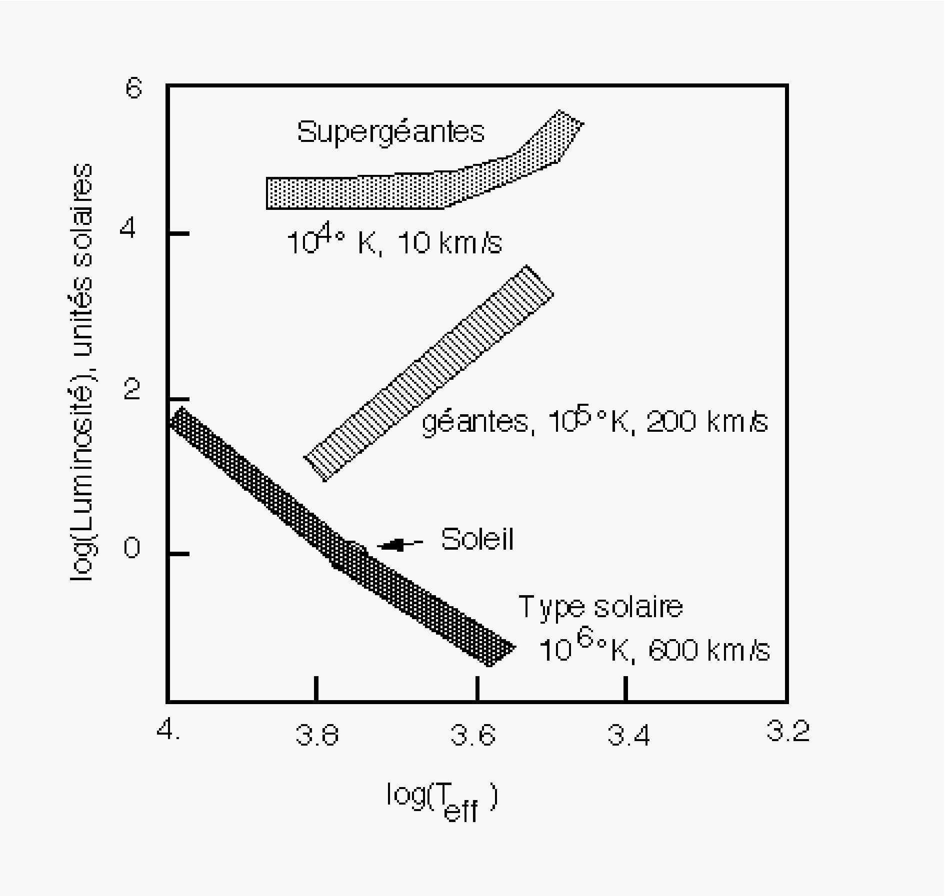
Heat conductivity : not very well known

Magnetic field energy but B not measured !

Complex geometry (including filling factor)

Temporal variations

Coronae and Stellar Winds



Hot coronae associated to diluted, hot and fast winds

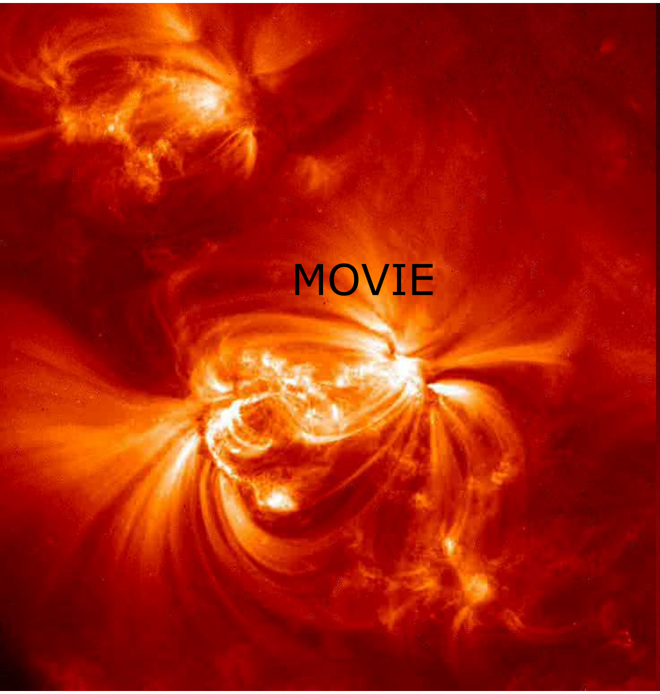
vs.

Dense and cool winds

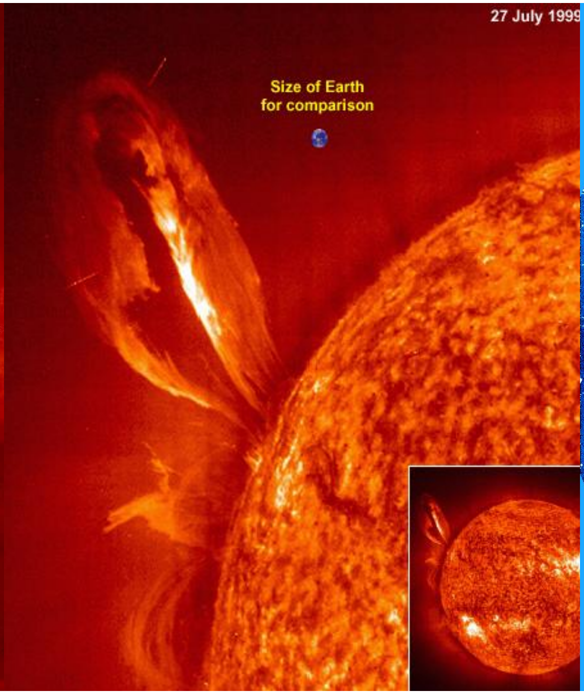
A. Mangeney, A. Roux, J.-C. Vial (1998)

III. The Sun and its activity-related plasma losses

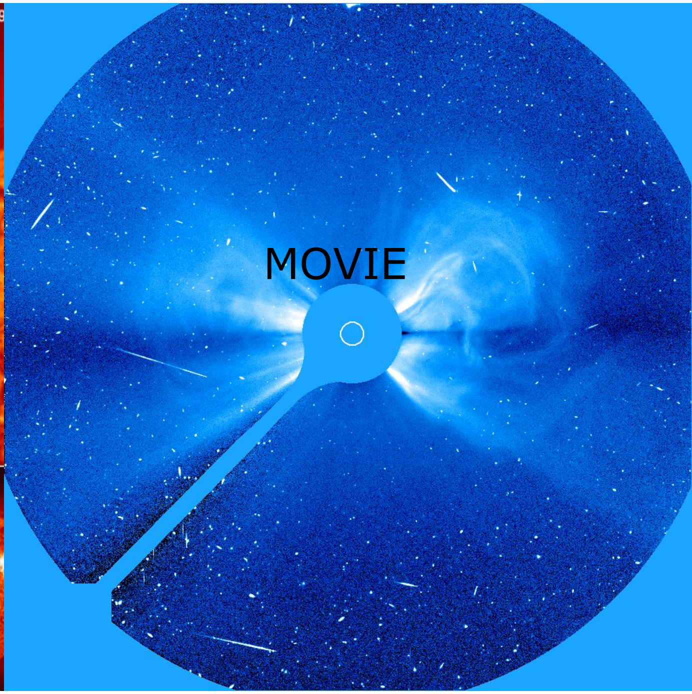
Flare



Erupting
Prominence (EP)

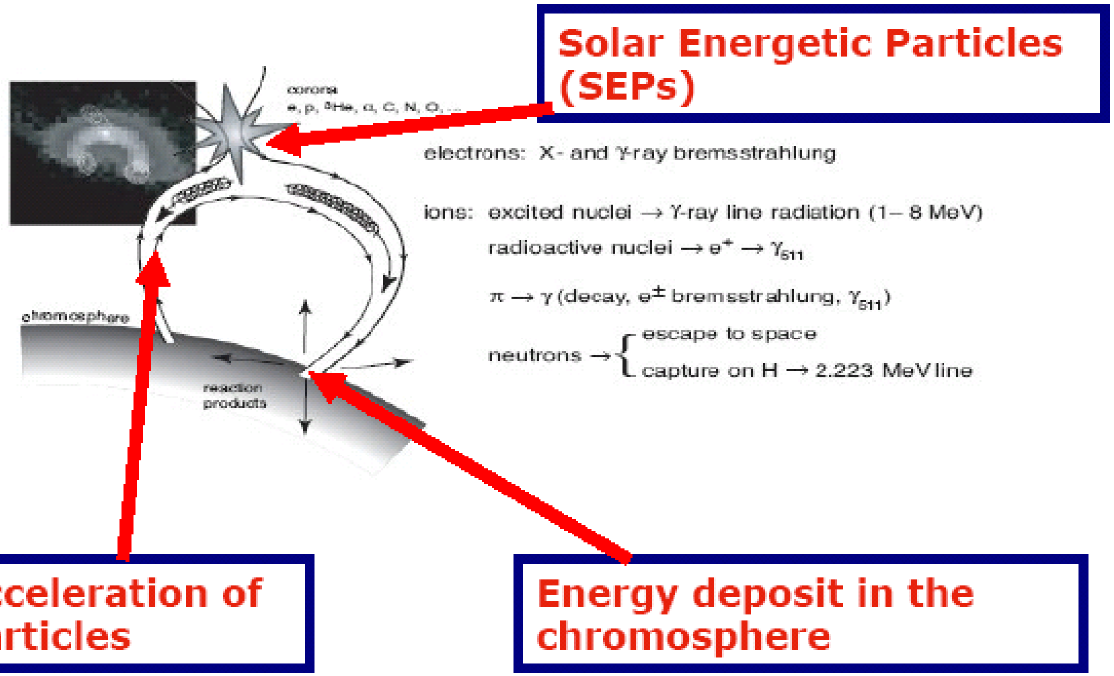


Coronal Mass
Ejection (CME)



Flares, EPs, CMEs : large energies, small mass losses ?

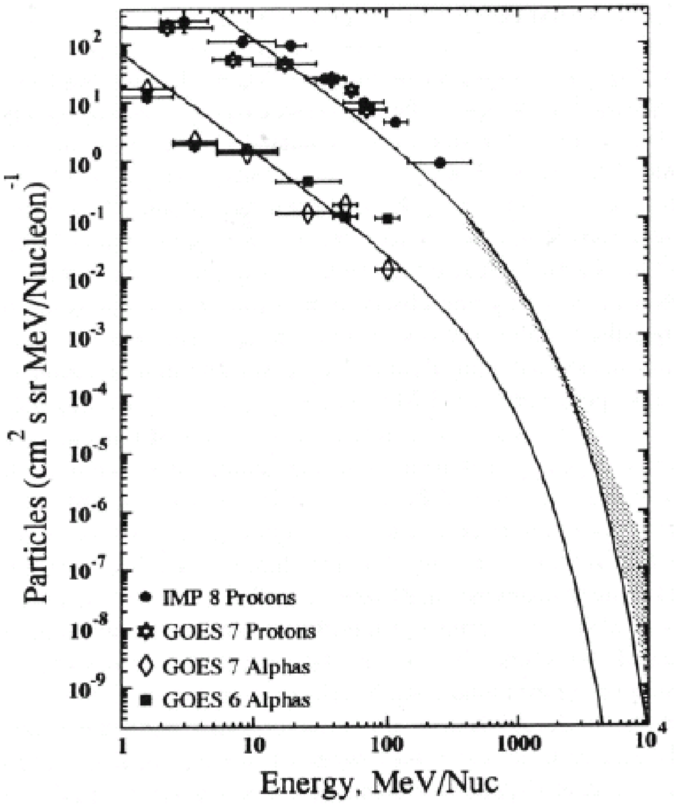
Flares
Energy release 10^{26} J, which goes into :
heating,
particle acceleration,
Solar Energetic Particles
(SEP) release
and (sometimes)
CME …
SEPs :



SEPs

Loss mass < 10^4 kg/s for the duration of the event (< hours)
(but E > MeV ..)

And some SEP associated **only** with CMEs ...



Flares, EPs and CMEs : closely related phenomena (1)

What is a prominence ?

Cool ($T \approx 10^4$ K) and dense (10^9 - 10^{11} cm^{-3}) material suspended and confined in the corona

$M \approx 5\ 10^{15}$ g within a factor 10 (at least) because it depends on the volume (i.e. the morphology of the filament/prominence)

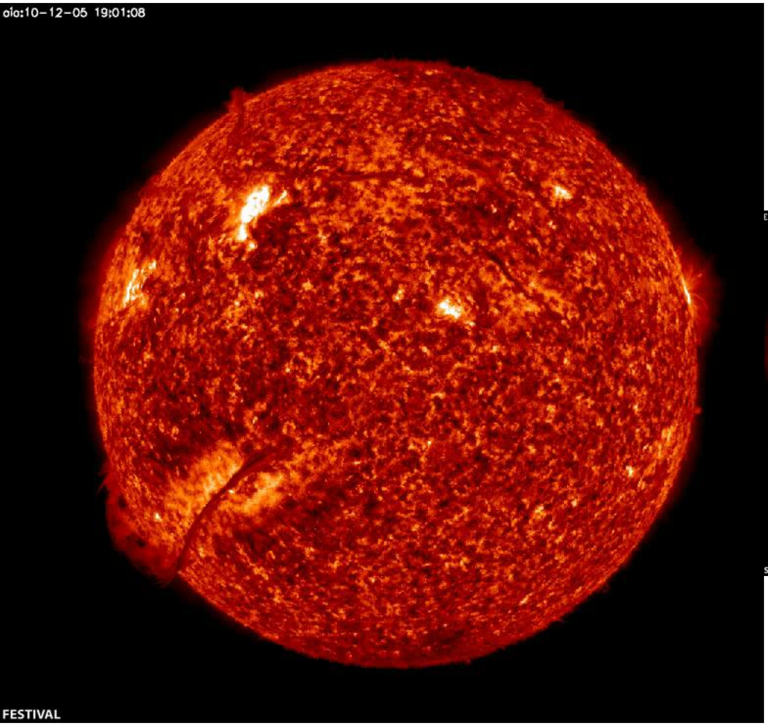
(Labrosse et al. 2010)

$M_{prom} \approx M_{cor}$

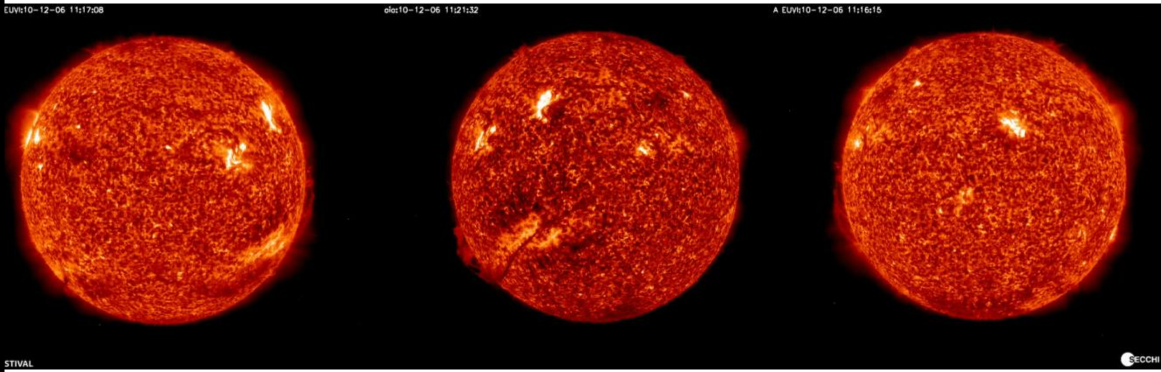
Prominence eruption?

How much material actually leaves the Sun ?

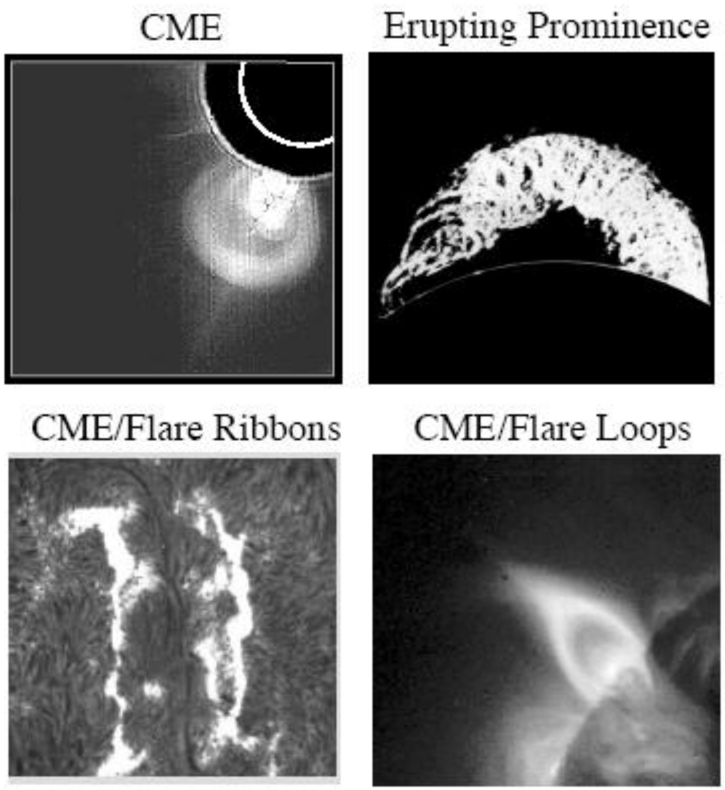
Prominence eruption :
How much material actually leaves the Sun ?

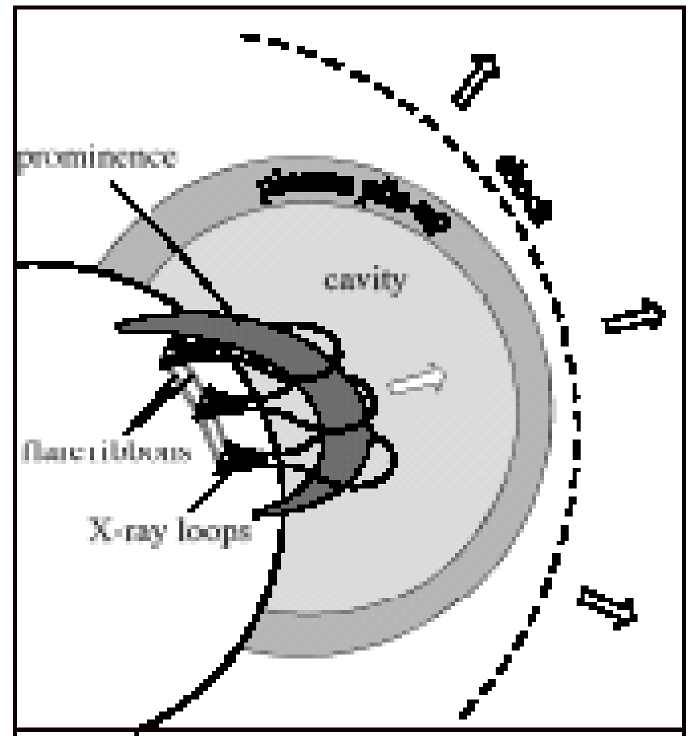


SDO and STERE movies which evidence that not all the material is lifted away.



Flares, EPs and CMEs : closely related phenomena (2)





Forbes et al., 2006

Flares, EPs and CMEs : closely related phenomena (3)

Mass involved in a CME : (essentially material from the EP)

10^{12}-10^{13} kg

At minimum of activity : two events per week

on average : 3 10^{6} - 3 10^{7} kg/s $\ll$ SW

At maximum of activity : two events per day

3 10^{7} - 3 10^{8} kg/s $<$ SW

Kinetic Energy (velocity $\approx$ 1000 km/s):

0.5 10^{24} - 0.5 10^{25} J $<\approx$ Flare (10^{26} J)

Flares, EPs and CMEs : closely related phenomena (4)

Who starts first ? Chicken or egg ?

Same process : release of magnetic energy stored in coronal B

Energy Type	Formula	Value (J/m^3)	Parameter Values
Magnetic	$B^2/2\mu$	40	$B = 100$ gauss
Thermal	nkT	0.01	$n = 10^{15}\ \mathrm{m}^{-3}$, $T = 10^6$ K
Bulk kinetic	$m_p n v^2/2$	10^{-6}	$n = 10^{15}\ \mathrm{m}^{-3}$, $v = 1$ km/s
Gravitational	$m_p n g h$	0.04	$n = 10^{15}\ \mathrm{m}^{-3}$, $h = 10^8$ m

Forbes et al. 2006

But :

V (SW) <≈ 800 km/s, perhaps a few 10 km/s

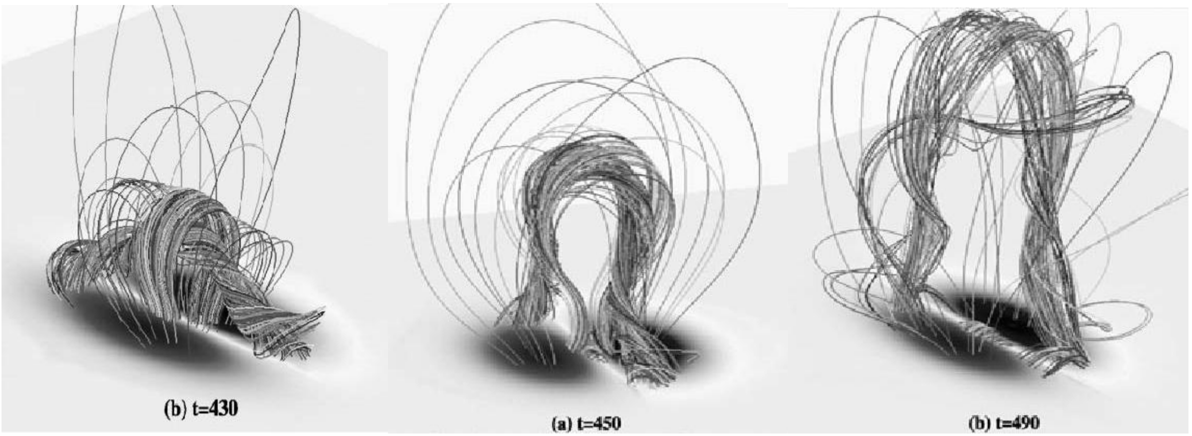
100 G (or 0.01 T) is not the average coronal field !

Possible only in active regions; B nowhere measured, actually

EPs and CMEs : models

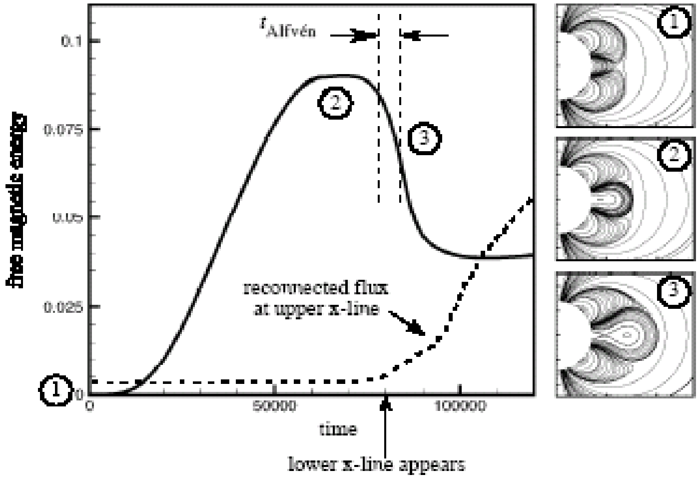
Flux rope
Amari et al. 2003

Emergence of stressed magnetic field from the convection zone ?



Breakout
Antiochos et al. 1999
Aulanier et al. 2001

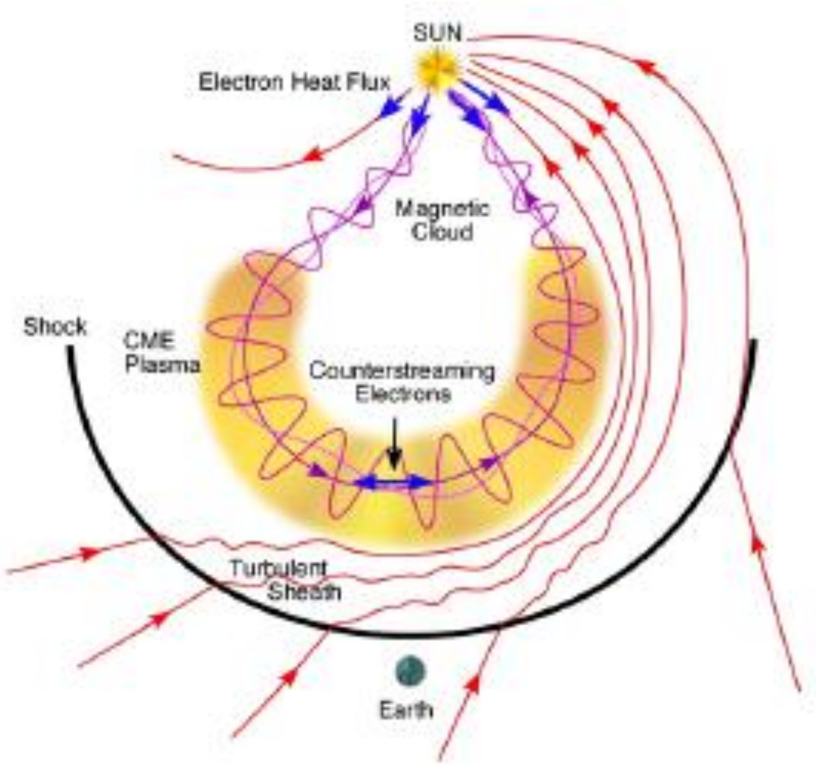
Stress develops in the corona (feet flows, ..)



Forbes et al. 2006

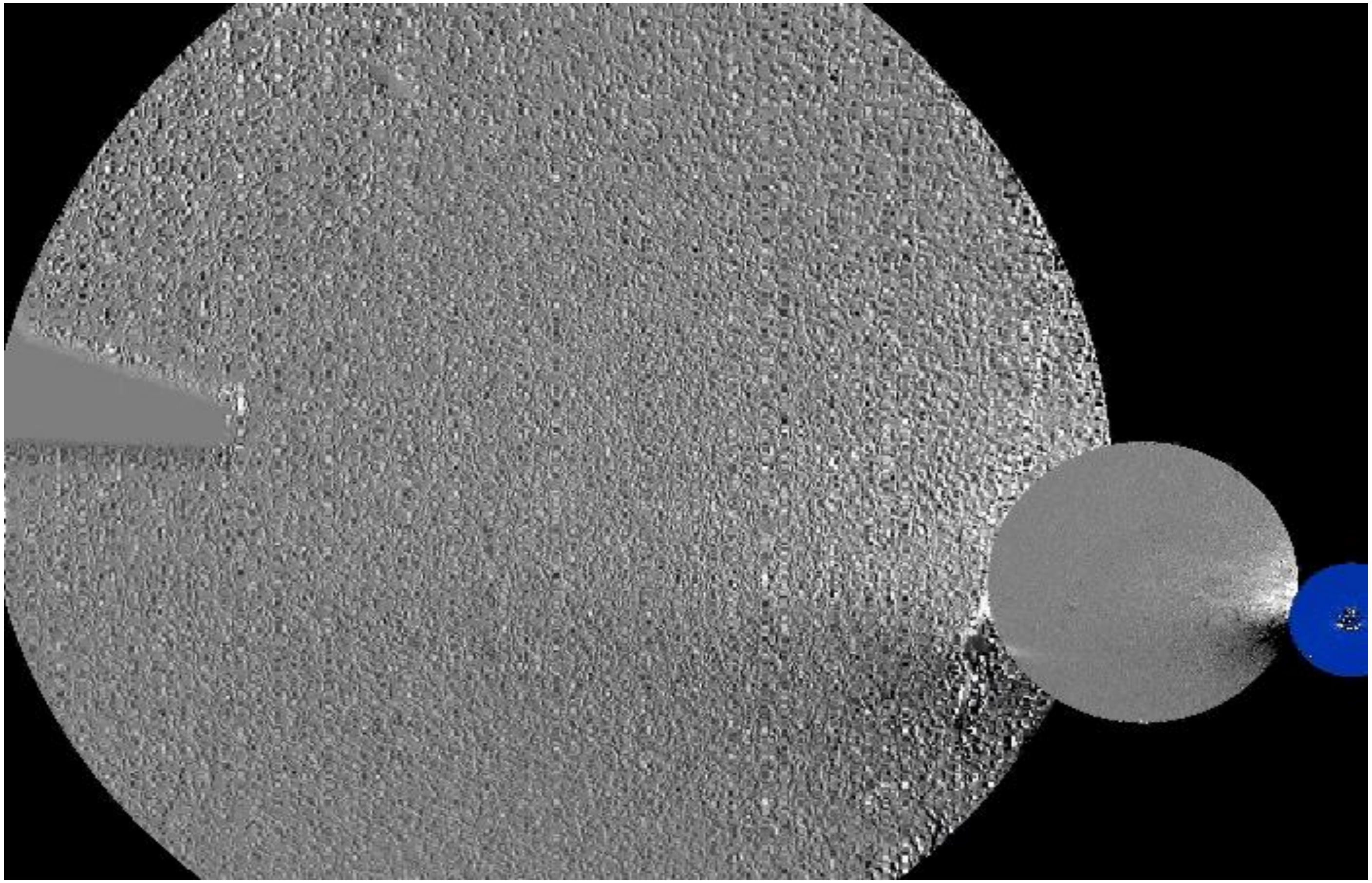
ICME and upstream shock

Cartoon indicating magnetic field, plasma and solar wind suprathermal electron flows



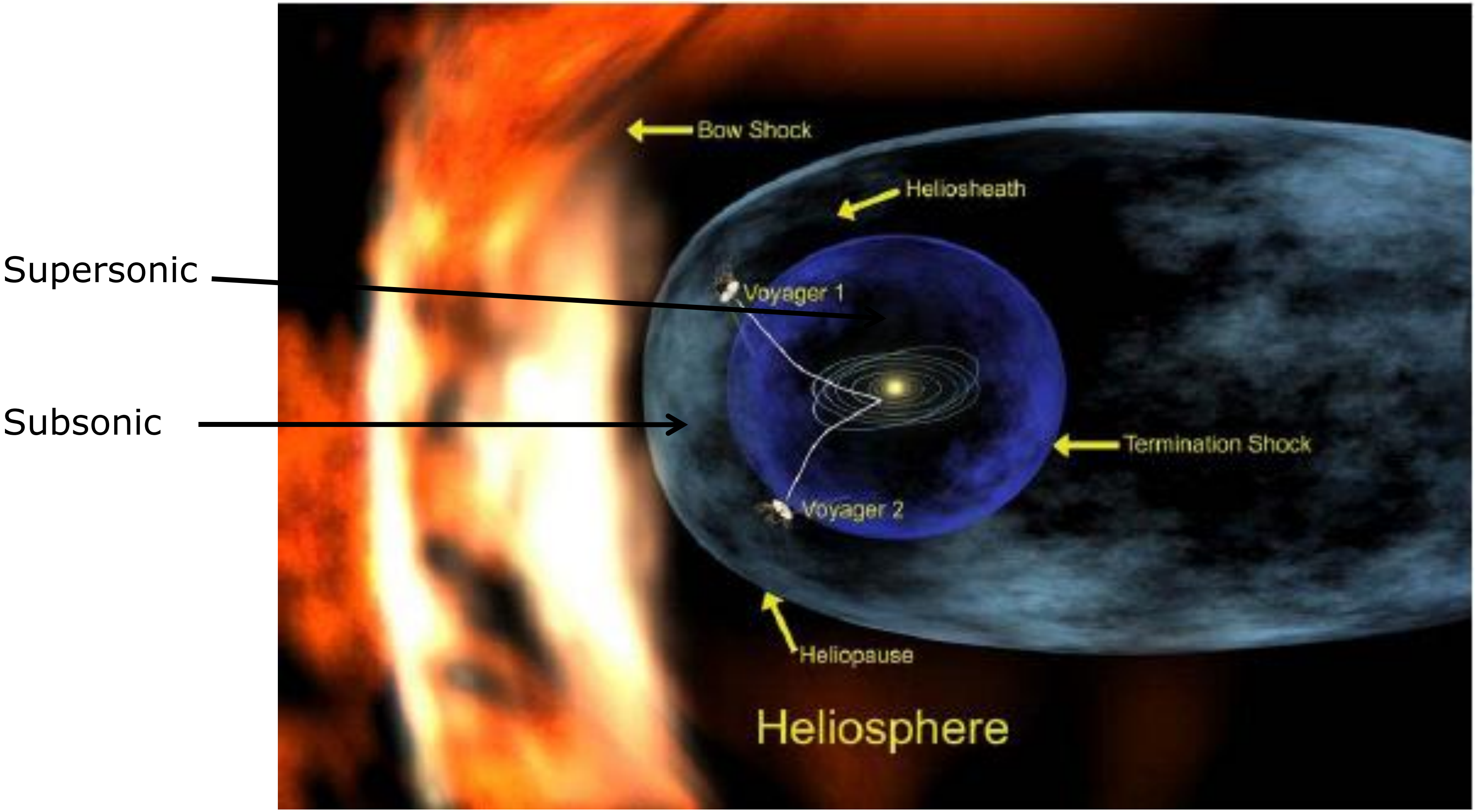
Zurbuchen & Richardson 2006

Further away … to the Earth



MOVIE of a CME (STEREO) reaching the Earth

Further out : the heliosphere



The Heliosphere (1)

- Elongated bubble with « radius » $\approx$ 100 AU (can be deduced from the equality of SW and ISM pressures)

- Bound by the interstellar medium of the Local Cloud (« the low-pressure exit of the SW nozzle » NMV)
  - $n_H \approx 0.2\ cm^{-3}$
  - V = 26 km/s
  - B = 2 -3 μG

- Importance of charge exchange (« hydrogen walls », anomalous cosmic rays, X-ray emission)

The Heliosphere (2)

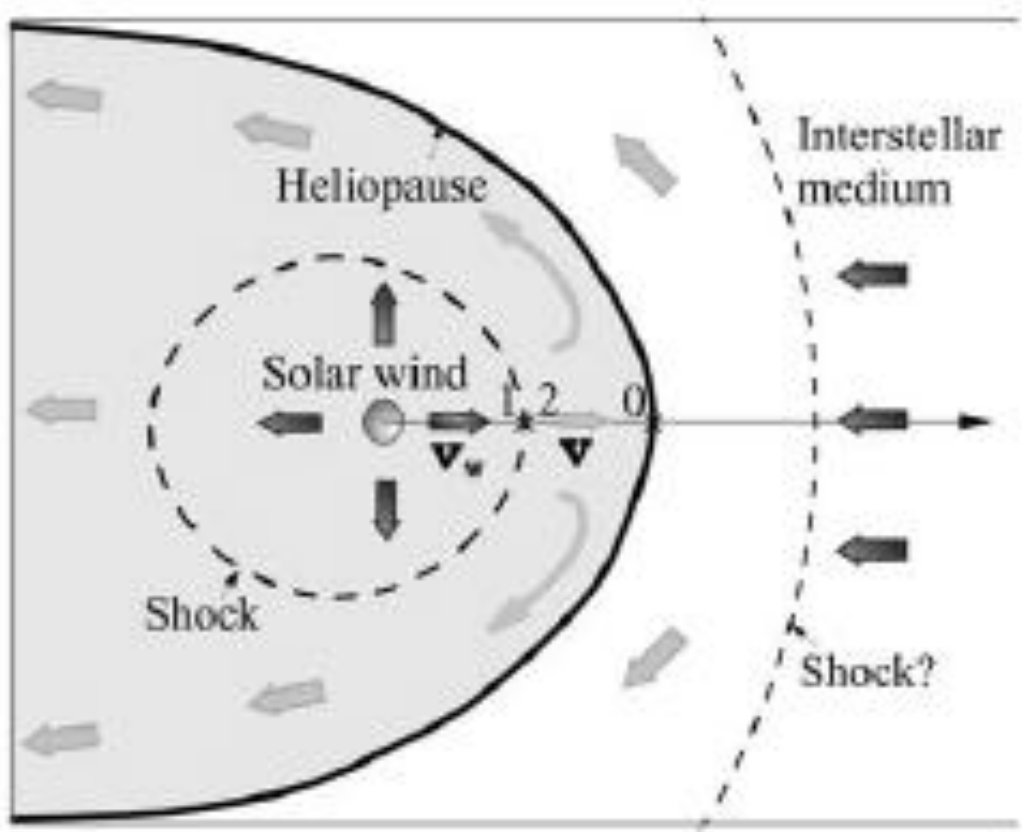
- Energy density of the interstellar medium

Bulk plasma motion, $\rho_I v_I^2/2$, with $\rho_I \simeq n_I m_p$ (J m^{-3})	Proton + electron thermal motion, $3n_I k_B T_I$ (J m^{-3})	Magnetic field, $B_I^2/2\mu_0$ (J m^{-3})
$(2-4)\times 10^{-14}$	$(1-2)\times 10^{-14}$	$(2-4)\times 10^{-14}$

N. Meyer-Vernet 2007

- Total energy density ≈ Cosmic Rays

The Heliosphere (3)



N. Meyer-Vernet 2007

Astrospheres

2 bow shocks close to young stars in Orion Nebula

Size ≈ 10^4 * heliosphere
Mass flux ≈ 10^8 * helio

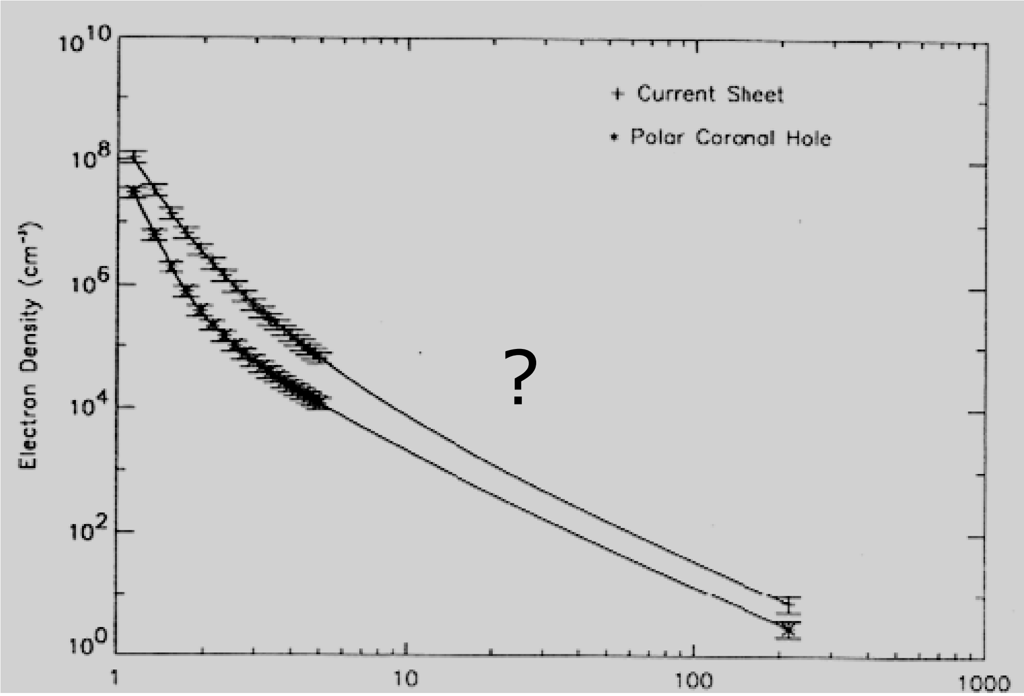
Prospects (1)

The need to fill the **gap** between a few R and 1 AU

To go **closer** to the Sun : Solar Orbiter, Solar Probe$^+$

To go **away** from the ecliptic : Solar Orbiter, Solar C (A)

To **measure** the coronal magnetic field : Cosmic Vision proposals

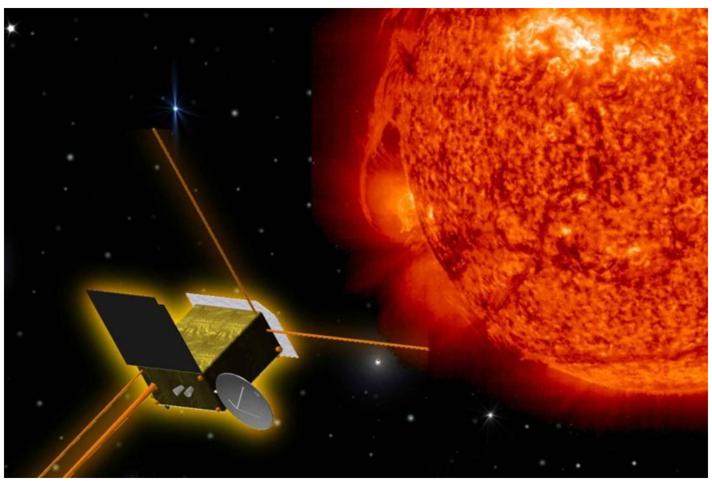


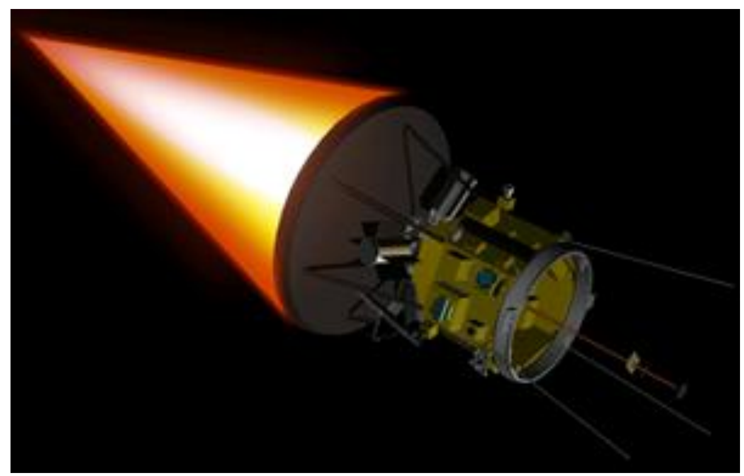
Guhathakurta and Sittler, 1999, Ap.J., 523, 812

Prospects (2)

And also understand better the **sources** in the low corona, especially in the complex chromosphere

Which requires better **diagnostic** tools and observations for B, non-maxwellian distributions, ionization degree, flows, …





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