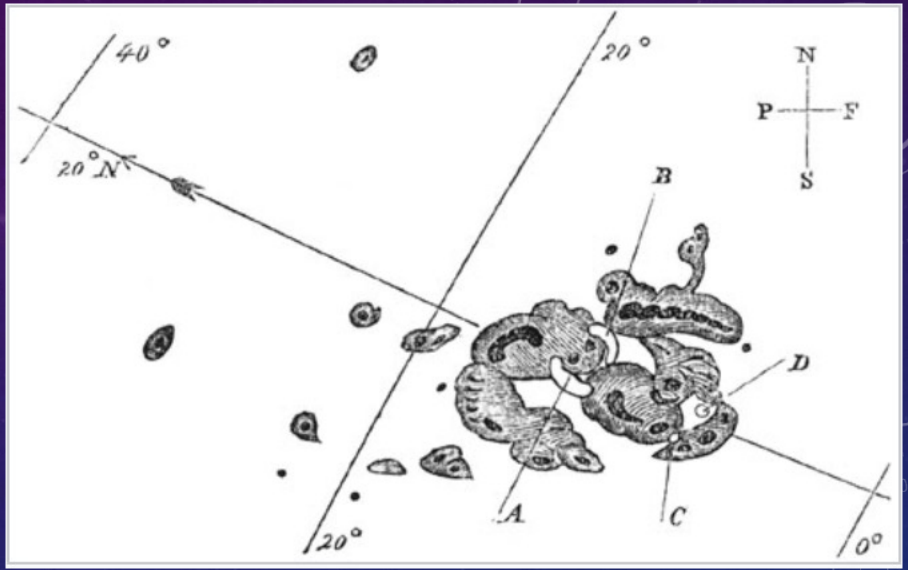
THE SOLAR WIND

MASTER 2 PPF – E3 SPACE PLASMAS
2025-2026

ARNAUD ZASLAVSKY

arnaud.zaslavsky@sorbonne-universite.fr
arnaud.zaslavsky@obspm.fr

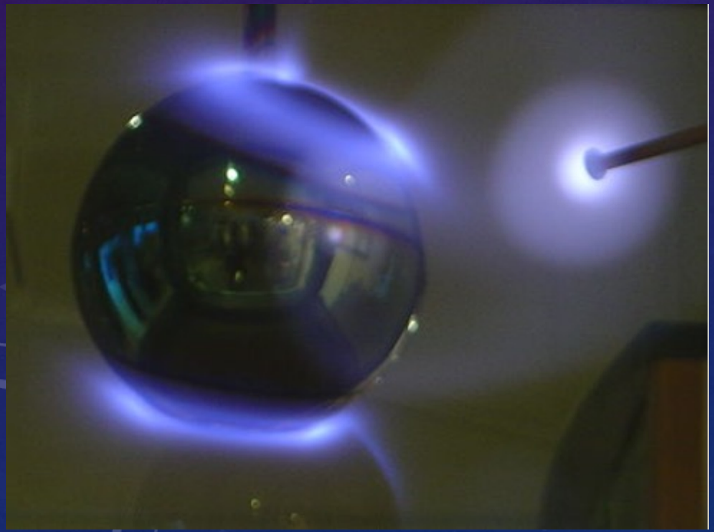
FIRST IDEAS



1859 : **Richard Carrington** drew spots on a projected image of the Sun and observed a sharp increase in luminosity: a flare.

17 hours (very short time, usually $\sim 60\ h$) later, very strong auroral phenomenas observed (possible to read newspaper at midnight in Panama)

Carrington observations constitute the first direct observationnal link between solar and atmspheric events.

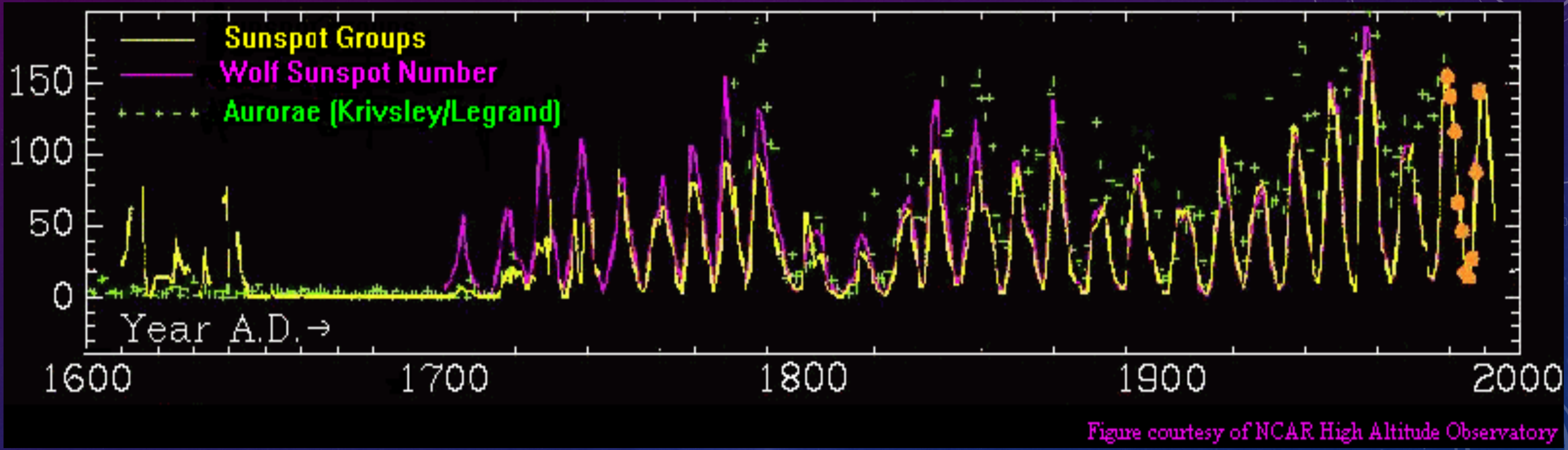


1900 : **Kristian Birkeland** proposes that

"The Earth is permanently bombarded by electric corpuscles emitted by the Sun" (discovery of the electron in 1897)

Terrella experiment (electron canon + magnet in a vaccuum chamber) illustrates the mechanisms of auroras

A BRIEF HISTORY: THE FIRST IDEAS

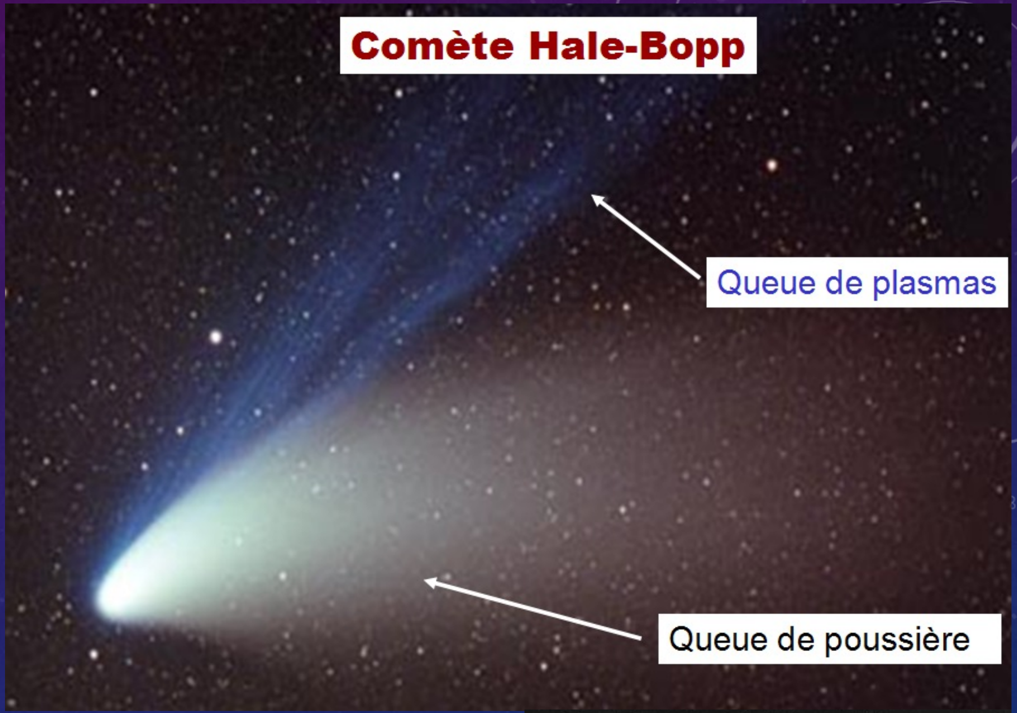


Sunspot number vs auroral activity

PLASMA PHYSICS : THE 50'S

Sydney Chapman

- Because the corona is very hot and conductive, the heat from the Sun should be cat great distances.
- The solar atmosphere should extend to very large distances
- Earth and other bodies travel through the Sun's static corona



Ludwig Biermann: comet observation suggests that the plasma tail is due to the solar wind, measuring "blobs" flowing at speeds of around 100 km/s.

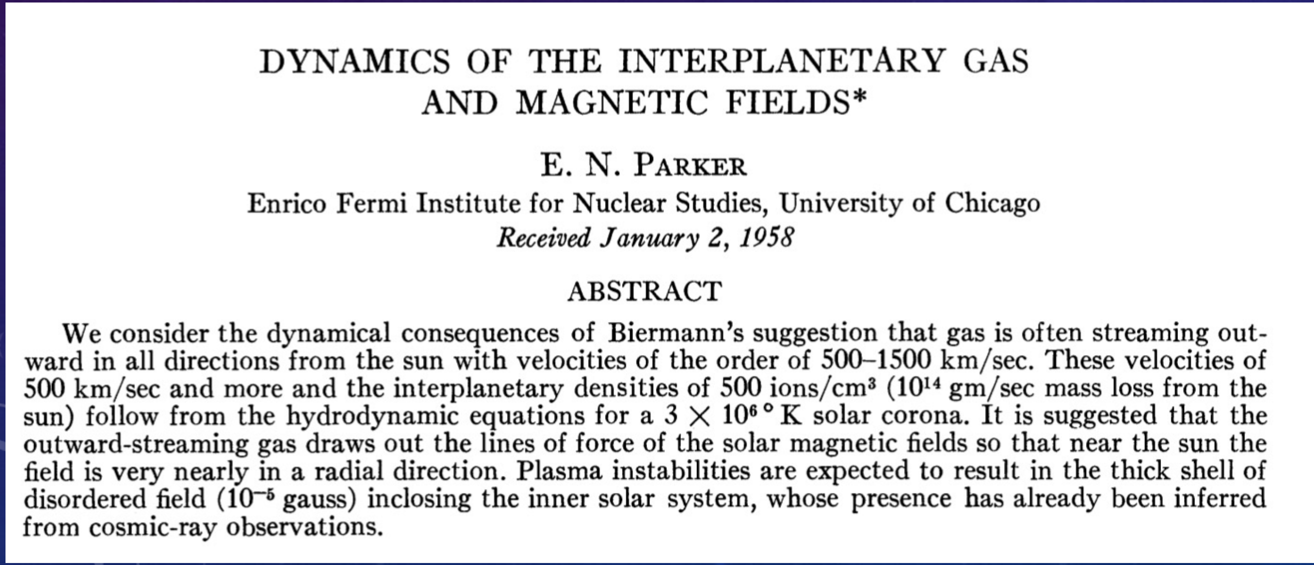
BEGINING OF SPACE ERA

Луна 2 impacts the moon on 13 September of 1959.

On the way, first in-situ measurements of a supersonic ion flow in the interplanetary medium.

Mariner 2 (1962) on the way to Venus provides the first directional measurements of the ion flux.

Confirms the theoretical prediction of Eugene Parker, 1958



DYNAMICS OF THE INTERPLANETARY GAS AND MAGNETIC FIELDS*

E. N. Parker
Enrico Fermi Institute for Nuclear Studies, University of Chicago

Received January 2, 1958

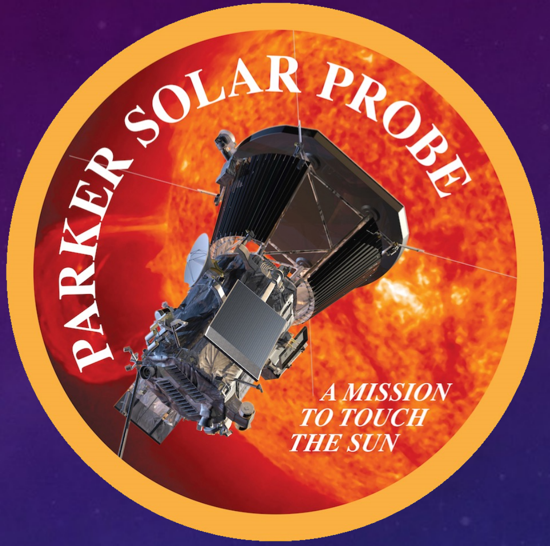
ABSTRACT

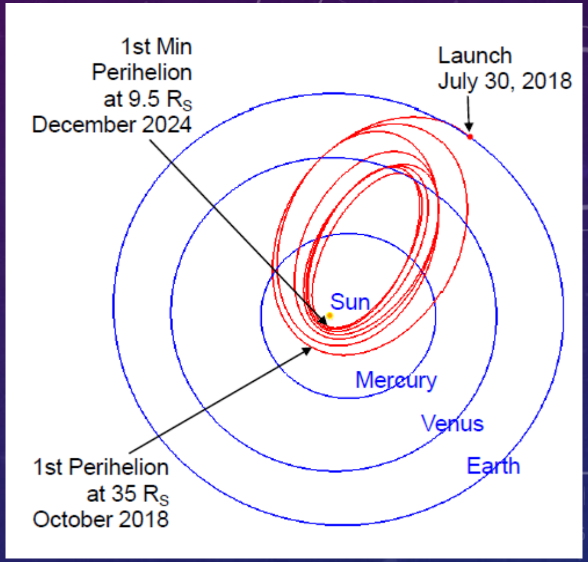
We consider the dynamical consequences of Biermann's suggestion that gas is often streaming outward in all directions from the sun with velocities of the order of 500–1500 km/sec. These velocities of 500 km/sec and more and the interplanetary densities of 500 ions/cm^3 (10^{14} gm/sec mass loss from the sun) follow from the hydrodynamic equations for a 3×10^6 °K solar corona. It is suggested that the outward-streaming gas draws out the lines of force of the solar magnetic fields so that near the sun the field is very nearly in a radial direction. Plasma instabilities are expected to result in the thick shell of disordered field (10^{-5} gauss) inclosing the inner solar system, whose presence has already been inferred from cosmic-ray observations.

Mariner 2 engineering model

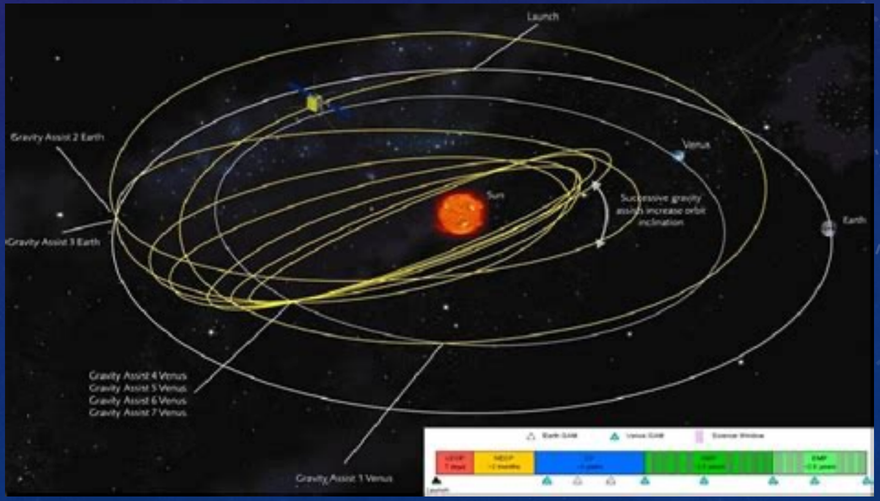
TODAY…

- Numerous probes have been launched, and a wealth of data has been collected.
- In-situ observations of interplanetary plasma in great detail
- Multi-wavelength observations of the solar corona

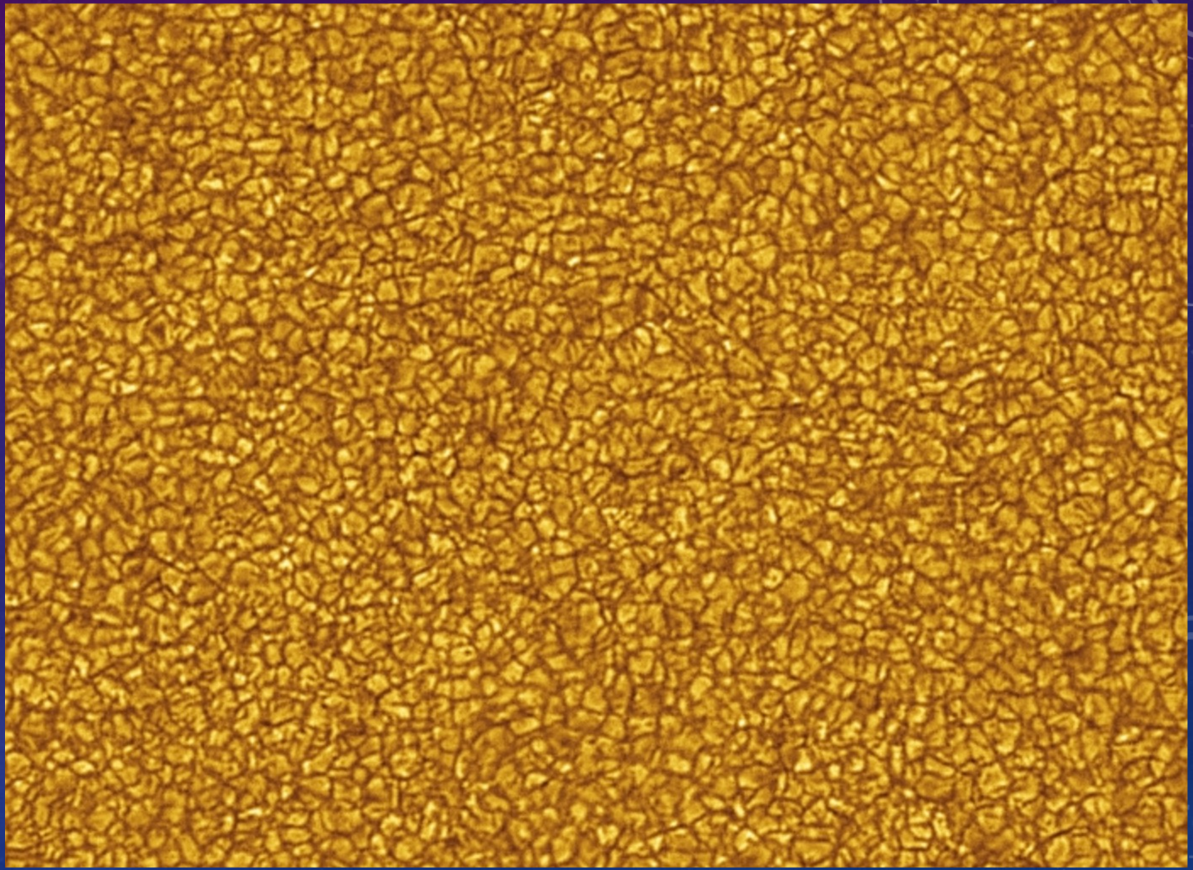




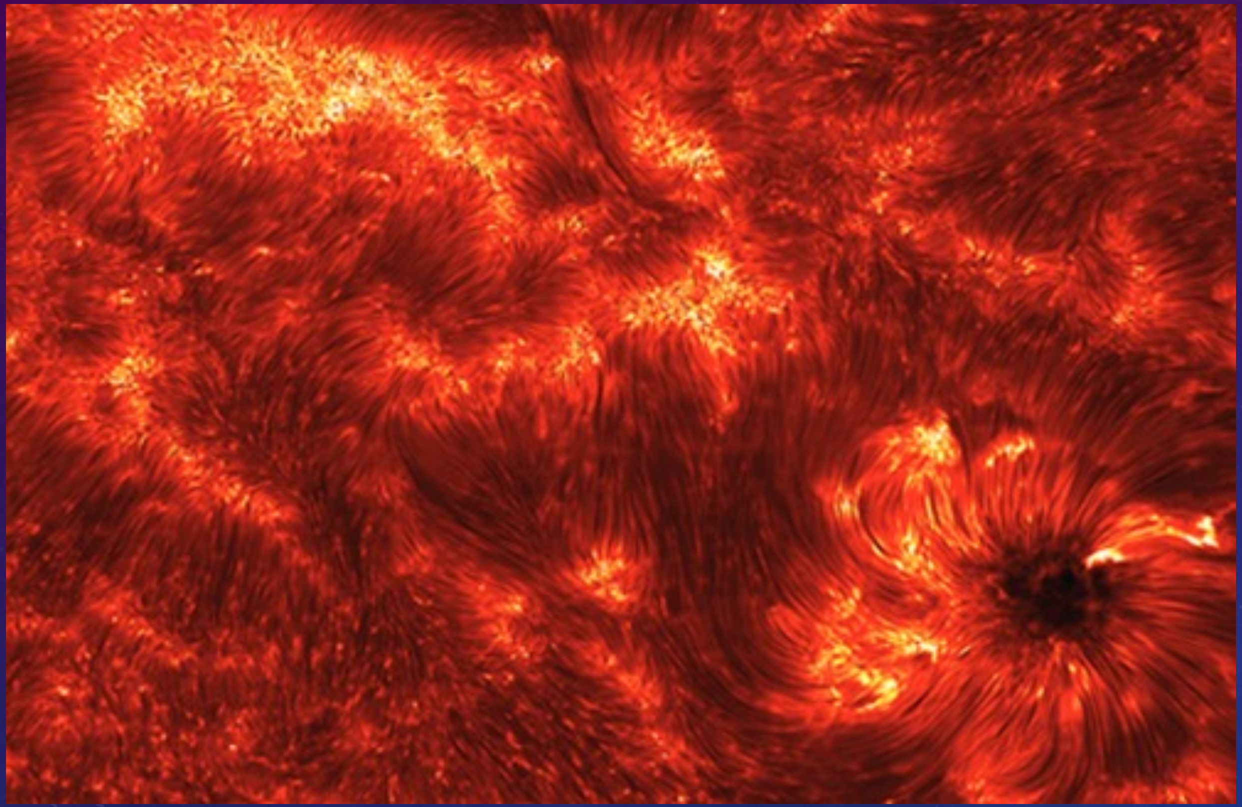
- Parker Solar Probe (NASA, launch Aug. 2018)
- Sonde Solar Orbiter (ESA, launch Feb. 2020)



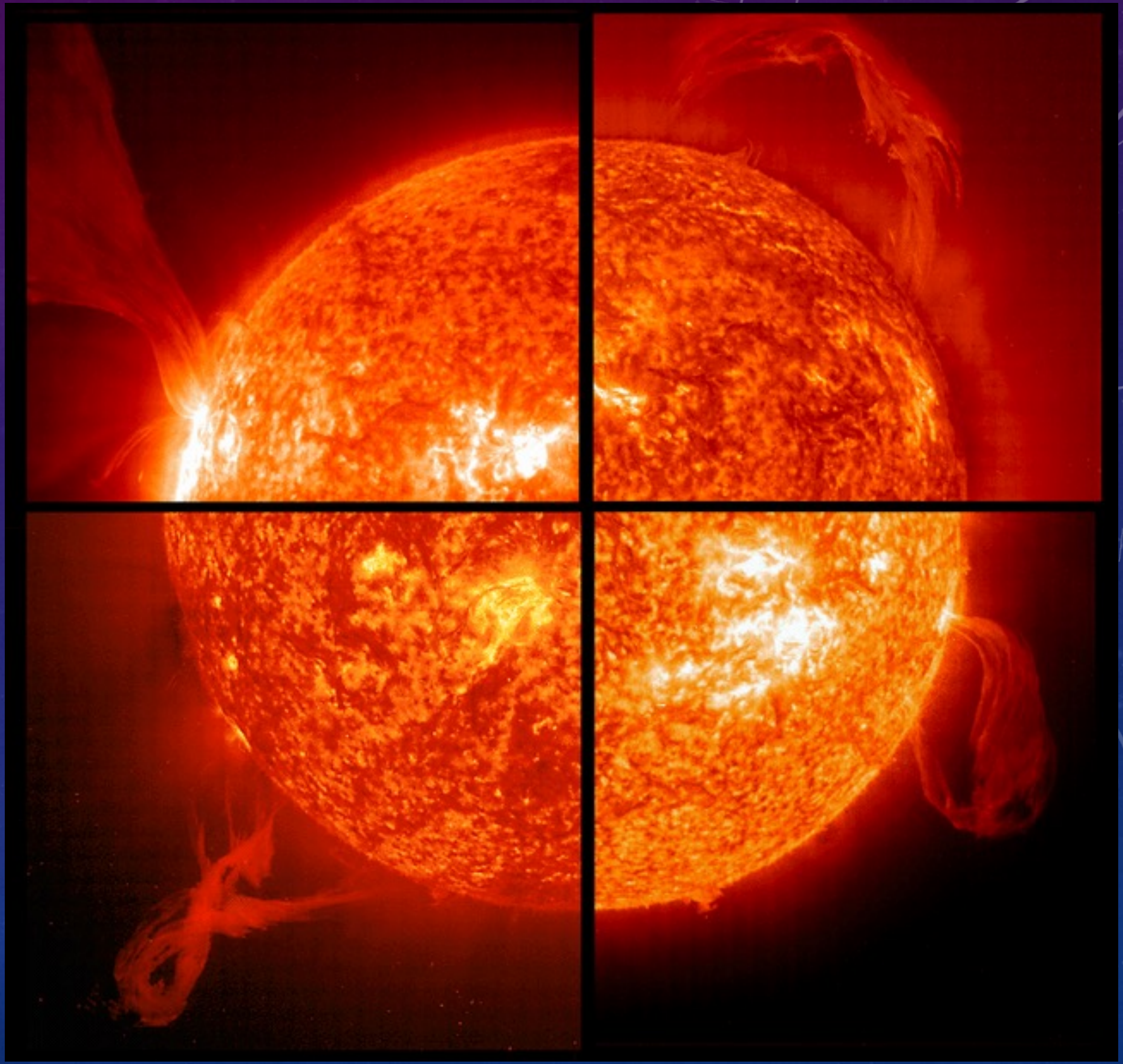
THE PHOTOSPHERE



THE CHROMOSPHERE

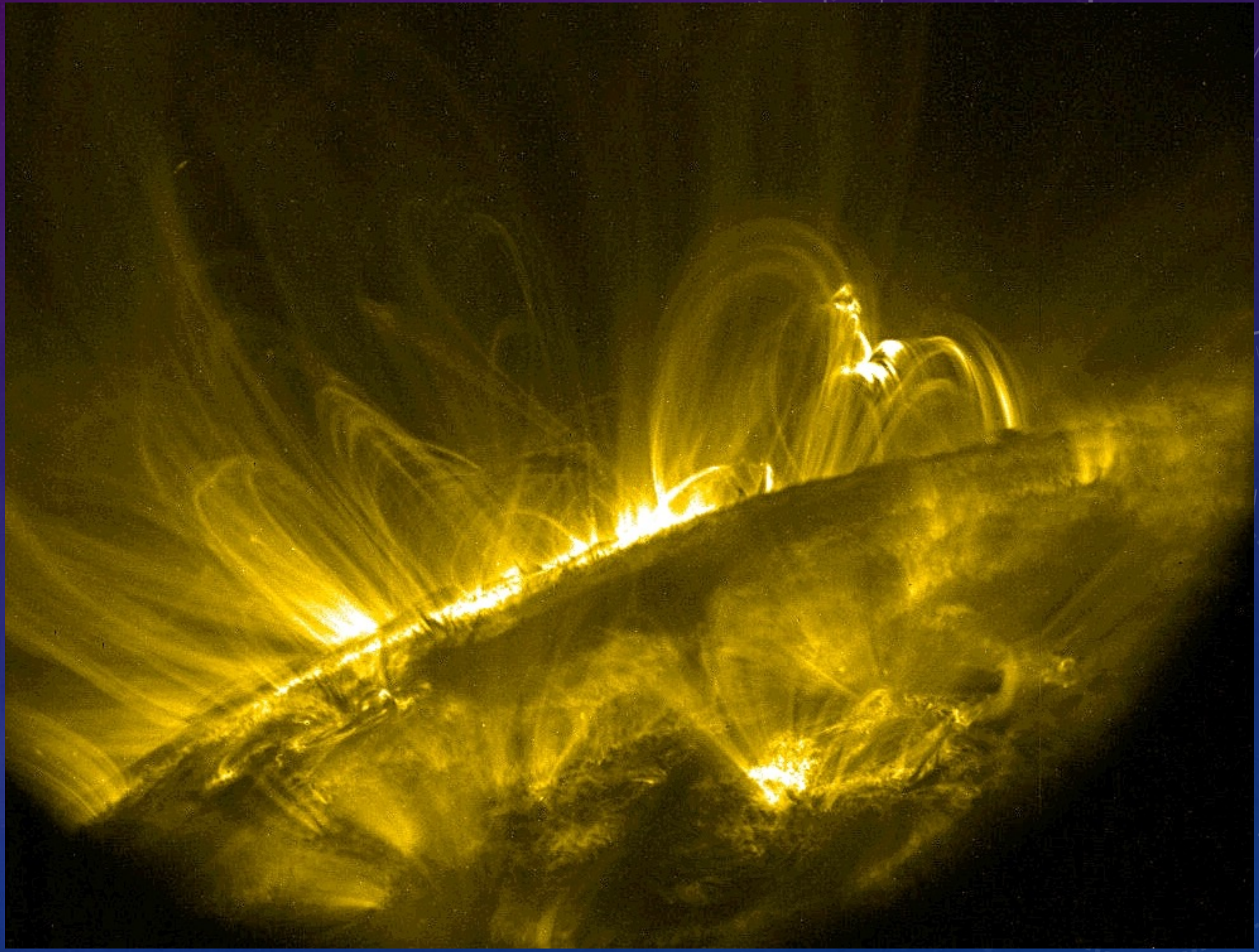


SDO, He II, 30.4 nm

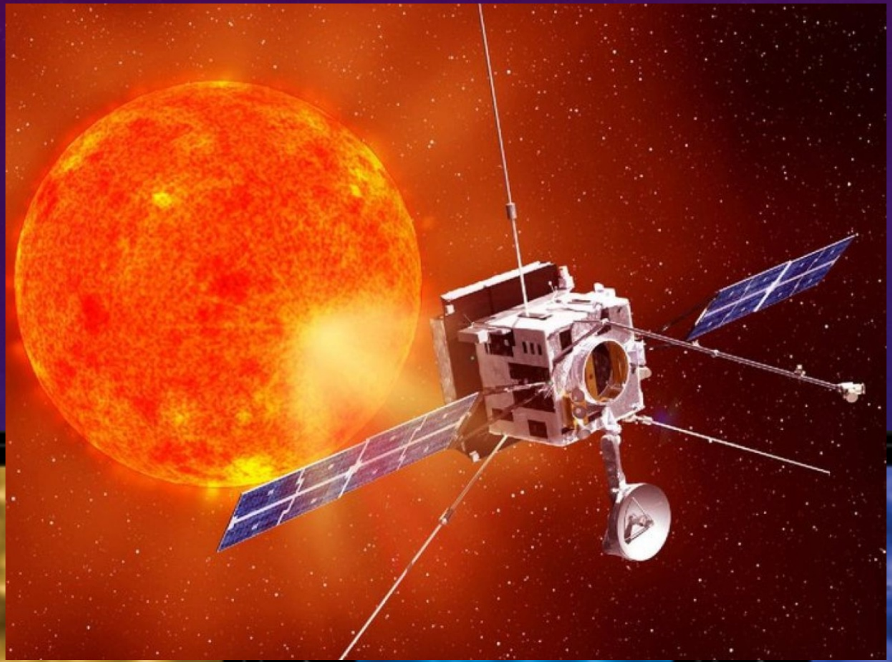


SOHO/EIT

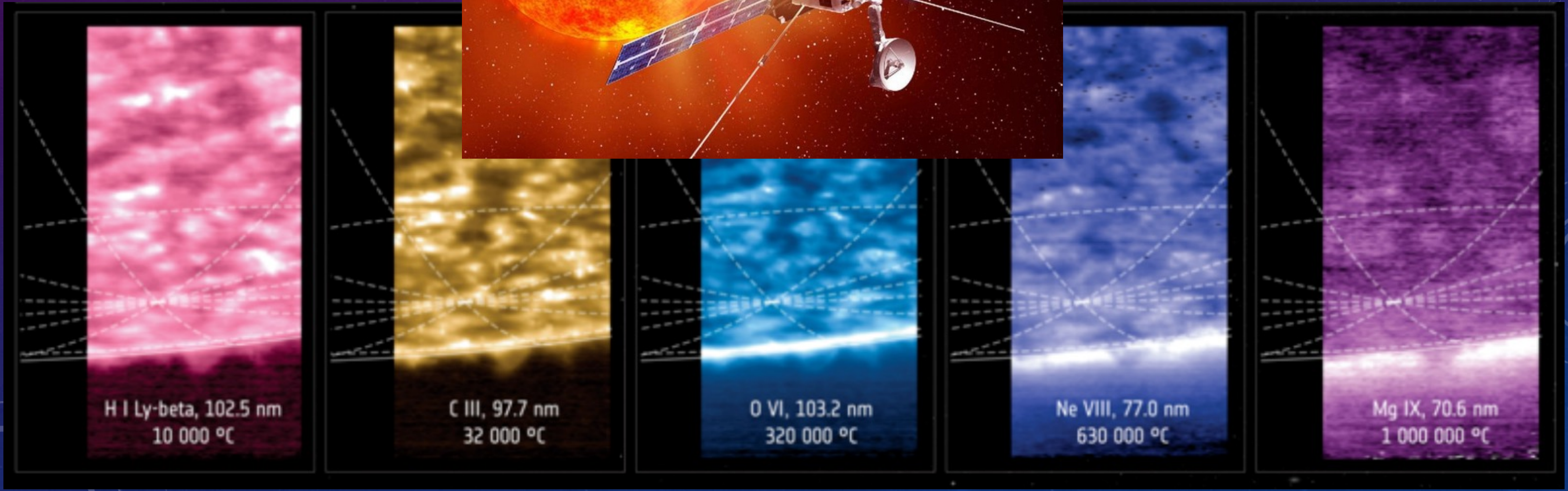
THE CORONA



STRUCTURE OF SOLAR ATMOSPHERE: THE TRANSITION REGION

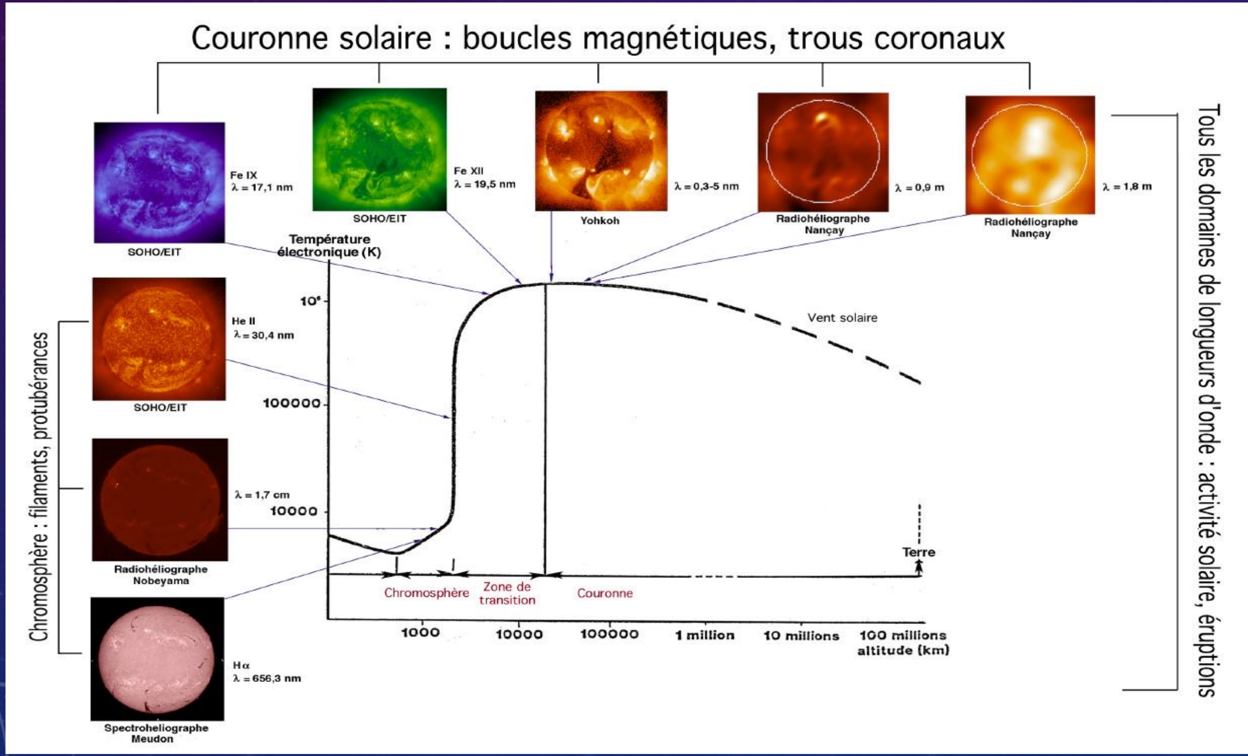


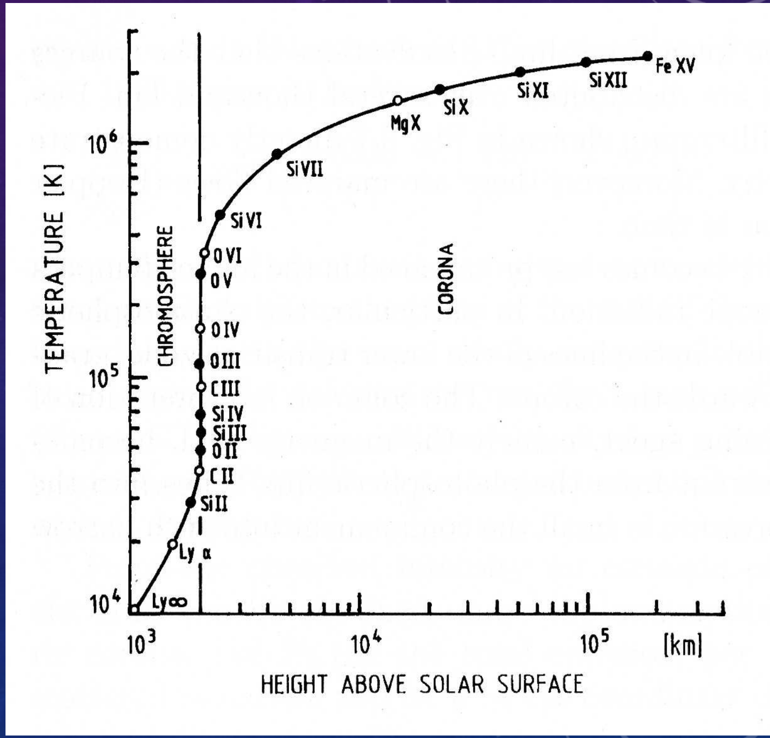
Solar Orbiter, EUV, march 2025



STRUCTURE OF SOLAR ATMOSPHERE: THE TRANSITION REGION

- Thin layer: thickness still poorly known but < 100km
- Extreme temperature gradient: rise from $\sim 10^4$ K to $\sim 10^6$ K
- Density: 10^9 to 10^{10} atoms/cm3 (5.10^{-15} to 5.10^{-14} g/cm3)
- Abrupt transition between chromospheric and coronal physical conditions
- Abrupt transition in the appearance of the Sun (emissive regions)





Temperature profile and emission lines typical of TR.

THERMAL INSTABILITY IN THE TRANSITION REGION

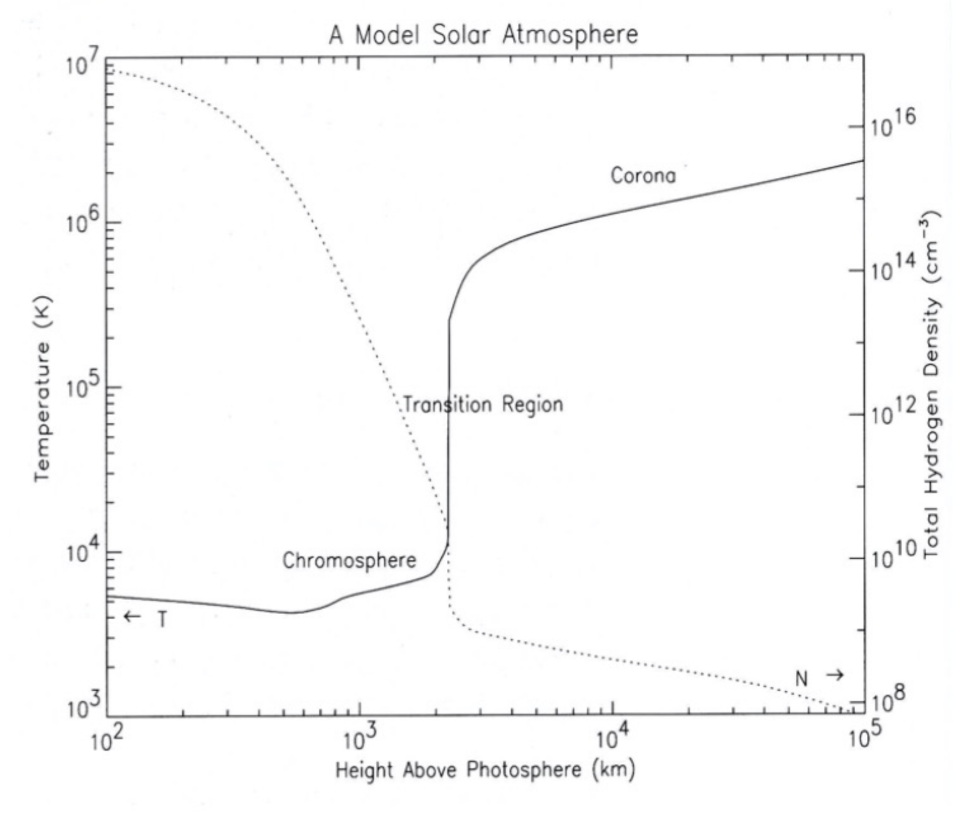
Steady-state heat balance: $\mathrm{div}\ j_c = Q_c - Q_{ray}$

Jc: Heat flux density
Qc: Heating term
Qray: Radiative cooling term

Jc is linked to the temperature gradient by a Fourier type law $j_c = -\kappa \nabla T$

Where the thermal conductivity (to be discussed) is given by

$$\kappa = K_0 T^{5/2}, \qquad \text{avec } K_0 \simeq 5,6 \times 10^{-12}\ \mathrm{W.m^{-1}K^{-7/2}}$$



Div jc is weak in chromospheric conditions (cold)
Div jc is strong in coronal conditions

HEAT BALANCE IN THE CHROMOSPHERE

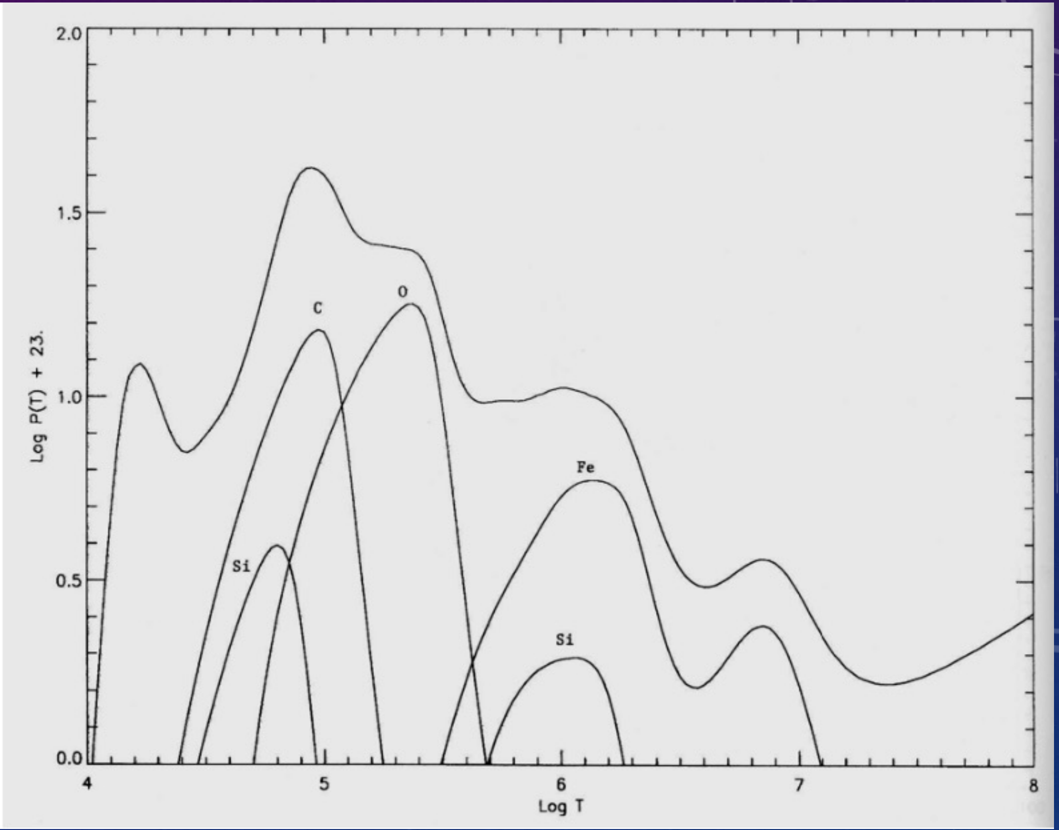
Neglecting the conduction term, we see that the temperature is determined by the local balance between heating and radiative cooling.

$$\Lambda(T) \simeq \frac{Q_c}{n_e^2}$$

Density decreases with height (stratification by solar gravity): the RH term increases (more or less) exponentially.
On the other hand, the efficiency of radiative cooling decreases from a temperature of about 10^5K.

Below a critical density, radiative losses can no longer compensate for heating.

$$n_e \simeq \left(\frac{Q_c}{\Lambda_{max}}\right)^{1/2} \sim \left(\frac{Q_c}{1\ \mathrm{W.m^{-3}}}\right)^{1/2} 10^{17}\ \mathrm{m^{-3}}$$



STABILISATION BY CONDUCTION IN THE CORONA

The temperature rises sharply from the height at which the critical density is reached.

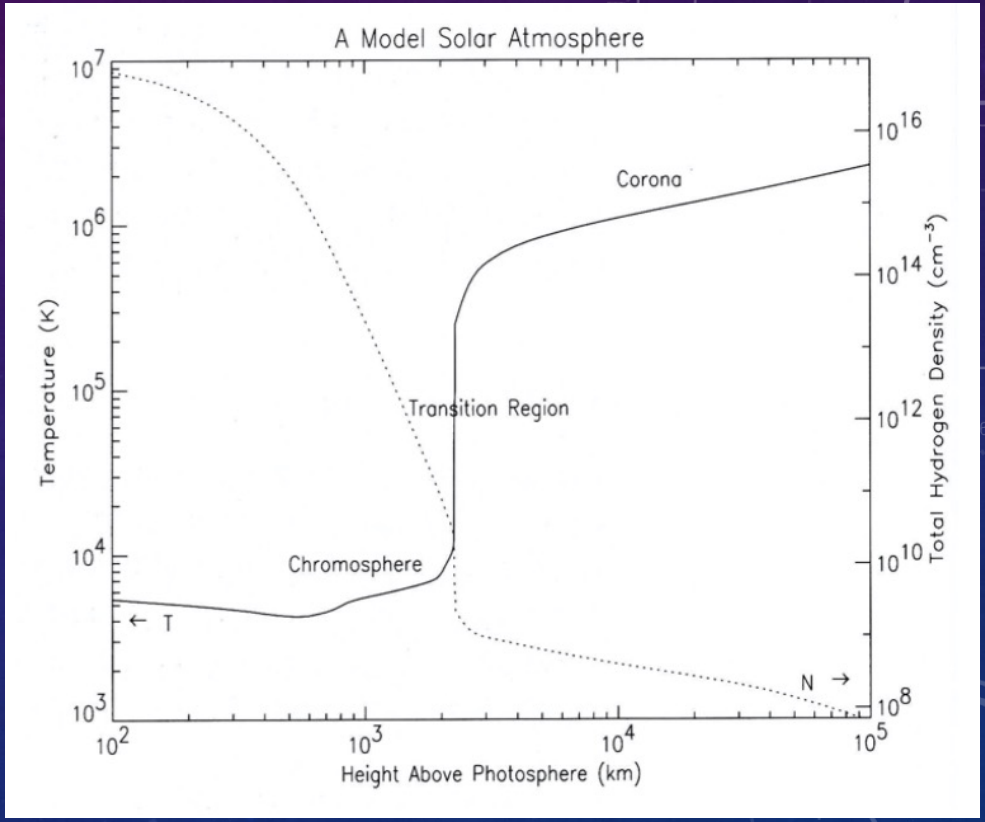
This instability stabilises at a temperature where conduction becomes important (conductivity is a sensitive function of T).

Approximation: radiative cooling at the top of the RT is totally neglected.

The value of the coronal temperature is :

$$T_{couronne} \simeq \left(\frac{L^2}{K_0} Q\right)^{2/7} \sim \left(\frac{Q_c}{1 \text{ W.m}^{-3}}\right)^{2/7} 10^6 \text{ K}$$

That's about the million-degree temperature observed if Qc is of the order of Watt per cubic metre.



(Very) rudimentary model for Q = 1W/m3:
n_crit = 10^{11} cm-3
T = 10^6 K

THERMAL STABILITY OF THE TR

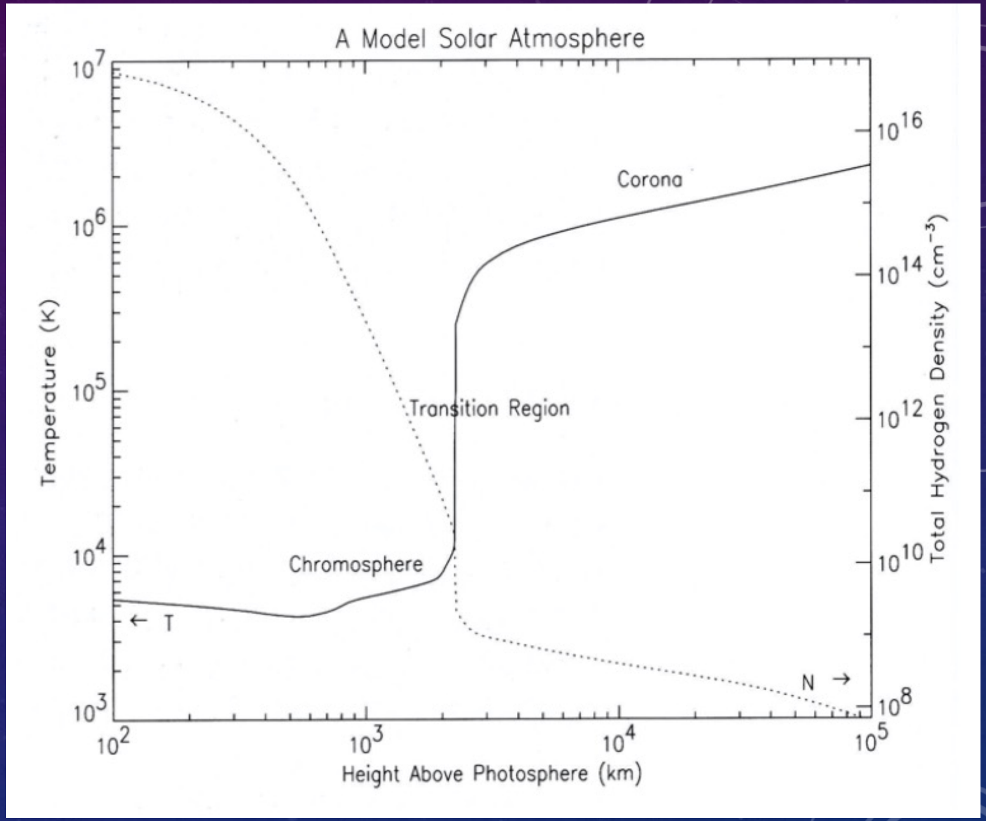
Heat flux through the transition region :
$\Phi_{\mathrm{th}} = S(r)j(r) \sim 4\pi R^2 J_{TR}$

j : heat flux density
S(r) : section of the flux tube

Assuming j is given by a Fourier law : $j = -\kappa\nabla T \sim \frac{-\kappa T_{cor}}{\Delta h_{TR}}$

The thermal power flowing from the corona to the chromosphere
Is of the order of

$\Phi_{\mathrm{th}} \sim \frac{4\pi R^2 \kappa T_{cor}}{\Delta h_{TR}}$ Cooling timescale : $\tau \sim \frac{C_v \Delta h_{TR}}{4\pi R^2 \kappa}$

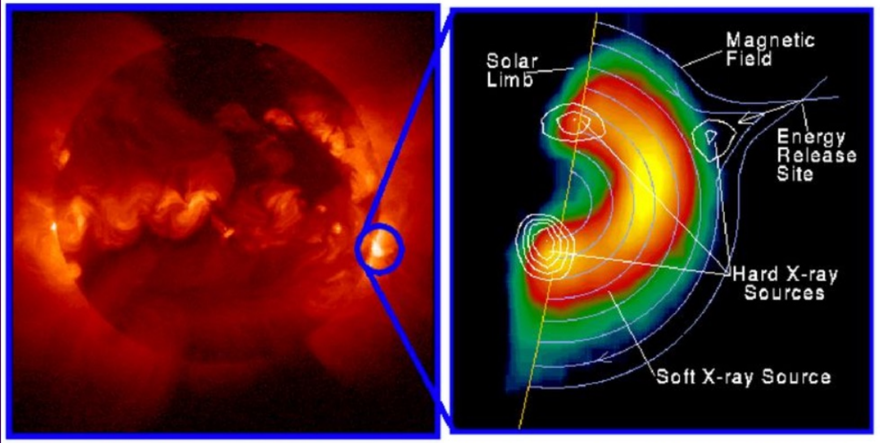


Strong uncertainties on the value of the thermal conductivity. Assuming a thermal conductivity in a coulomb-collisional medium (Spitzer), one has $\kappa = K_0 T^{5/2}$ with $K_0 \sim 5.10^{-12} W.m^{-1}.K^{-7/2}$.

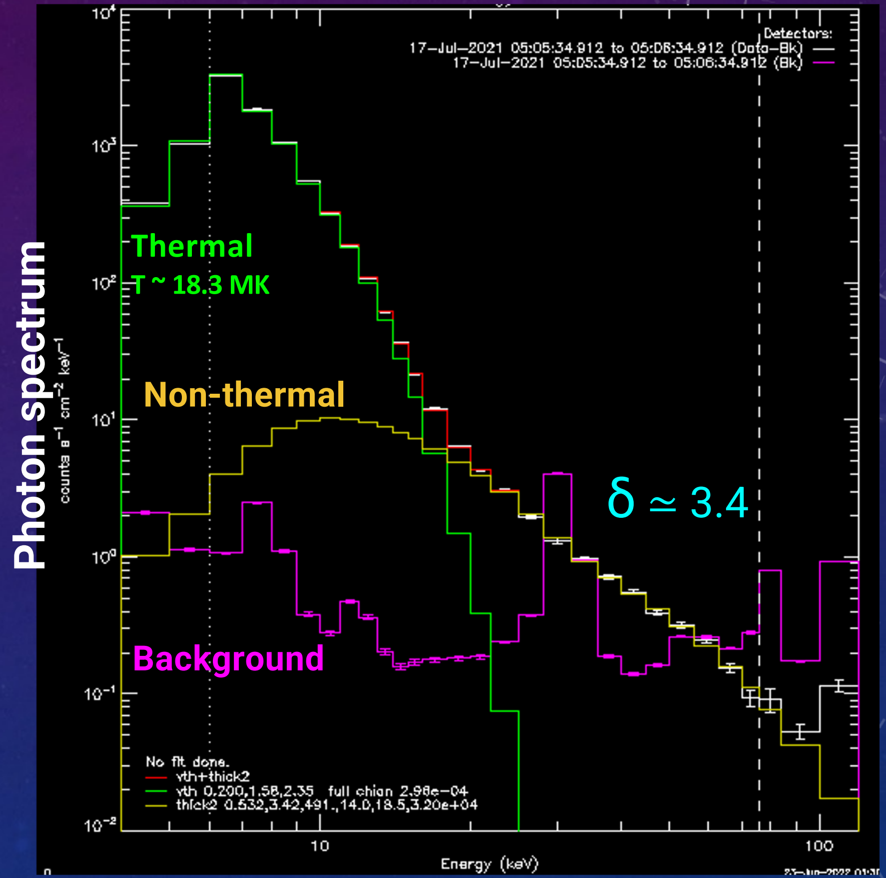
$\Rightarrow$ An amount of heat $Q \sim \Phi_{th} \sim \frac{4\pi R^2 K_0 T_{cor}^{7/2}}{\Delta h_{TR}}$ needs to be deposited per unit time to sustain the coronal temperature

$\Rightarrow$ For typical solar parameters, and per unit volume, $Q[W.m^{-3}] \sim T_{cor}[MK]^{7/2}$

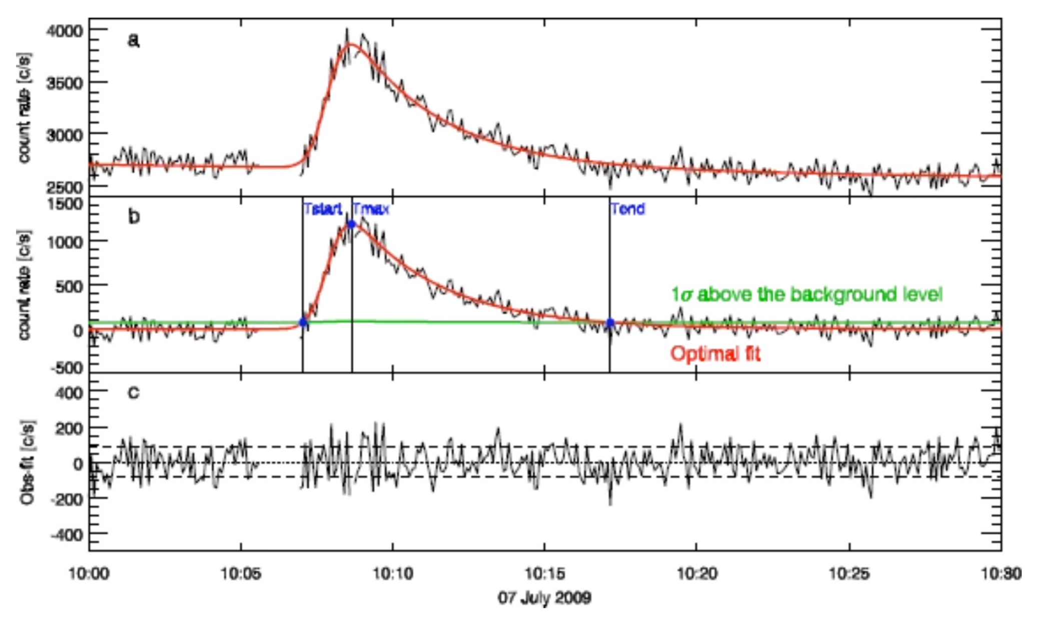
THE COOLING OF CORONAL LOOPS



Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.



X-Ray spectroscopy with STIX



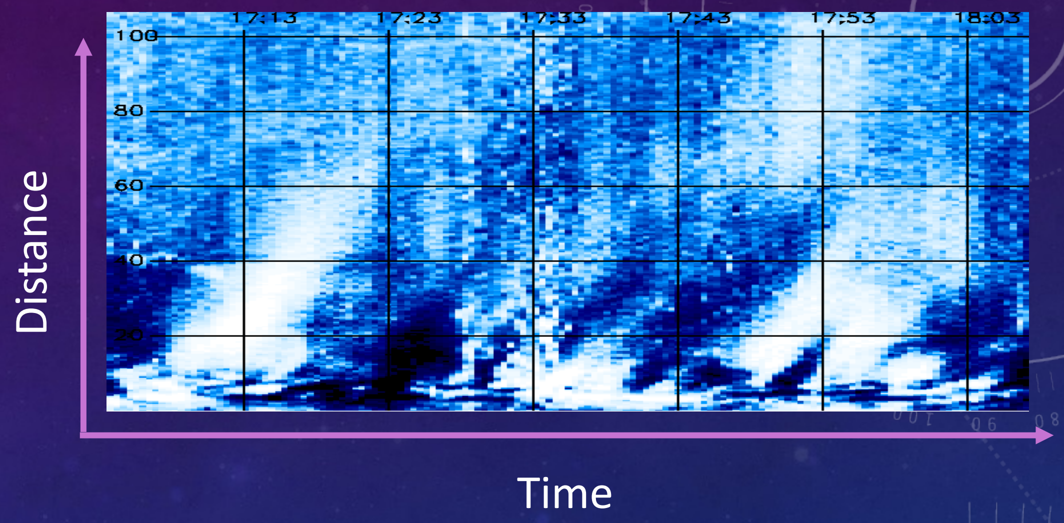
X-ray light curves ($T \sim 2{\times}10^{7}$ K)

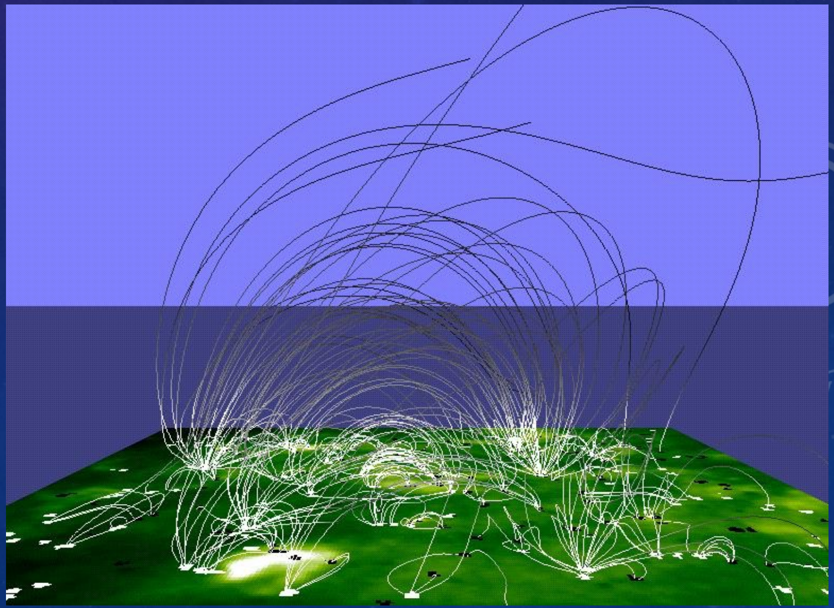
CORONAL HEATING : WHERE IS THE ENERGY COMING FROM ?

Two main classes of mechanisms are considered :

- AC heating : hydro-magnetic waves are excited by the convective motions at the photospheric level and propagate through the solar atmosphere, depositing energy.
- DC heating : Large electric field are produced at current layers. Ohmic dissipation here produces reconnection and Joule heating of the plasma.
- In both cases, the energy source is the mechanical energy stored in the photospheric convection motions. The magnetic field (and potentially pressure field) is the vector through which this energy is carried away from the photosphere and dissipated in the plasma.

Slow magneto-actoustic mode (*Robbrecht et al. 1999, 2001)*





MAGNETIC RECONNECTION

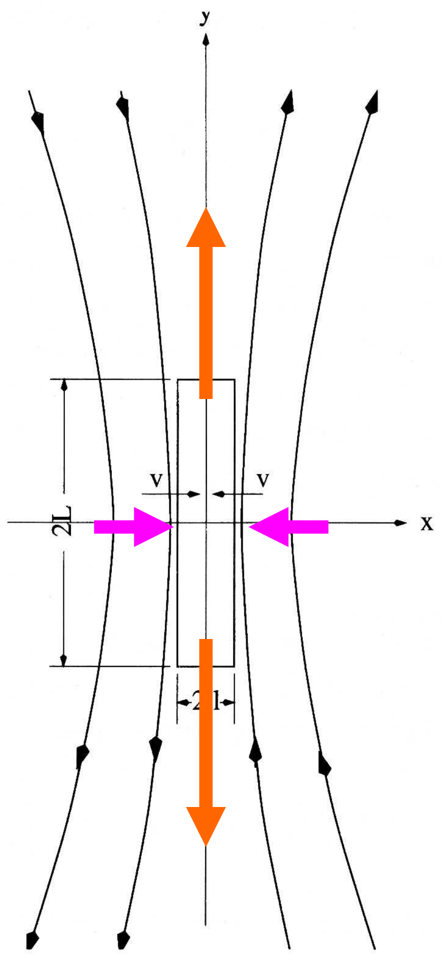
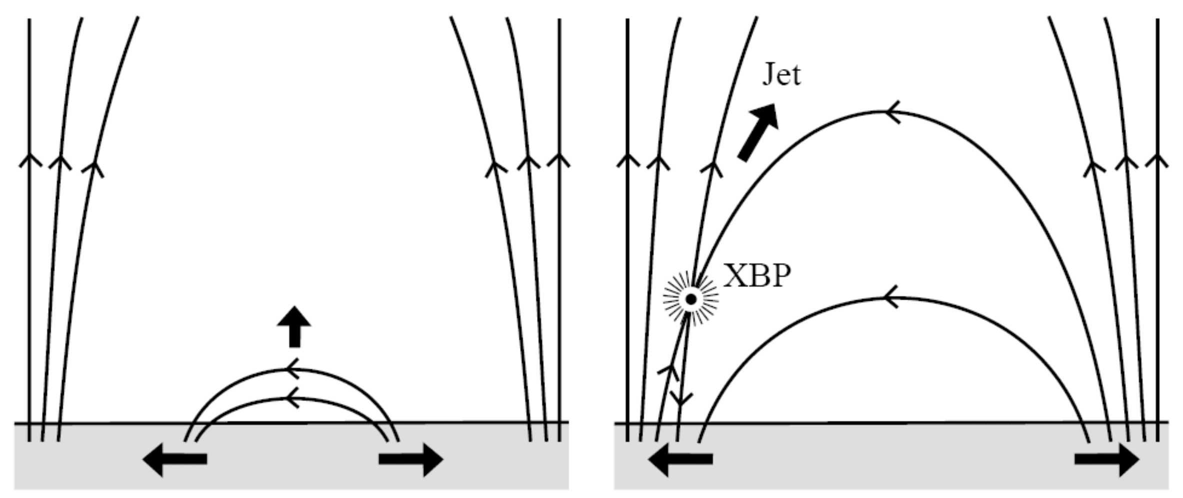


Figure 9.4 Magnetic reconnection at a neutral sheet; **B** reverses direction along the *y*-axis leading to a current j_z in the *z*-direction. Inflow of magnetic field at velocity *v* is balanced by fluid outflow along the *x*-direction. Diagram on right shows magnetic field configuration in the Petschek geometry, including standing waves.

The random motion of the feet of magnetic loops, driven by photospheric convection, produce random and intricated magnetic field configurations upward, with probabilities to produce X points and reconnection.



EXPANSION OF THE HOT SOLAR CORONA

The hot corona expands into the interplanetary space, as implied by conservation of mass (steady state assumed),

$$\nabla \cdot (n\boldsymbol{u}) = 0$$

$$n(r)u(r)S(r) = const.$$

The conservation of momentum for electrons and protons

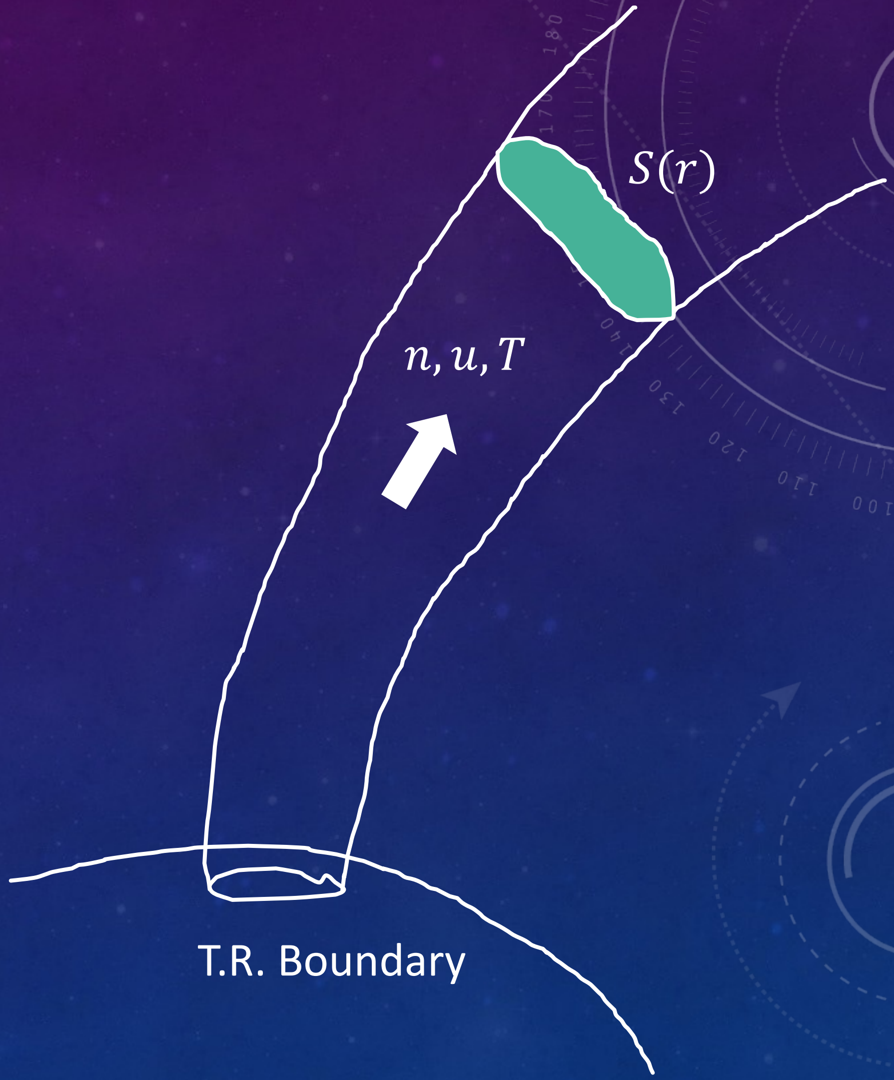
$$n_p m_p u_p \partial_r u_p = -\partial_r p_p + e n_p E - n_p m_p GM/r^2$$

$$n_e m_e u_e \partial_r u_e = -\partial_r p_e - e n_e E - n_e m_e GM/r^2$$

Simplifies after assuming quasi-neutrality and zero current into

$$n m_p u \partial_r u = -\partial_r n k (T_p + T_e) - n m_p GM/r^2$$

Finally, we assume, following Parker, an isothermal expansion



EXPANSION OF THE HOT SOLAR CORONNA

We obtain the equation for the isothermal flow

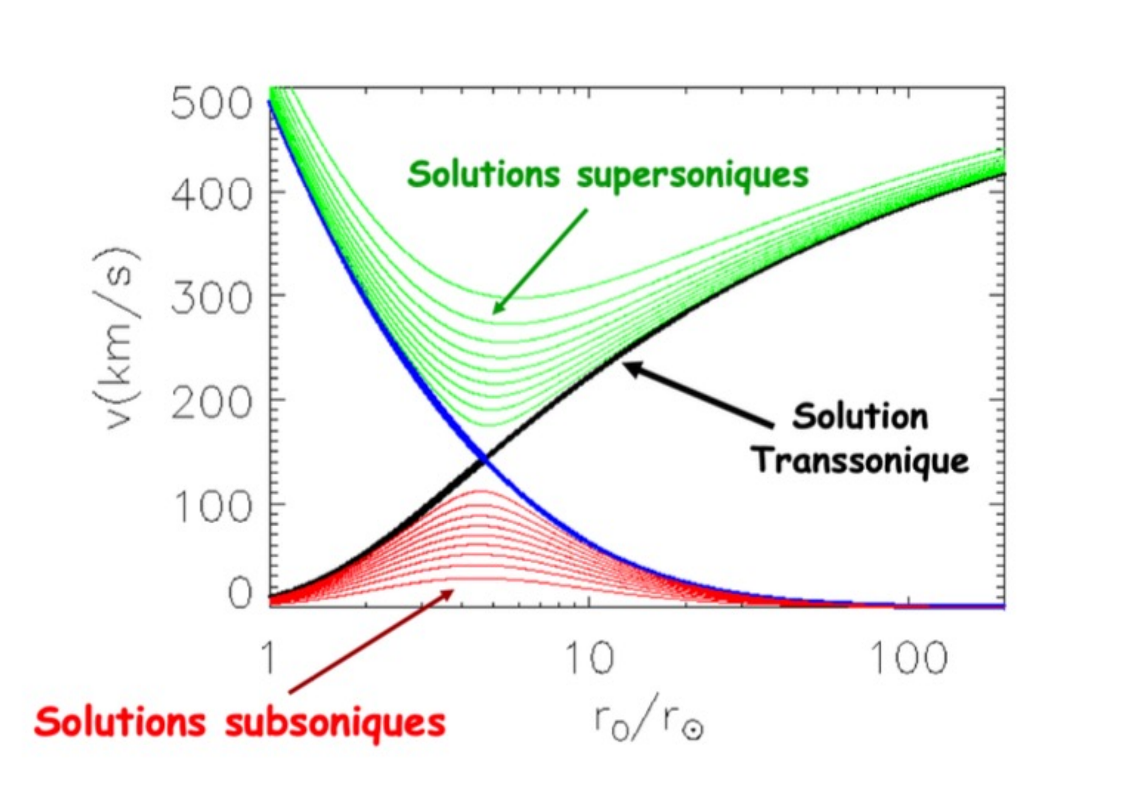
$$(u^2 - c_s^2)\,\frac{1}{u}\frac{d}{dr}u = \frac{2c_s^2}{r}\left(1 - \frac{r_c}{r}\right)$$

Question of the closure equation… Assume isothermal (detailed discussion this afternoon with Jean-Baptiste!)

$$\frac{u^2}{2} - c_s^2 \ln u = 2c_s^2 \ln r + 2c_s^2\frac{r_c}{r} + C$$

Which admits different kind of solutions depending on boundary conditions

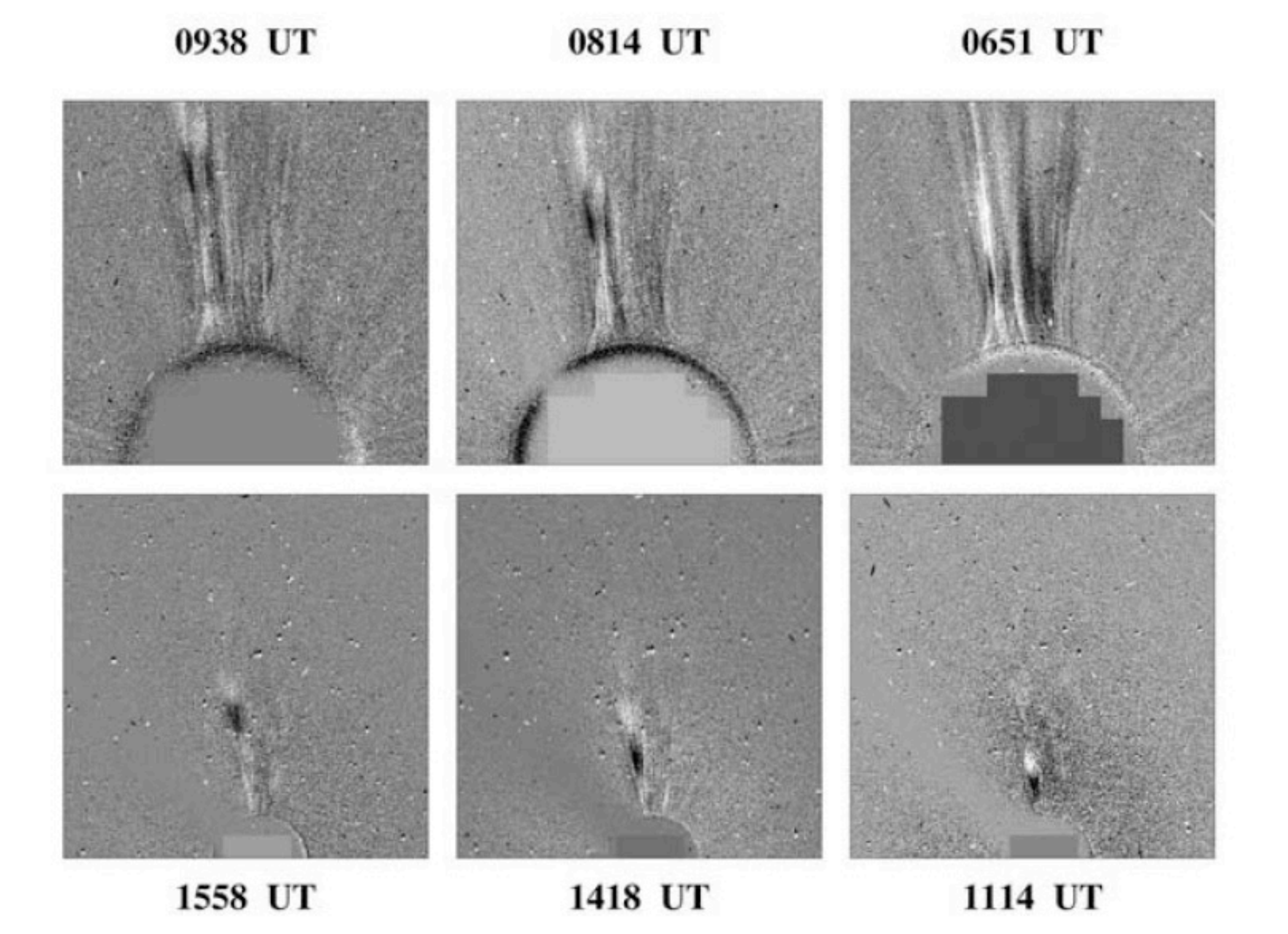
$$r_c \simeq \frac{GMm_p}{4kT} \simeq 2,9\left(\frac{10^6\ \mathrm{K}}{T}\right)R_s$$



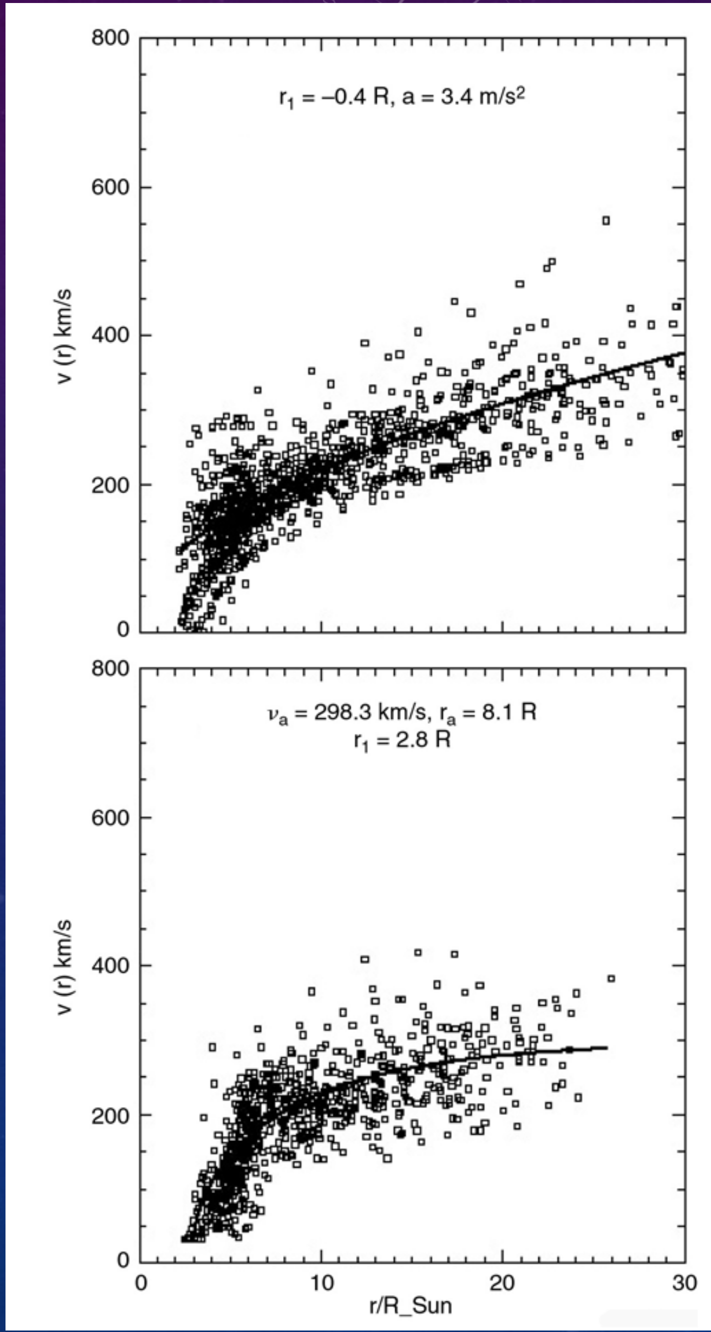
$$u_\infty \simeq 1,5\left(\frac{4kT}{m_p}\right)^{1/2} \simeq 272\left(\frac{T}{10^6\ \mathrm{K}}\right)^{1/2}\ \mathrm{km.s^{-1}}$$

(the calculation actually gives $u(r \gg r_c) = 2c_s\sqrt{\ln r/r_c}$)

SOLAR WIND VELOCITY PROFILE: OBSERVATION



White light (Sheeley et al., 1997)



SOLAR WIND'S MASS FLUX

From the continuity equation, $\dot{M} = 4\pi r^2 n m u(r) = cste$

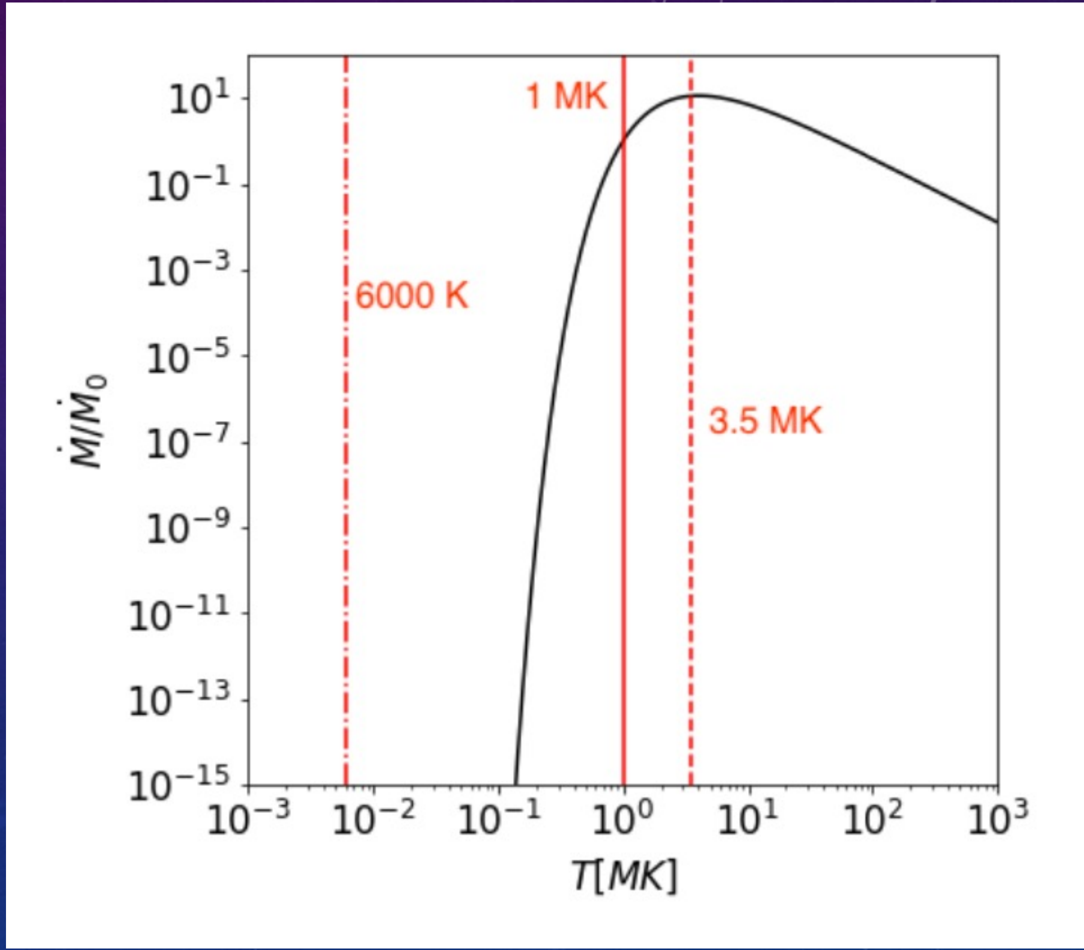
From Parker's solution, we have $u(r \to 0) \simeq c_s \left(\frac{r_c}{r}\right)^2 \exp\left(-\frac{2r_c}{r} + \frac{3}{2}\right)$

So that the mass flux can be evaluated as

$$\dot{M} \sim 5 \times 10^{10} \left(\frac{T}{10^6\ \mathrm{K}}\right)^{-3/2} \exp\left(-\frac{6.10^6\ \mathrm{K}}{T}\right) \mathrm{kg.s}^{-1}$$

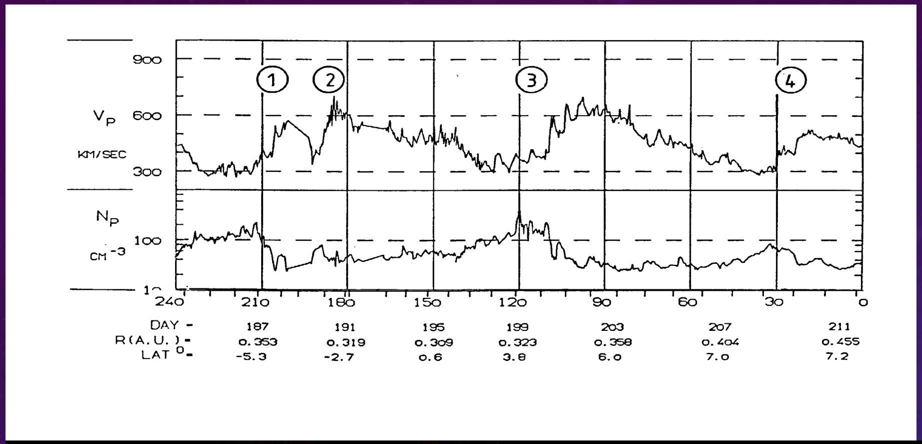
At T = 10^6K the formula gives 10^8 kg/s (exactly what is observed!)

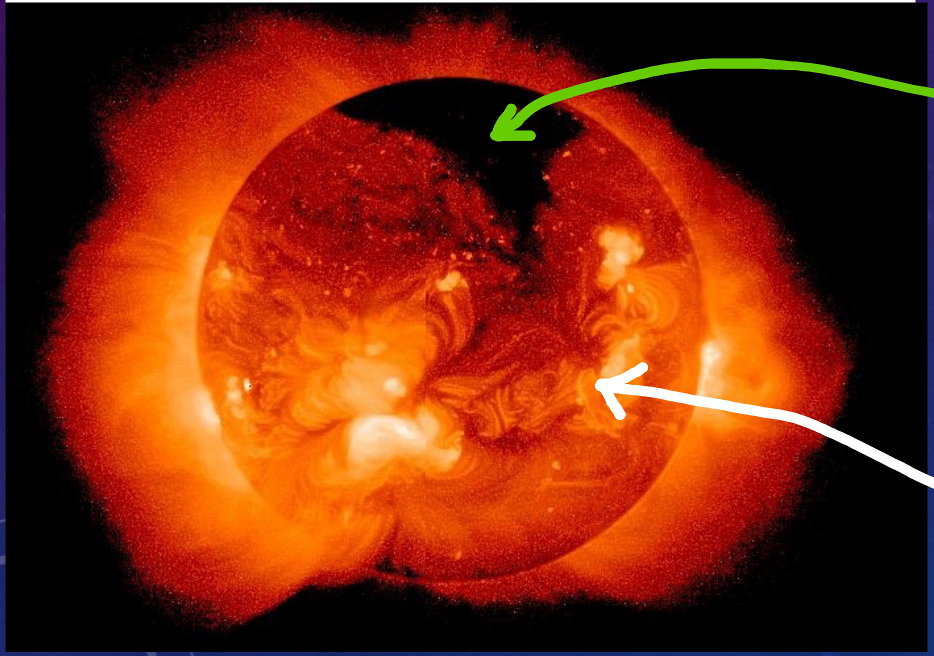
Note the extreme sensitivity to the coronal temperature - and so to the coronal heating rate Q !



Sensitivity to coronal temperature

THE SOLAR WIND AS A PLASMA LABORATORY: IN SITU OBSERVATIONS





Yohkoh

Composition :

- e^-
- H^+ : ~95%
- He^{2+} : ~4%
- ~1% d' ions lourds (C, N, O, Ne, Mg, Fe)

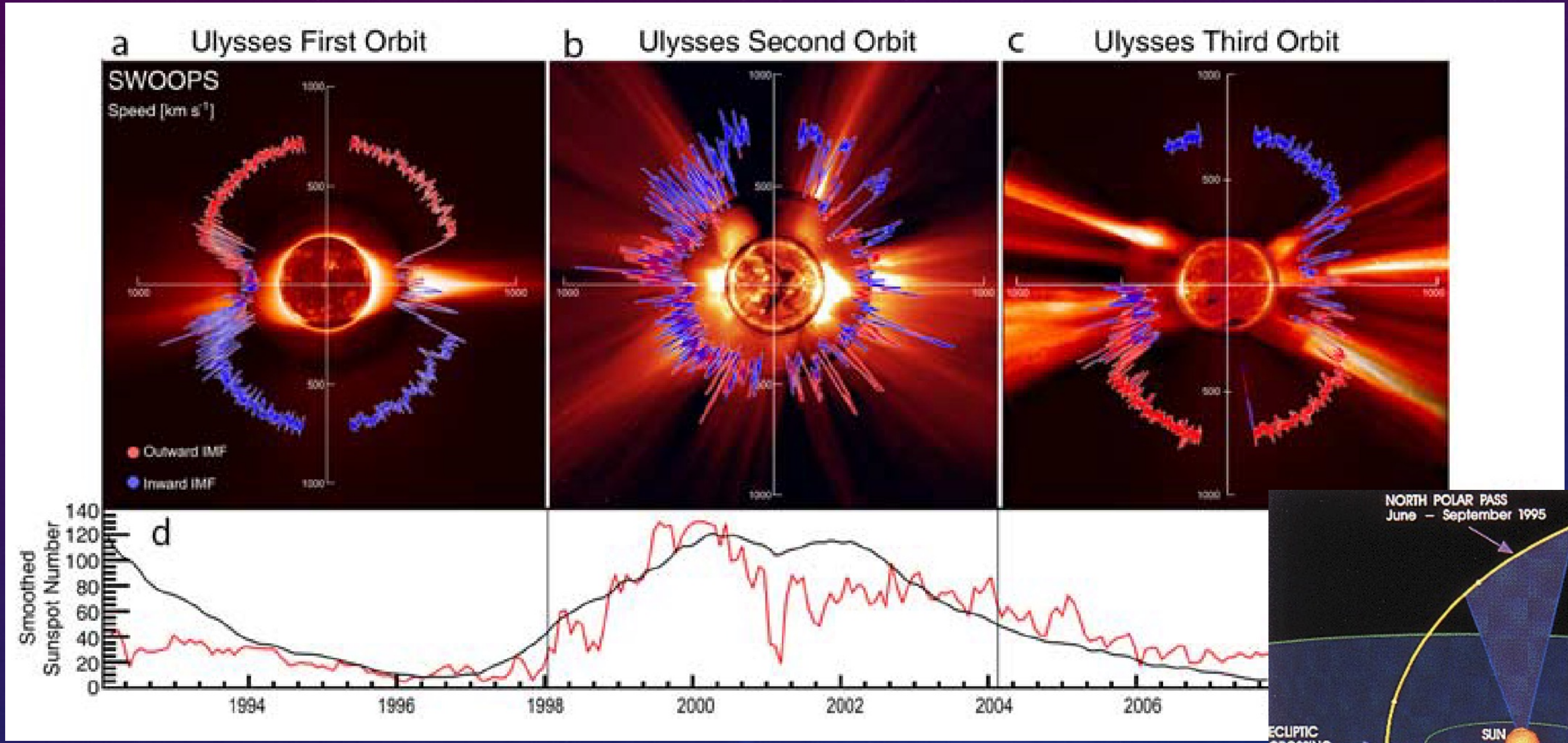
Fast wind (1 AU) :

- V ~ 600 à 800 km/s
- N_e ~ 1 à 5 cm^{-3}
- T_e ~ 1 à 2 x10^5 K → V_{the} ~ 2100 km/s
- T_p ~ 2 à 5 x10^5 K → V_{thp} ~ 80 km/s

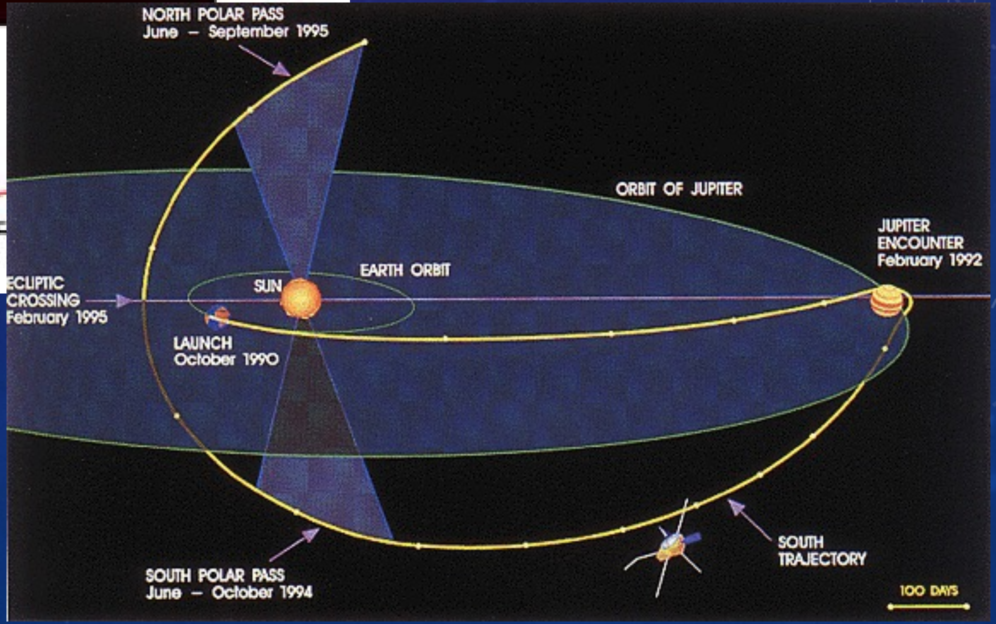
Slow wind (1 AU) :

- V ~ 200 à 600 km/s
- N_e ~ 5 à 20 cm^{-3}
- T_e ~ 1 à 3 x10^5 K ⟶ V_{the} ~ 2500 km/s
- T_p ~ 0.5 à 3 x10^5 K → V_{thp} ~ 40 km/s

SLOW, FAST, BOUNDARY CONDITIONS AND SOLAR CYCLE



Ulysses orbit allowed for the exploration of the out-of-the-eclitpic solar wind.



The slow/fast wind structure is completely conditionned by the solar magnetic field configuration. Open field lines: fast wind, complex/loops configuration : slow wind.

The evolution of the solar magnetic field configuration is cyclic (24 years)

THE INTERPLANETARY MAGNETIC FIELD: PARKER'S SPIRAL

The sun rotates with an angular frequency $\omega = 2.9 \times 10^{-6}\ rad.s^{-1}$ (25 days periodicity at the equator)

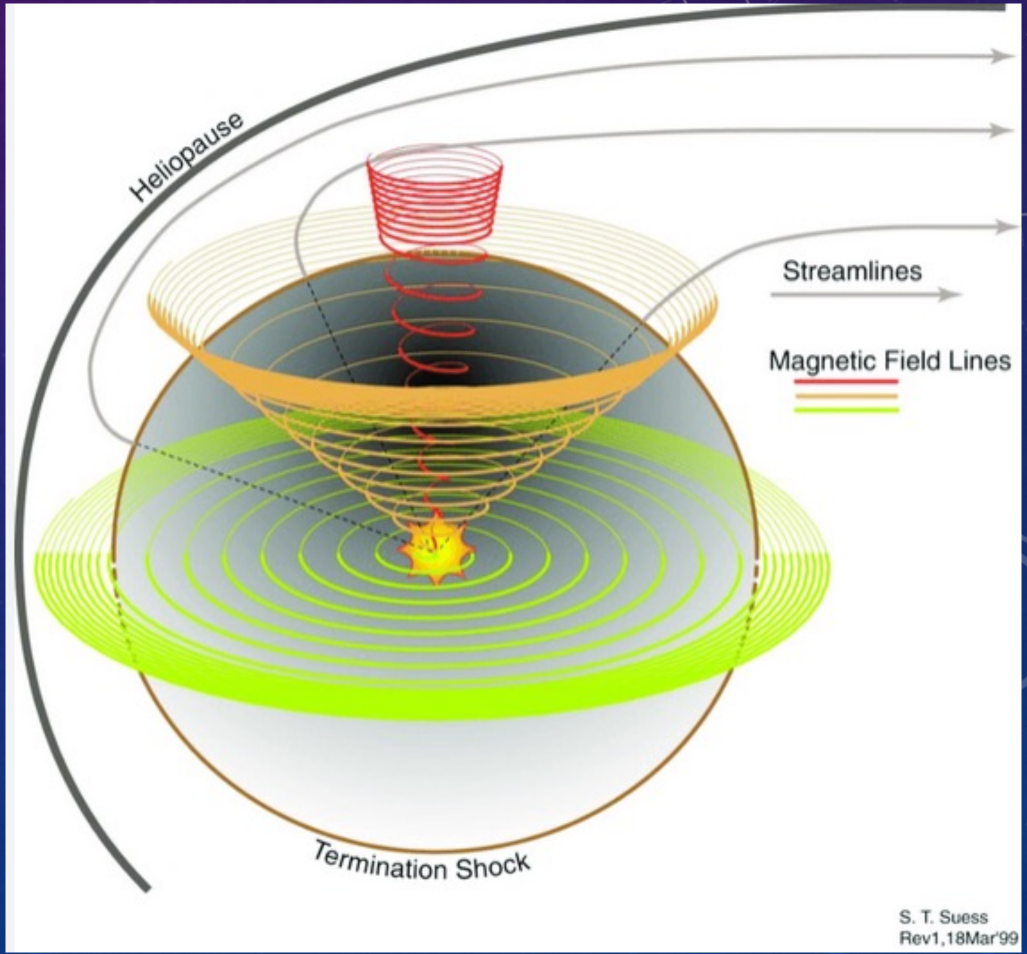
In the referential rotating with the Sun, the solar wind stream lines have equations

$$\begin{cases} u_r = v_{sw} \\ u_\phi = -\omega r \sin\theta \end{cases}$$

Because the plasma electrical conductivity is extremely high, the large scale magnetic field lines are « frozen » in the plasma.
=> The magnetic field lines coincide with the stream lines .

The equation of a field line is therefore $v_{sw} r d\phi = -\omega r dr$

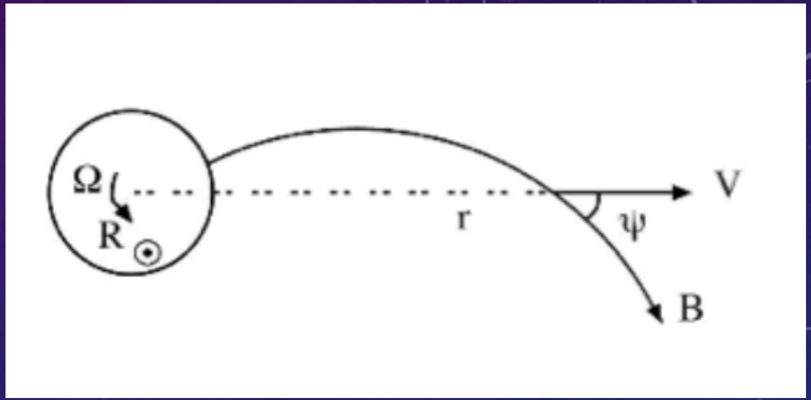
The equaiton of a field line is $r(\phi) = -\frac{v_{sw}}{\omega}(\phi - \phi_0)$



RADIAL EVOLUTION OF THE PARAMETERS (TP1)

The angle between the radial direction and the local magnetic field is

$$\tan\psi = \frac{B_\phi}{B_r} = \frac{r\sin\theta d\phi}{dr} = -\frac{\omega r\sin\theta}{v_{sw}}$$



The radial evolution of B is constrained by the div B = 0

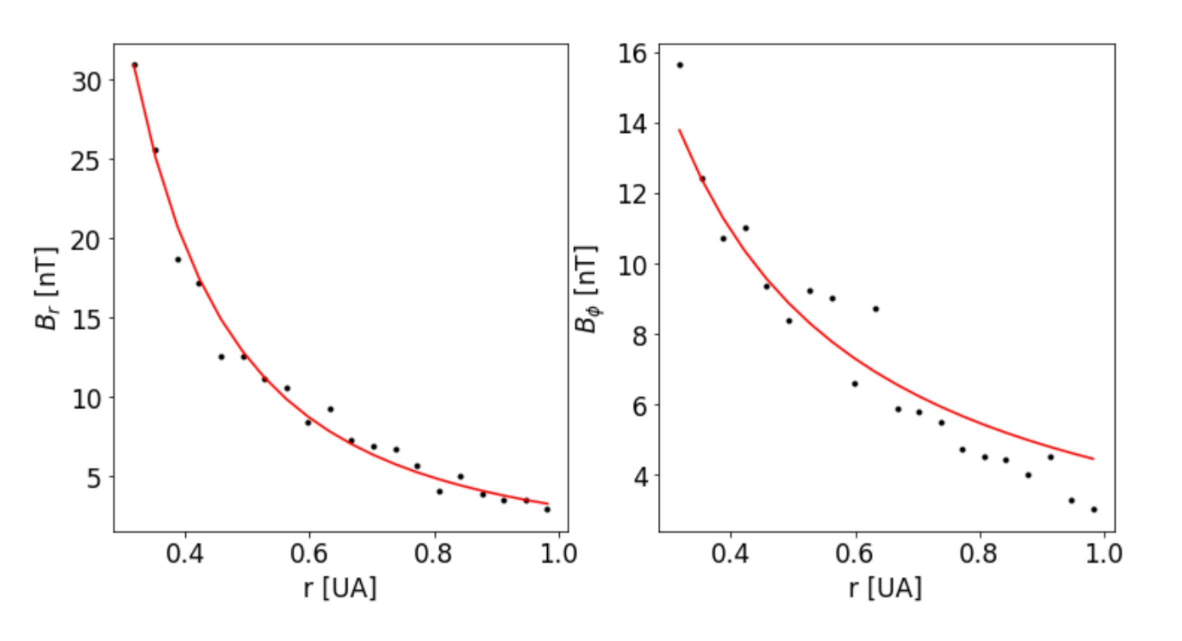
$$B_r(r) = B_r(a)\left(\frac{a}{r}\right)^2$$

From where we can get the radial evolution of the azimuthal component

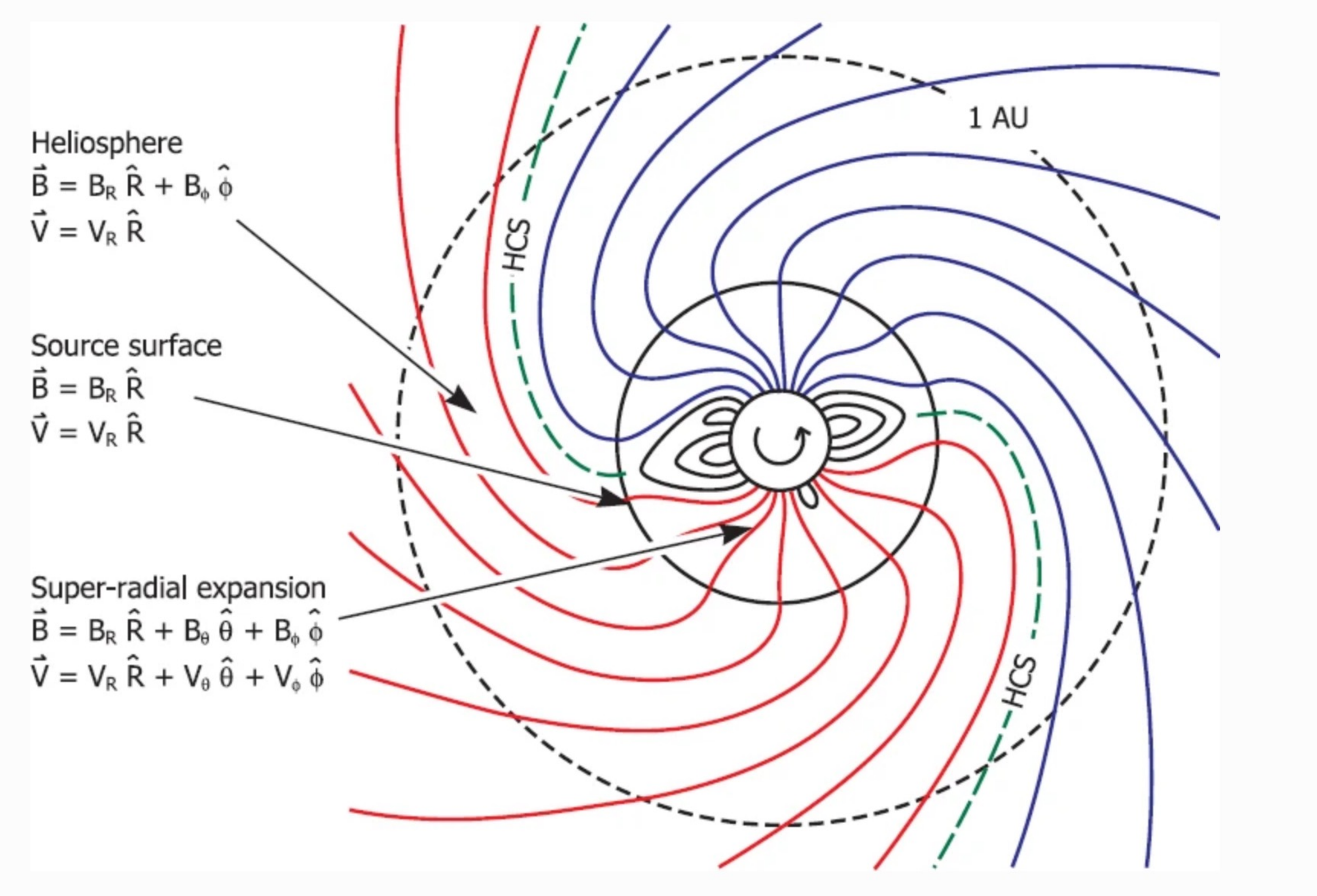
$$B_\phi(r) = -B_r(a)\frac{\omega a^2\sin\theta}{r v_{sw}}$$

And of the magnetic field modulus :

$$|B(r)| = |B_r(a)|\left(\frac{a}{r}\right)^2\sqrt{1+\left(\frac{\omega r\sin\theta}{v_{sw}}\right)^2}$$

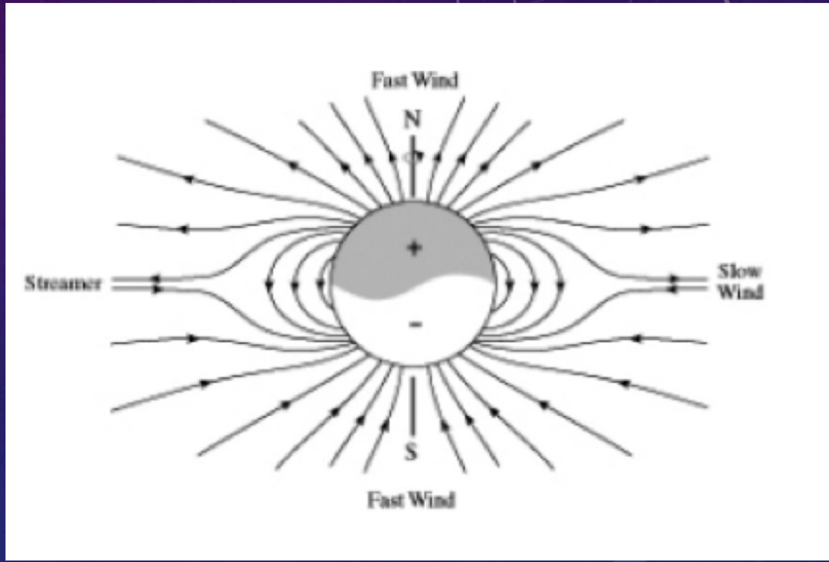


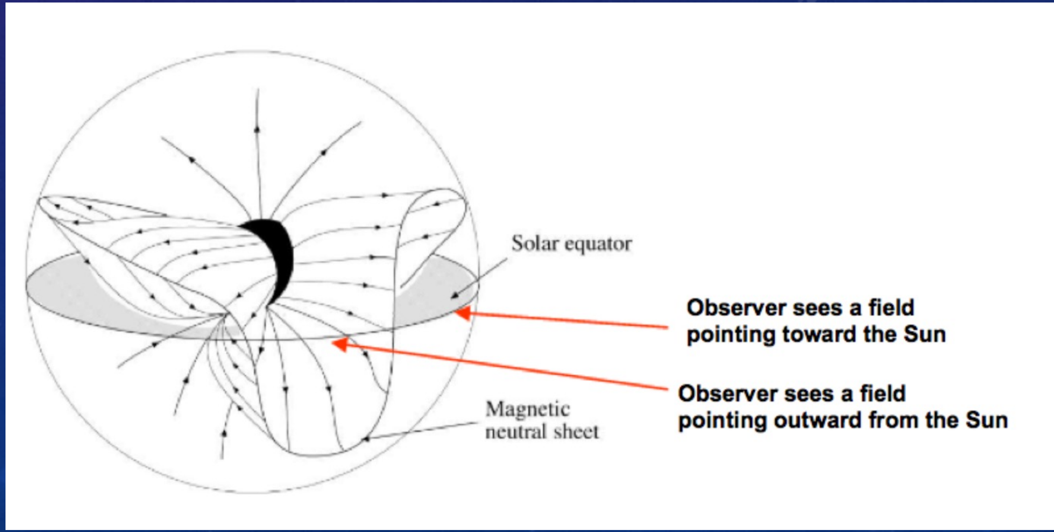
INTERPLANETARY MAGNETIC FIELD : A MORE COMPLICATED STRUCTURE



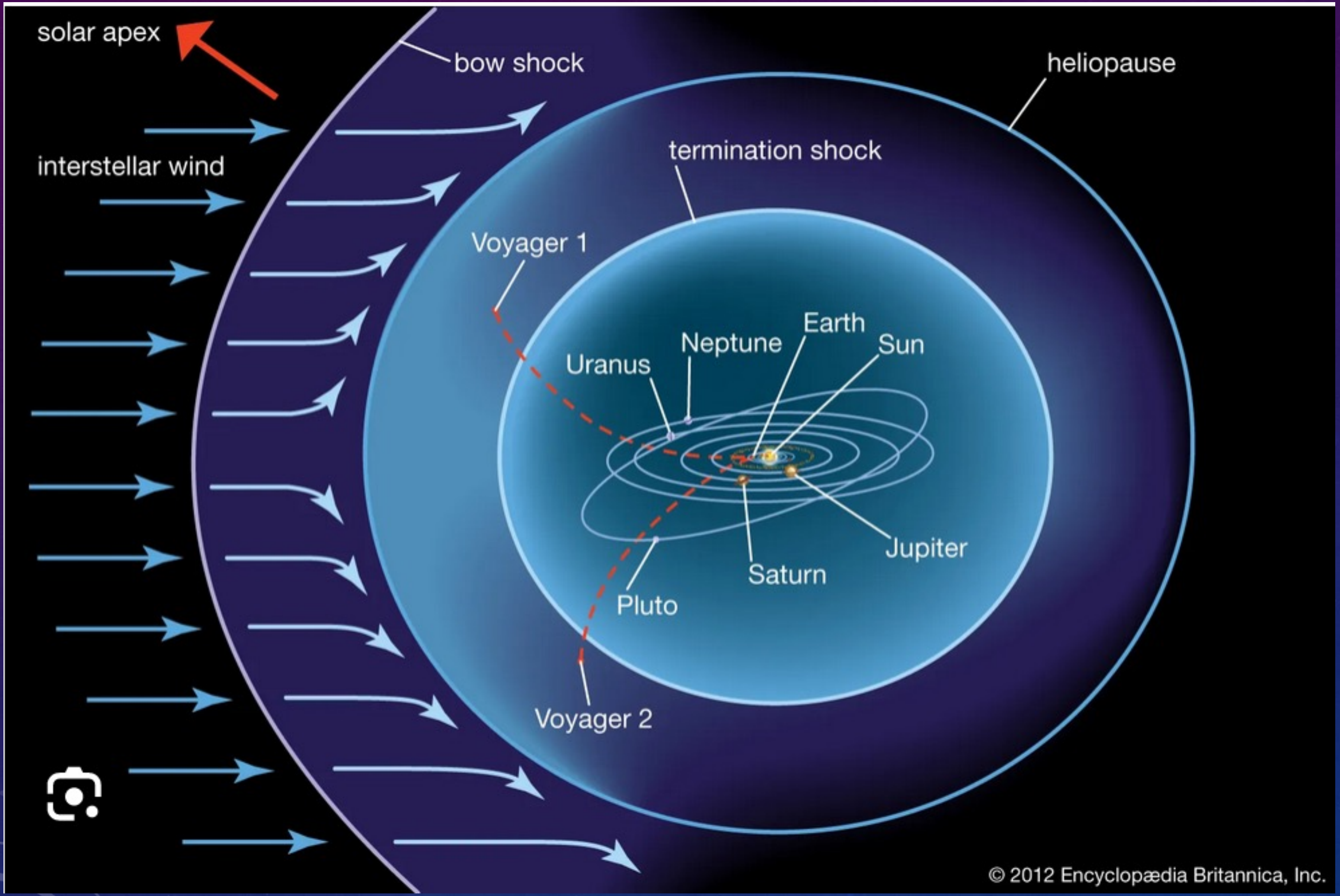
Latitudinal structure, close field effects and HCS tilt effect

Longitudinal structure





THE HELIOSPHERE, THE HELIOPAUSE



The heliosphere is the region of space in which the plasma is predominently constituted by the solar wind, and the local magnetic field is the Parker spiral.

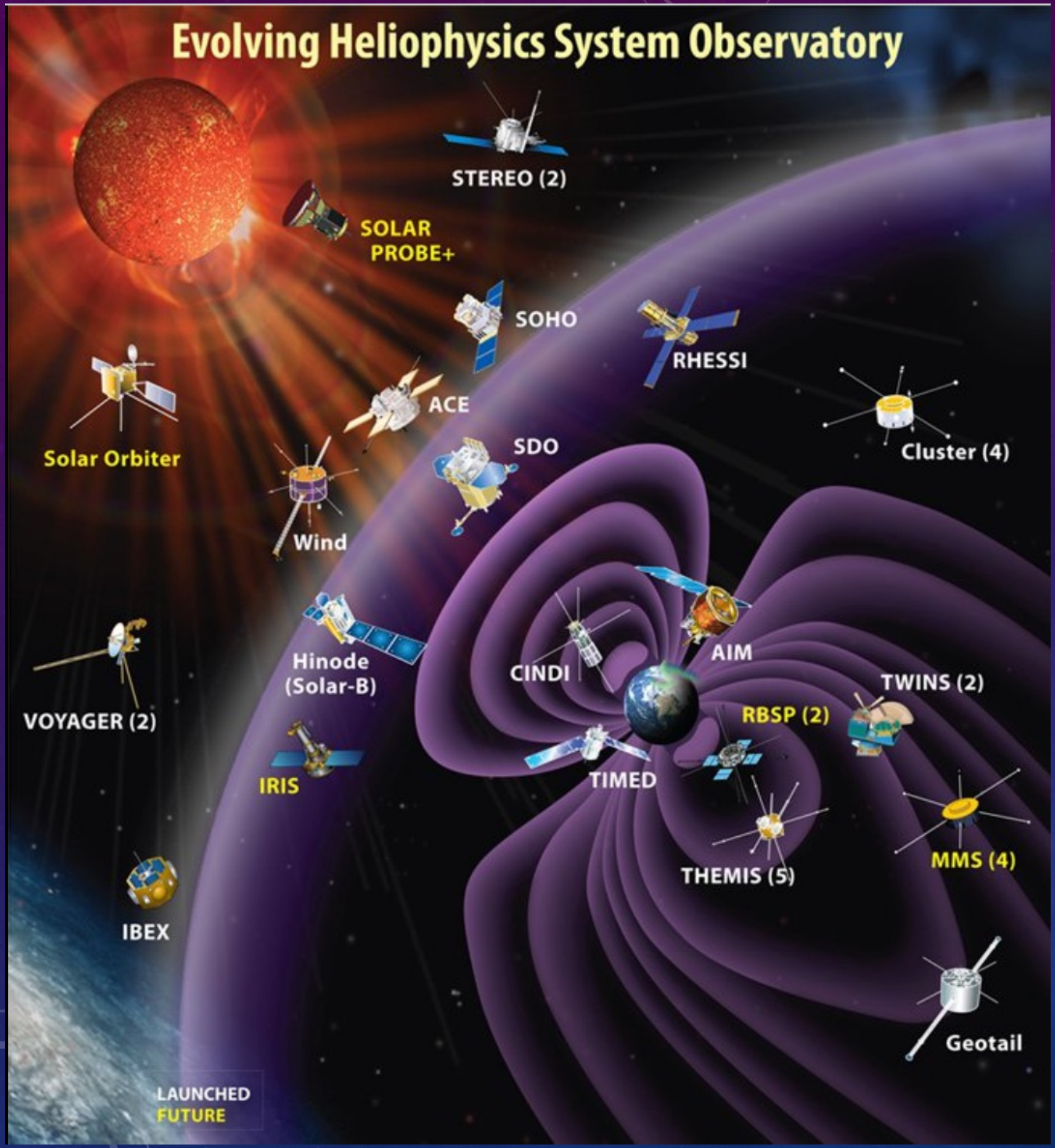
This is an almost spherical region, the outer boundary of which is the heliopause, where the dynamic pressure of the solar winds equals the pressure of the interstellar medium

$$\frac{1}{2}\rho_P v_{sw}^2 \sim P_{IS}, \qquad \dot{M} = 4\pi\rho_P R_P^2 v_{sw}$$

$$\Rightarrow \quad R_P = \left(\frac{\dot{M} v_{sw}}{8\pi P_{IS}}\right)^{1/2}$$

Order of magnitude : $P_{IS} \sim 10^{-14}$ Pa

$$\Rightarrow \quad R_P \sim 100\ AU$$



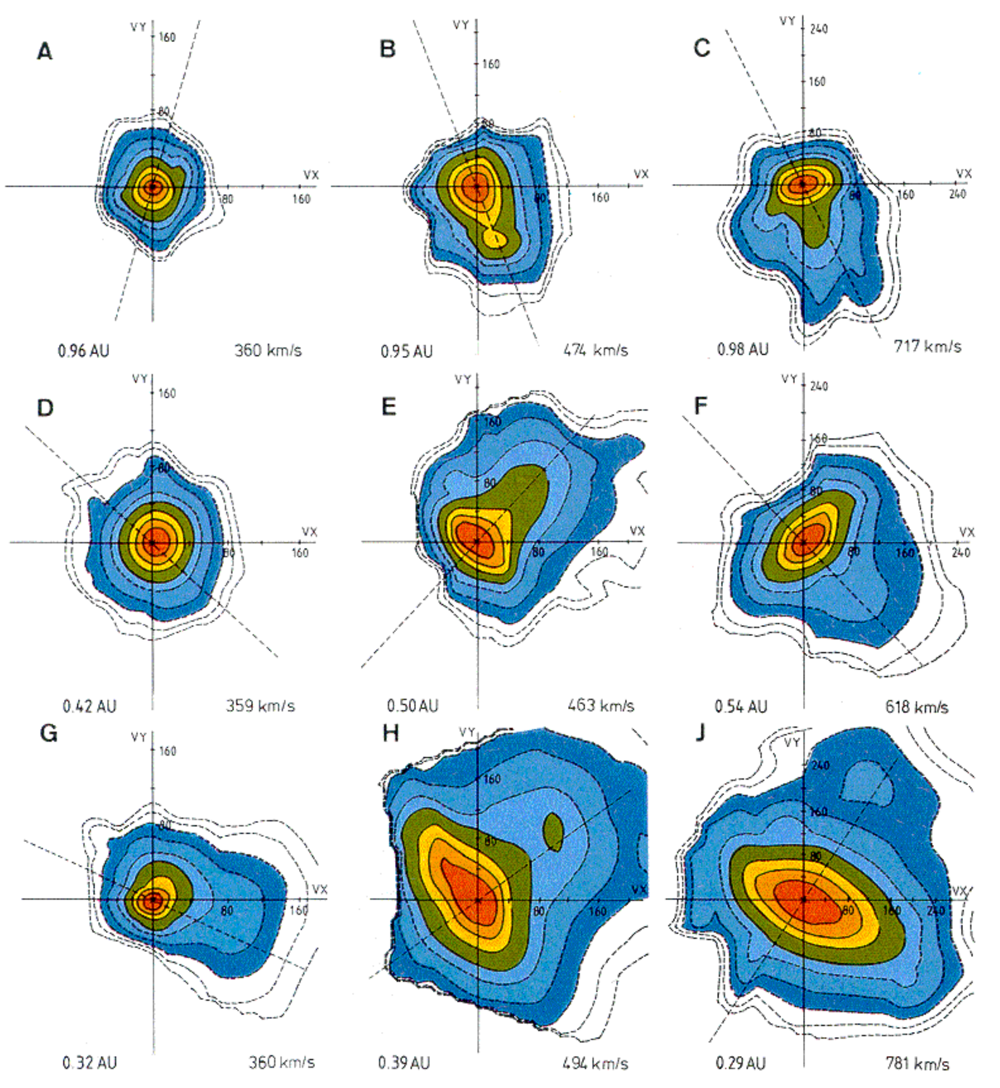
THE HELIOSPHERE: A PLASMA LABORATORY

A plasma bubble in the ISM, weakly collisional, in expansion, magnetized, which occupies a very large parameter space.

Accessible to in-situ measurement

An ideal experimentation site to understand astrophyiscal plasmas (and « out of equilibrium » plasma physics as a whole)

THE SOLAR WIND : VELOCITY DISTRIBUTION FUNCTIONS (IONS)



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

$dN = f(v_x, v_y, v_z)\mathrm{d}^3v$: 1 particle phase space density

Characterized by non-equilibrium features, structured by the local magnetic field

- Temperature anisotropies
- Ion beams
- …

Plasma measurements made by Helios at 10 s resolution (> 0.29 AU from the Sun) in the 1970's essentially.

New data is coming right now from solar orbiter and PSP : closer to the Sun, better resolution, questionable calibration – a lot of work to do.

FROM KINETIC TO FLUID DESCRIPTION?

The fluid variables are defined as the statistical centered moments of the velocity distribution function :

$$n(\mathbf{r},t) = \int d^3\mathbf{v} f(\mathbf{r},\mathbf{v},t).$$

$$n(\mathbf{r},t)\mathbf{u}(\mathbf{r},t) = \int d^3\mathbf{v} f(\mathbf{r},\mathbf{v},t)\mathbf{v}$$

$$\mathbf{p}(\mathbf{r},t) = \int d^3\mathbf{v} f(\mathbf{r},\mathbf{v},t)(\mathbf{v}-\mathbf{u})(\mathbf{v}-\mathbf{u})$$

The fluid equations are obtained by integrating the kinetic equation

$$\int d^3\mathbf{v} \left(\frac{\partial f}{\partial t} + \mathbf{v}\cdot\nabla_r f + \frac{\mathbf{F}}{m}\cdot\nabla_v f\right) = \int d^3\mathbf{v}\mathscr{C}(f)$$

$$\frac{\partial n}{\partial t} + \nabla\cdot n\mathbf{u} = 0$$

$$\int d^3\mathbf{v}\mathbf{v} \left(\frac{\partial f}{\partial t} + \mathbf{v}\cdot\nabla_r f + \frac{\mathbf{F}}{m}\cdot\nabla_v f\right) = \int d^3\mathbf{v}\mathbf{v}\mathscr{C}(f)$$

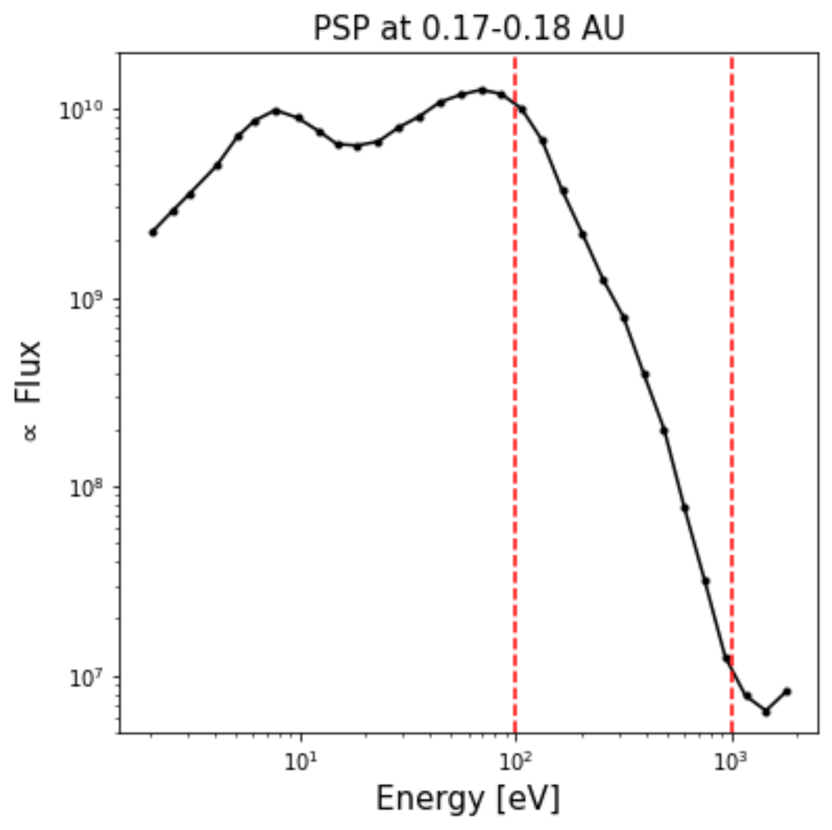
$$nm\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = -\nabla p - \nabla\cdot\overline{\boldsymbol{\pi}} + n\mathbf{F} + n\mathbf{R}$$

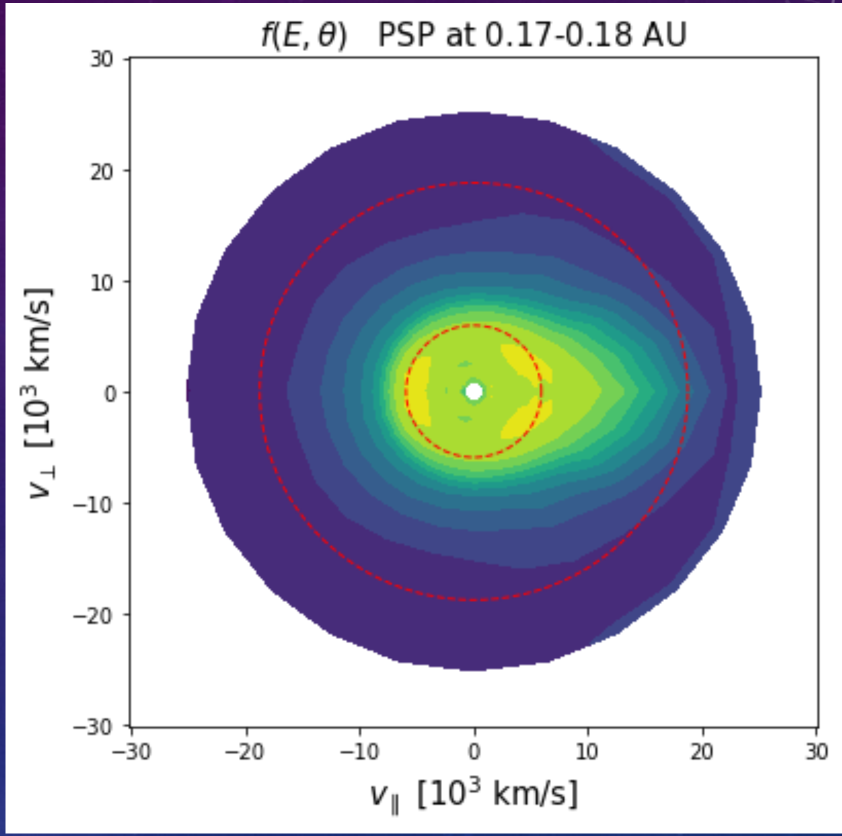
$$\frac{\partial}{\partial t}\left(\frac{1}{2}nmu^2 + \frac{3}{2}nkT\right) + \nabla\cdot\mathbf{j}_E = n\mathbf{u}\cdot\mathbf{F} + n\mathbf{u}\cdot\mathbf{R} + nQ$$

Etc.

Strictly speaking, in the limit of infinite number of moments, fluid and kinetic approaches contain the same information. The specifics of fluid models appears in the closure equation. Not necessarily related to LTE or things like that.

THE SOLAR WIND: VELOCITY DISTRIBUTION FUNCTIONS (ELECTRONS)





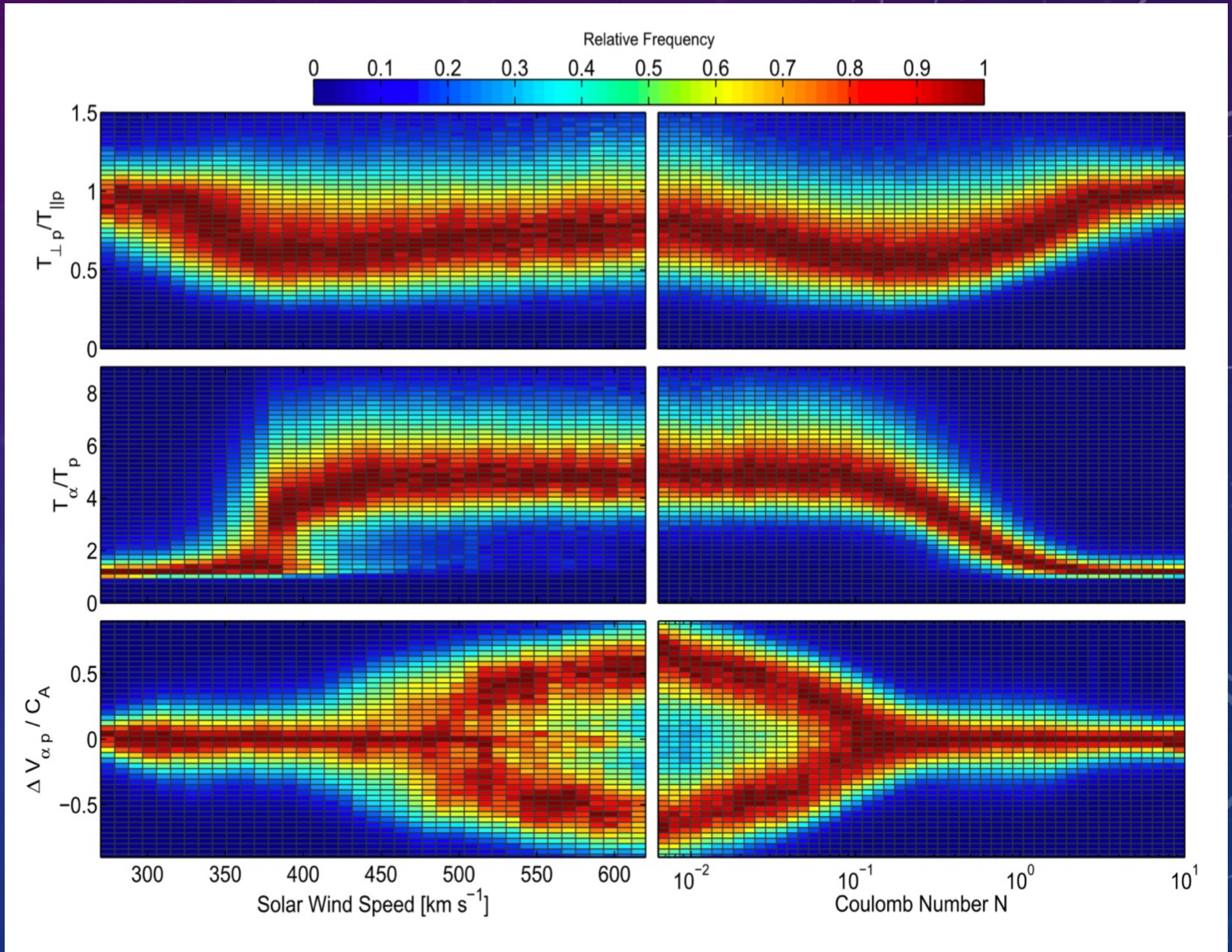
Non-equilibrium features, structured by the local magnetic field

In particular, determine the heat flux (along the magnetic field) : relevance for fluid closures. Validation of transport models. Coupling to electro-magnetic turbulence…

SOLAR WIND'S EXPANSION: A COLLISIONLESS MEDIUM?

- Wind's Faraday cup : 25 years of H^+ and He^{2+} continuous measurements
- $> 10^7$ accumulated spectra
- Parameters defining the non-thermal character of the distribution function are traced as a funtion of wind speed, and coulomb number

$$N_c = \frac{\nu_c^{ab} r}{v_{sw}} = \nu_c^{ab} \tau_{\mathrm{exp}}$$



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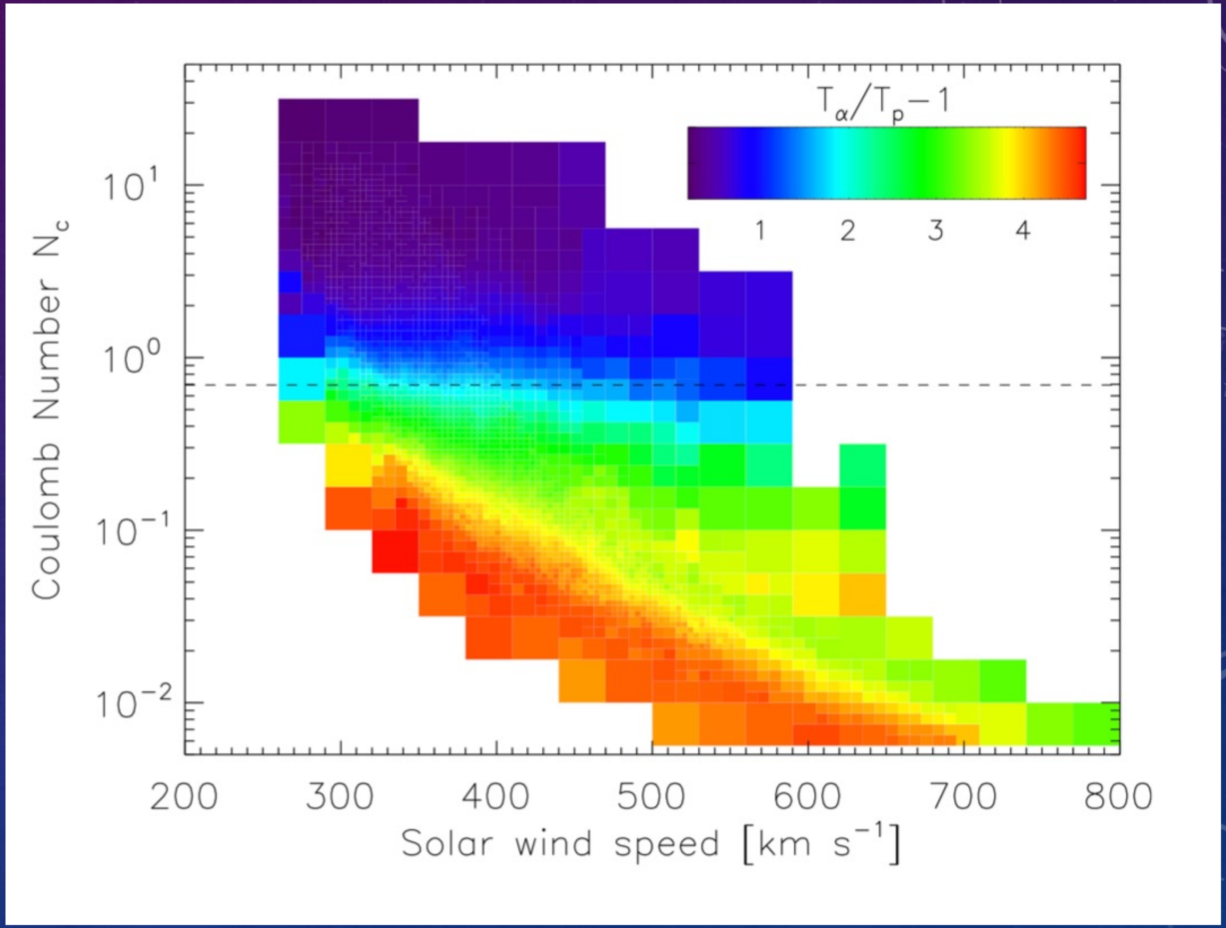


SOLAR WIND'S EXPANSION: A COLLISIONLESS MEDIUM?

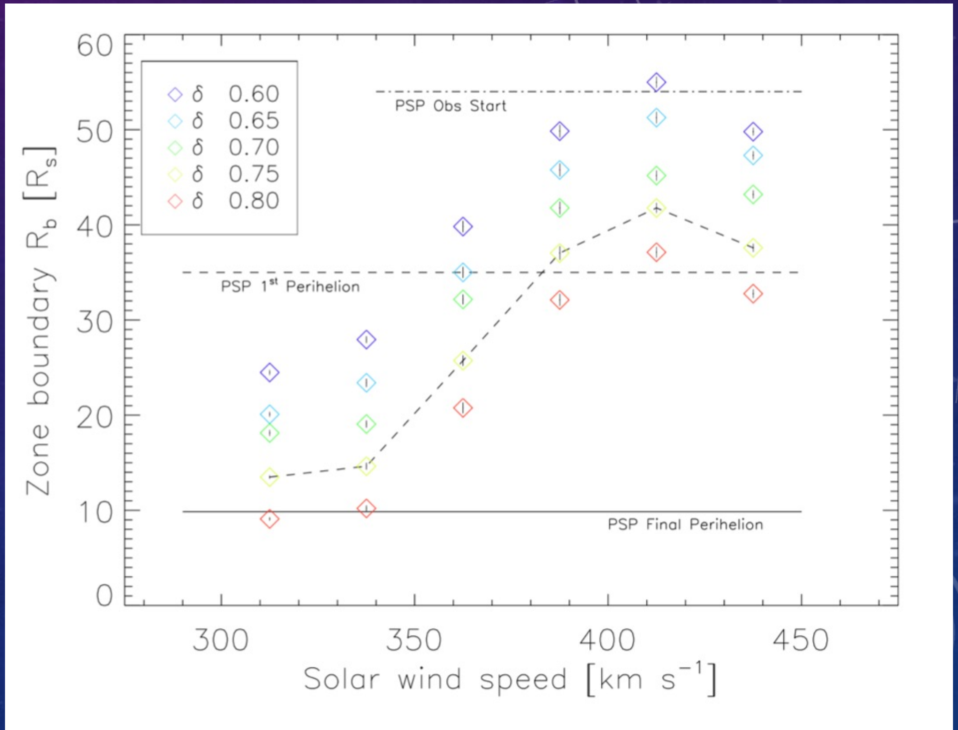
- Hypothèse : le plasma est chauffé par un mécanisme d'interaction ondes-particules, qui le maintient hors équilibre jusqu'à une distance R_b

- Au-delà de R_b, il n'y a plus aucun chauffage, et le plasma relaxe exponentiellement vers l'équilibre au cours de son expansion

$$\Delta T(r) = \Delta T(R_b) \exp\left(-\int_{R_b}^{r} \frac{\nu_{\alpha p}(r)}{u(r)} dr\right) \equiv \Delta T(R_b) e^{-A_c(R_b, r)}$$

- Les mesures Wind des écarts de température entre alpha et protons permettent de déterminer l'extension R_b de la région de chauffage

- On obtient des valeurs de l'ordre du rayon d'Alfvén.



LE CHAUFFAGE DU VENT SOLAIRE

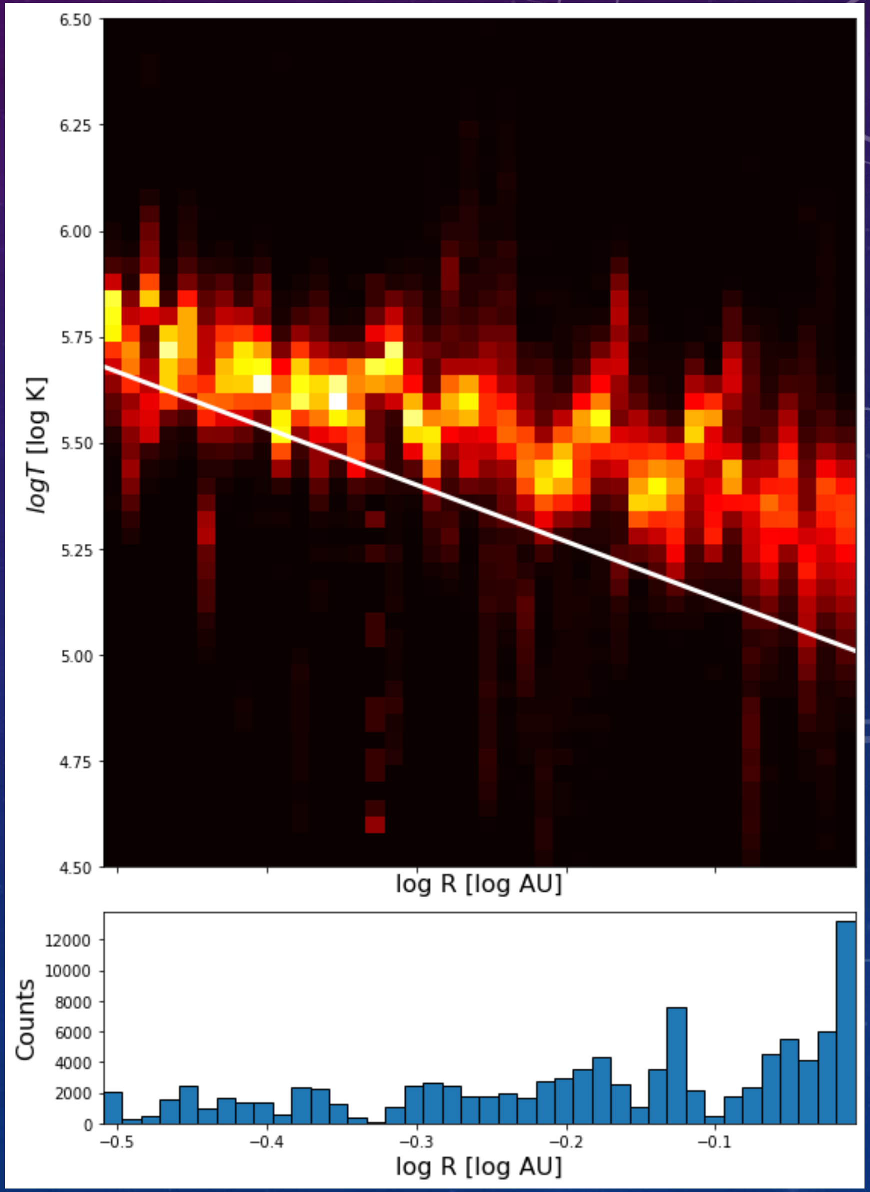
- Evolution radiale de la température d'un gaz parfait ?

$$\frac{dS}{dt} = \frac{Q_t}{T(r)},$$

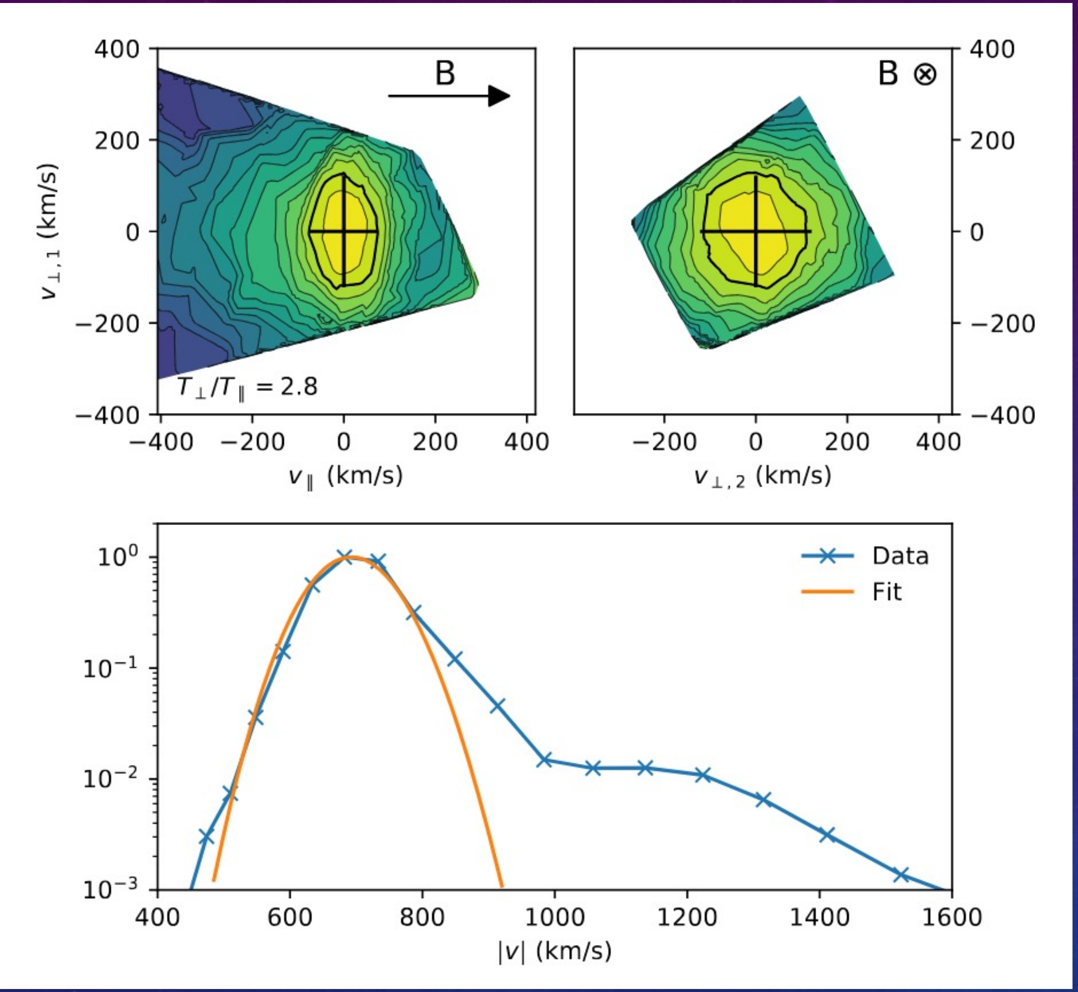
$$S(n,T) = k \ln \frac{T^{3/2}}{n} + cste$$

- En l'absence de chauffage, $T(r) \sim r^{-4/3}$

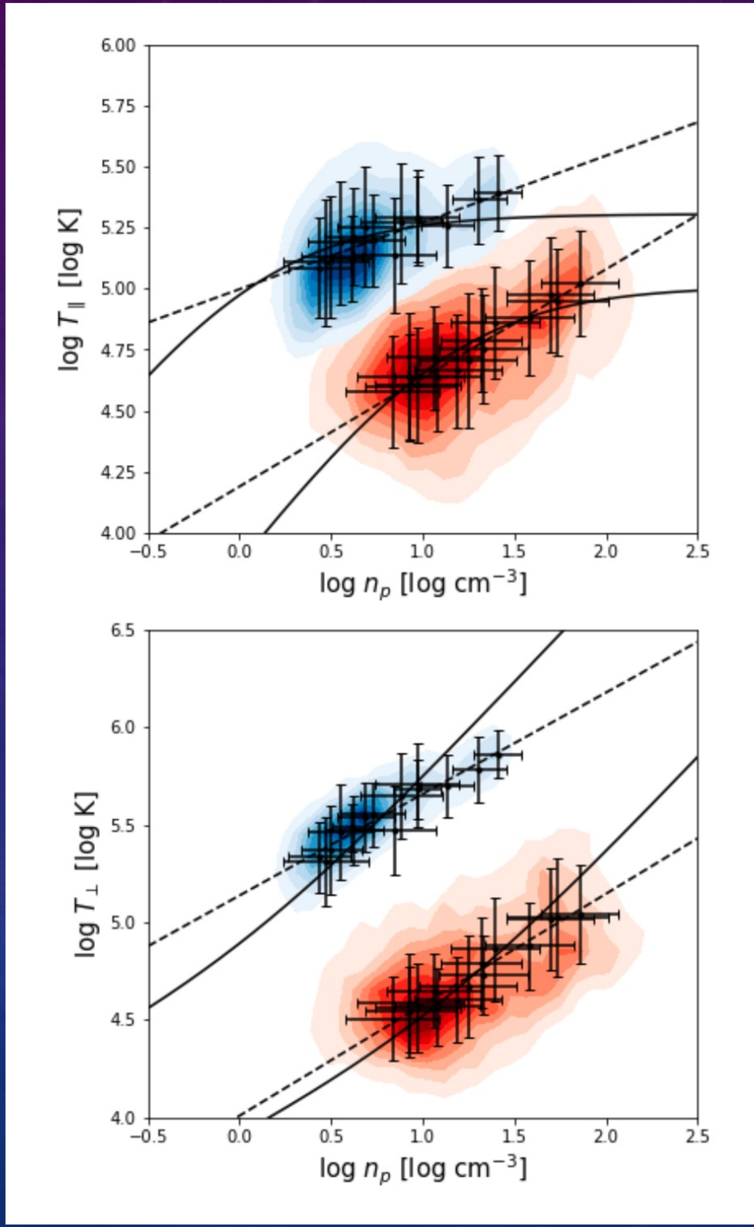
- L'évolution radiale « moyenne », en supposant une expansion en état stationnaire, montre un signe de chauffage.



ANISOTROPIES, ÉVOLUTION CGL & CHAUFFAGE



Détermination des moments par un fit bi-maxwellien [Stansby et al, 2018]



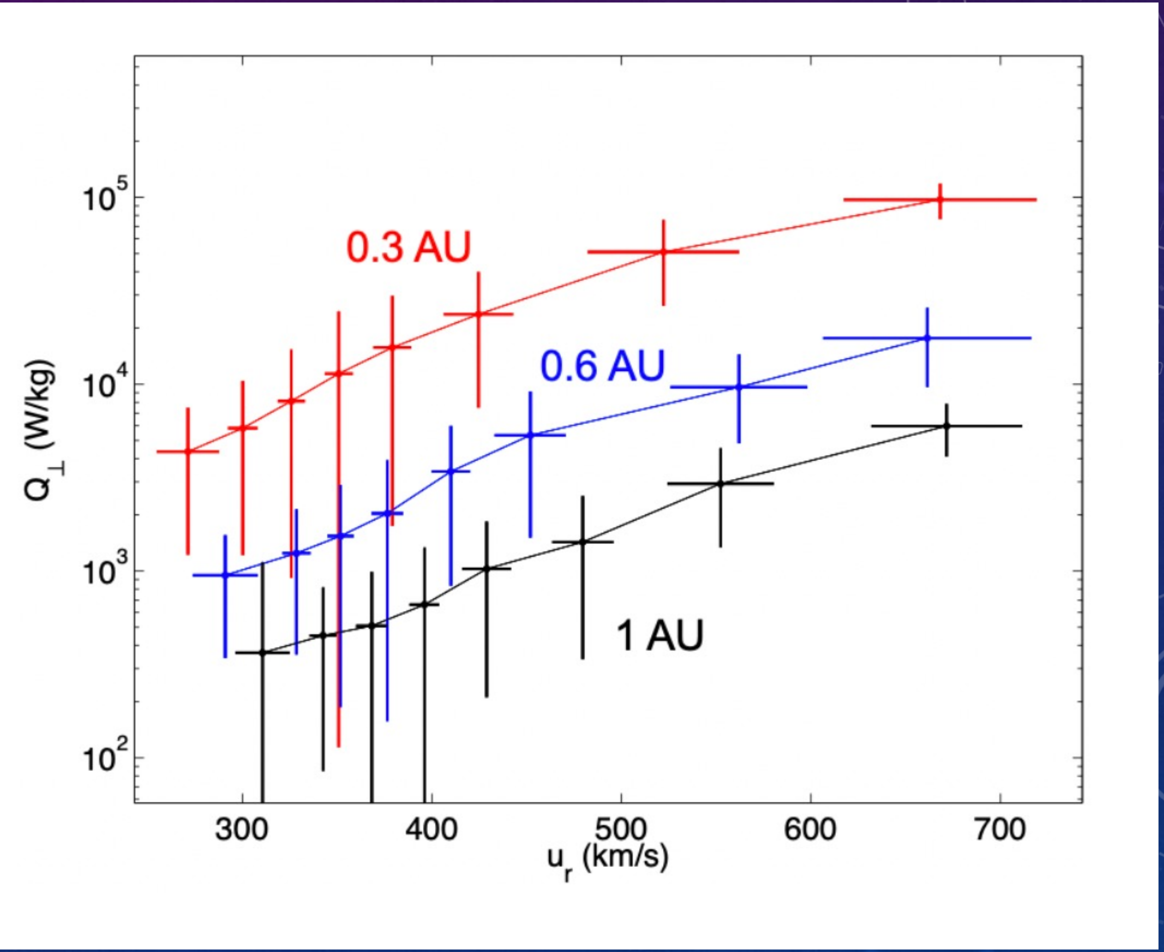
Evolution radiale dans le plan (n,T) présente une évolution compatible avec les lois CGL dans la direction parallèle, mais pas dans la direction perpendiculaire

Chauffage perpendiculaire !

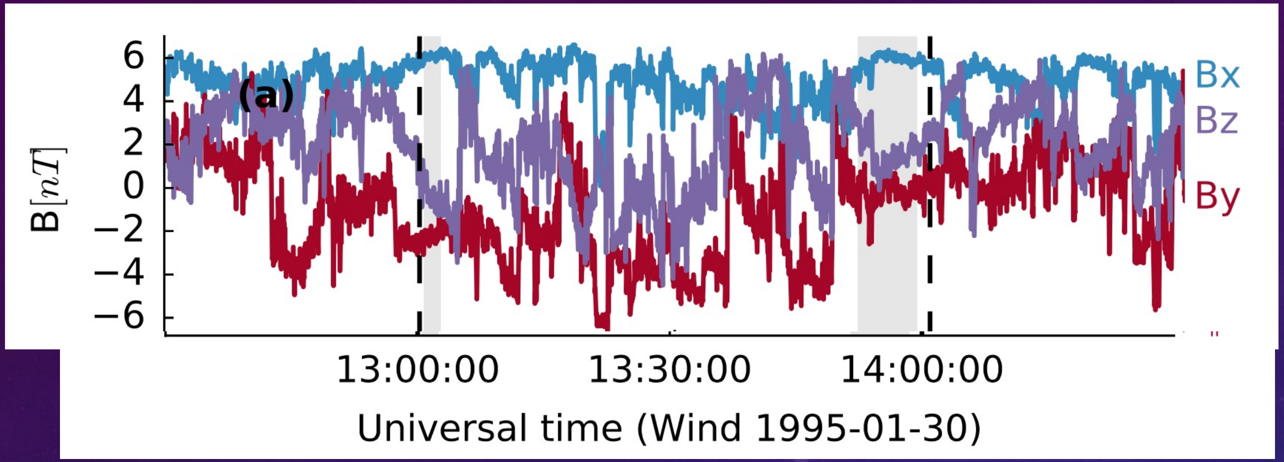
TAUX DE CHAUFFAGE, ET MÉCANISME

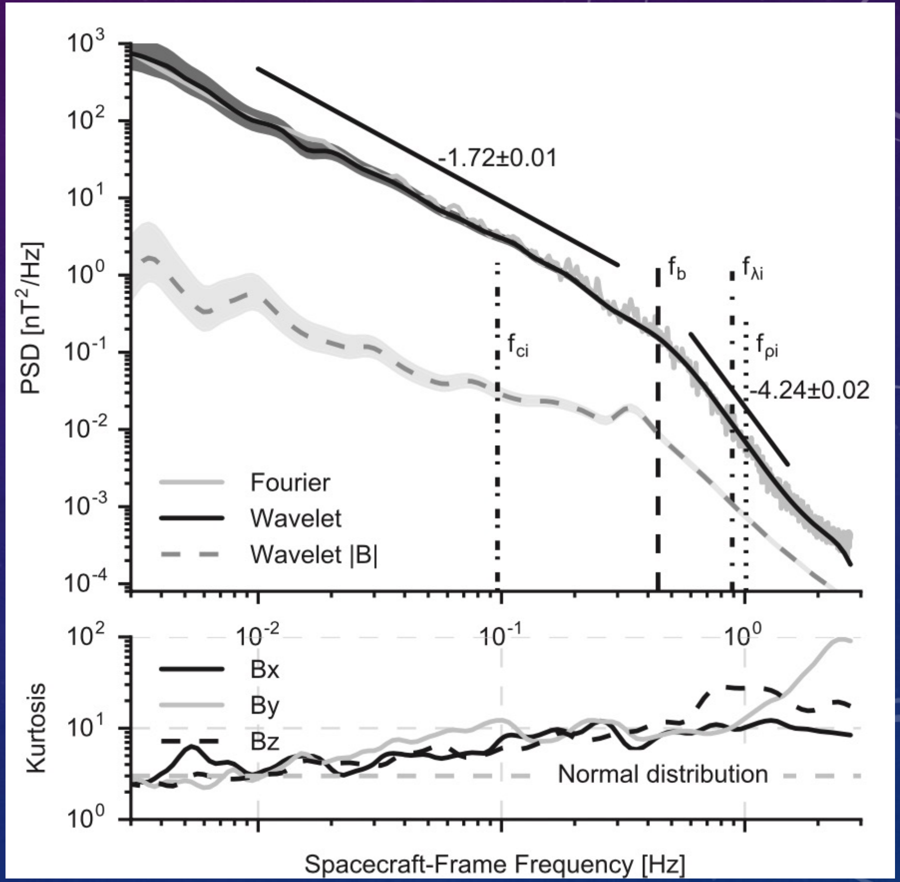
- Taux de chauffage perpendiculaire des protons mesuré par Helios, pour différentes vitesses de vent, et à différentes distances du Soleil
- Les protons sont chauffés de manière résonante (chauffage cyclotron ?) au cours de leur expansion
- Les taux de chauffage sont comparables aux taux d'énergie dans la cascade turbulente estimée par [MacBride et al, 2005] (données ACE)

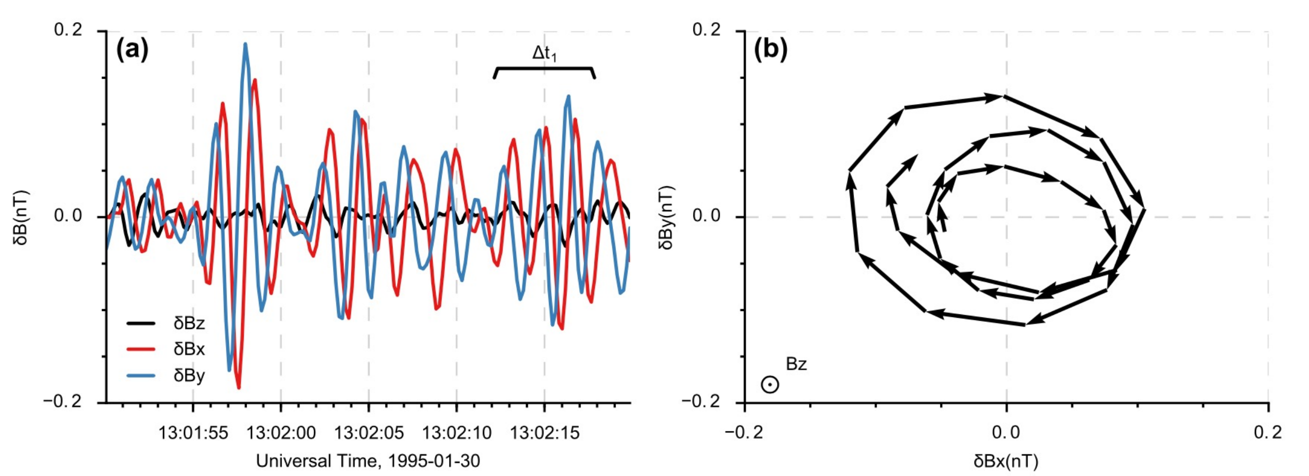
$$\epsilon \simeq 10^4 \text{ W.kg}^{-1}$$



SOLAR WIND: TURBULENCE, WAVES, INSTABILITIES

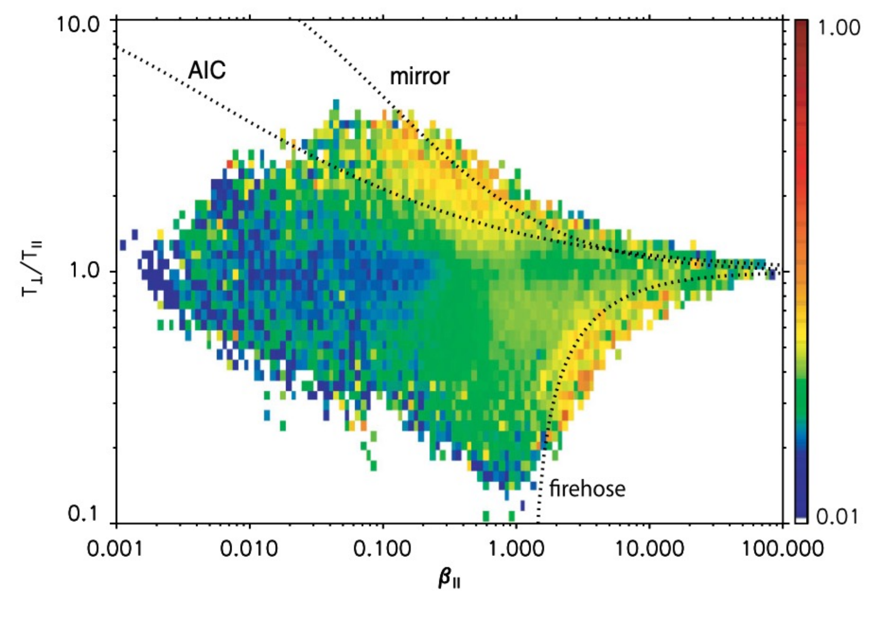




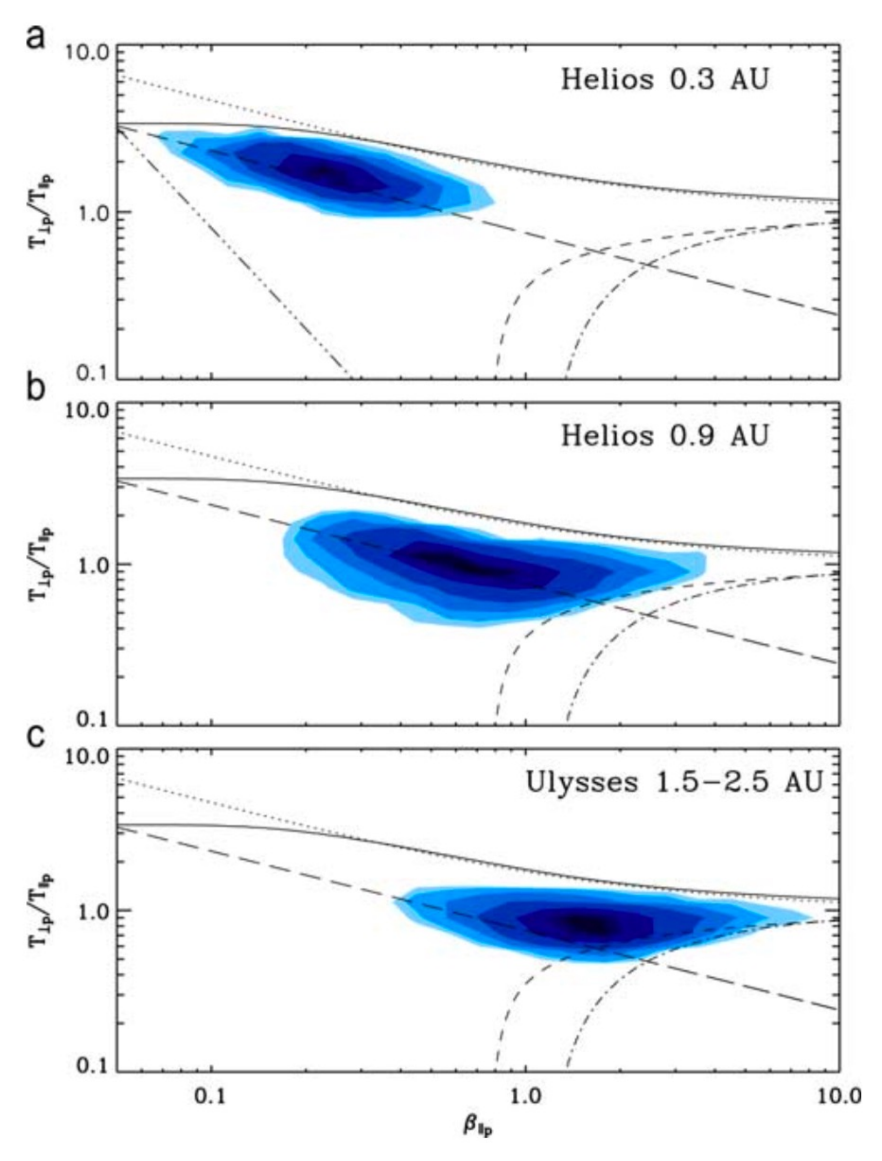


SOLAR WIND: TURBULENCE, WAVES, INSTABILITIES

- Expansion + heating : dotted line
- The instabilities (firehose + mirror) controls the proton expansion



Magnitude of the magnetic field fluctuations
[Bale et al, 2009]



[Matteini et al, 2007]