La Heliosfera

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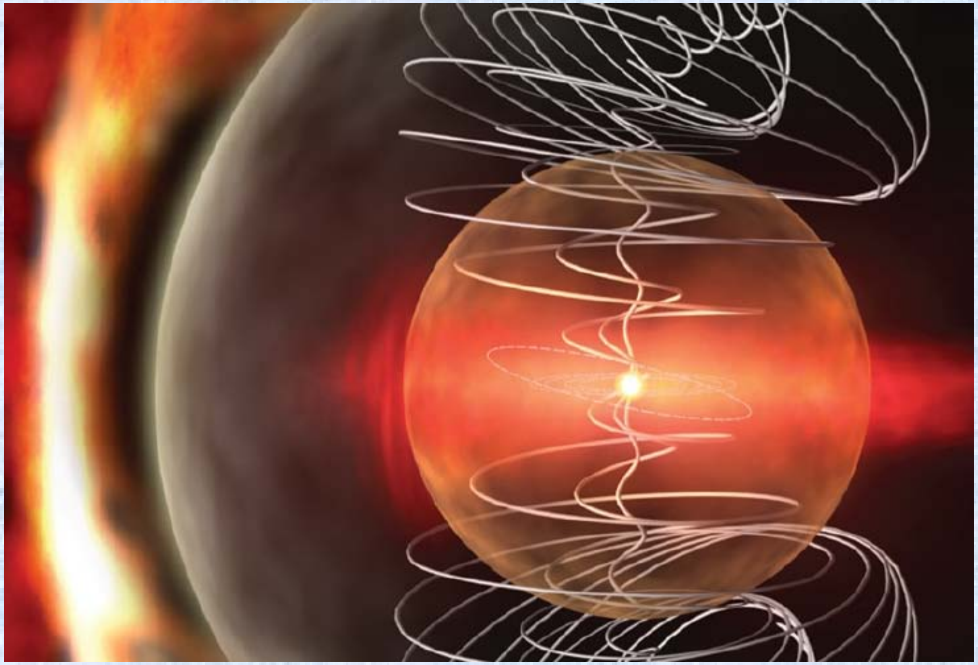

Departamento de Física
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Astropartículas y Física Solar – LAGO. Univ. San Francisco de Quito, 20-24 enero, 2014

Clase 2:

- La atmósfera solar
- El viento solar estacionario
- La espiral de Parker
- Calentamiento local en el viento solar

Static Corona (Chapman, 1957)

- Static, spherical symmetry
- Only force balance between gravity and fluid pressure
- Ideal Gas, isothermal
- R=solar radius
- p_0: pressure at solar surface
- T~10^6 K

$$0 = -\frac{d}{dr}p - \rho\frac{GM_{solar}}{r^2}$$

$$\frac{1}{p}\frac{d}{dr}p = -\frac{Gm_pM_{solar}}{2kT}\frac{1}{r^2}$$

$$p(r) = p_0\exp[\frac{Gm_pM_{solar}}{2kT}(\frac{1}{r}-\frac{1}{R})]$$

$$p(r)\xrightarrow[r\to\infty]{} p_0\exp[-\frac{Gm_pM_{solar}}{2kTR}] \sim 3\times10^{-4}p_0$$

Descubrimiento del **Viento Solar** (~50 años atrás)

- Dirección 2da cola de cometas → anticipó viento solar
- Biermann (1951) estimó correctamente su velocidad (~ 400 km/s)
- Parker (1958) lo predijo teóricamente. Gravedad solar insuficiente para sostener atmósfera estática (**alta temperatura coronal**)
- En 1959 se observó por primera vez el viento solar con las sondas espaciales soviéticas Luniks

- $T \sim 10^5$ K → plasma (mayoría protones y electrones)
- 10 partículas por cm^3 cerca de la Tierra
- Flujo de materia ~ $3x10^9$ kg/seg
(~ masa equivalente a la energía de fotones radiados)

The Solar Wind

MHD

Exospheric models

Modelos exosféricos para el viento solar

- Gas en evaporación desde la corona solar
- Similar a exosfera terrestre (e.g., ∃ exobase), pero: {$g_S >> g_T$, $T_{\infty S} >> T_{\infty T}$, plasma no neutro}
- Exobase (λ_{mfp} ~ H): $r_{exobase}$ ~ 3 R_S
- Velocidad escape

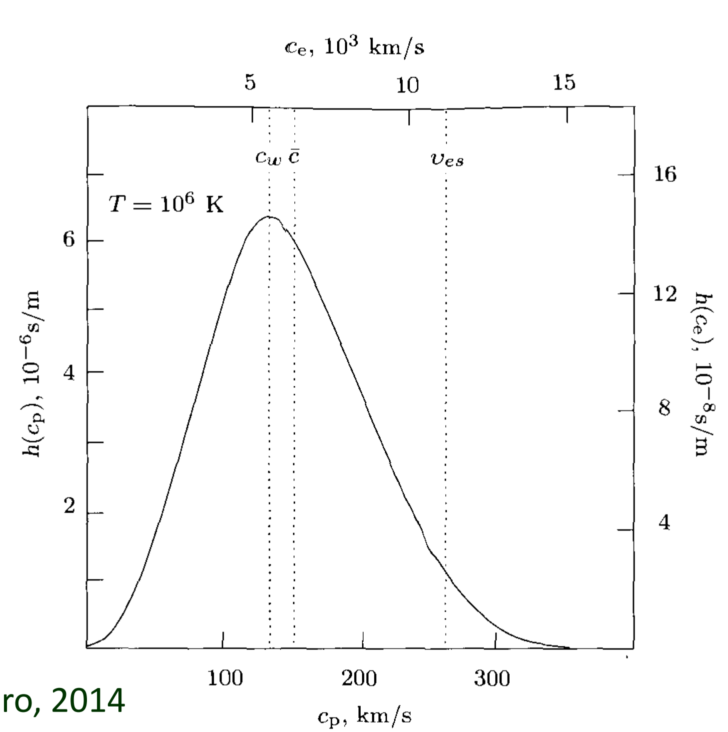
$$v^{\mathrm{p}}_{es} = \sqrt{g_S(r)\ r}$$

v_{es}^{e} ~ 43 v_{es}^{p}

$$v^{\mathrm{e}}_{es} = \sqrt{\frac{m_{\mathrm{p}}}{m_{\mathrm{e}}}}\ v^{\mathrm{p}}_{es}$$

- La diferencia entre v_{es}^{e} y v_{es}^{p} produciría Sol con carga + (**E**)

  (e- escapan mas rápido que p+ !!!)
  Entonces el campo **E** de polarización:
  Frena e- y acelera p+



Modelo de Parker: Viento Solar radial estacionario isotérmico

Conservación masa

$$\frac{\partial}{\partial t}\rho + \nabla \bullet (\rho \mathbf{U}) = 0 \qquad r^2 \rho(r) U(r) = A$$

Conservación momento (desprecio fuerza magnética, ya que B es radial cerca del Sol y la inercia gana lejos del Sol)

$$\rho \frac{D}{Dt}\mathbf{U} = -\nabla p + \mathbf{J}\times\mathbf{B} - \frac{\rho G M_{Sun}}{r^2}\hat{\mathbf{r}} + \rho\mathbf{F} \qquad U\frac{d}{dr}U = -\frac{1}{\rho}\frac{d}{dr}p - \frac{G M_{Sun}}{r^2}$$

Gas ideal isotérmico

$$pV = \sum_j^{especies} N_j k_B T_j = (N_p + N_e) k_B T = 2 N k_B T \qquad \frac{dp}{dr} = 2 k_B T \frac{dn}{dr}$$

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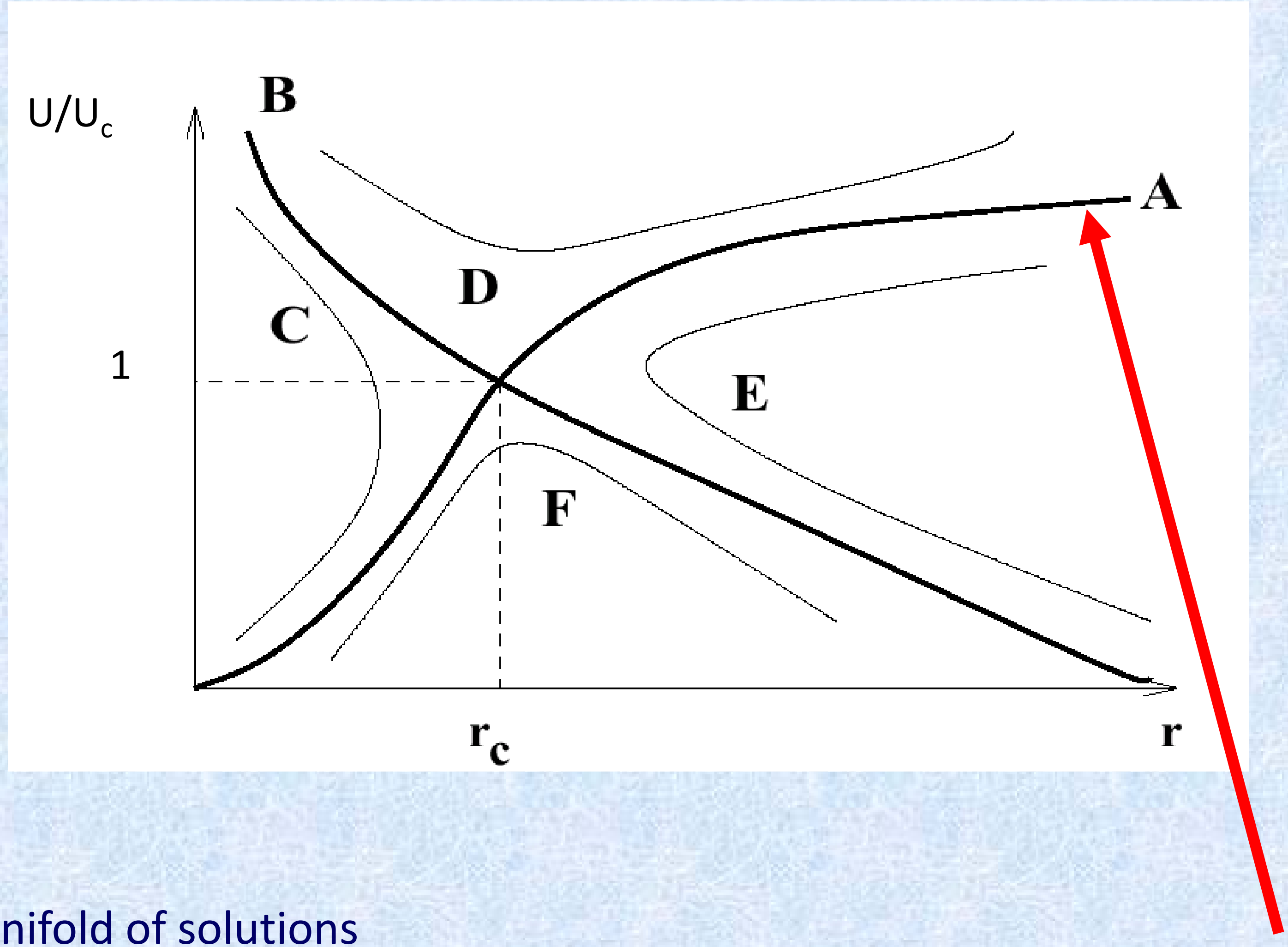
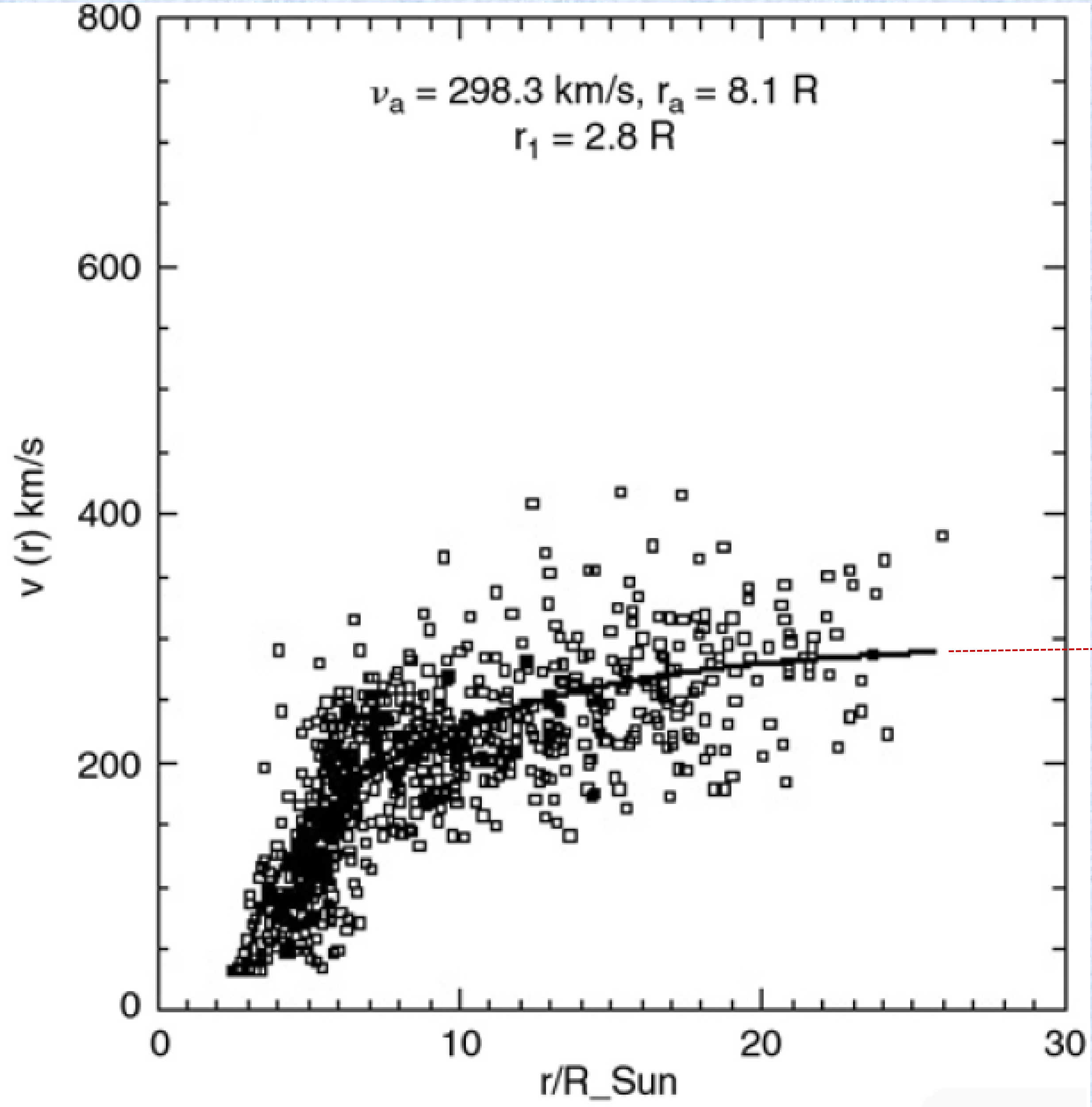
$$UU' - 2k_B T(2U + rU') + \frac{GM_{Sun}}{r^2} = 0 \qquad r_c = \frac{GM_{Sun} m_H}{4 k_B T} \ \text{(critical point)}$$

$$\ln\left(U^2 / U_C^2\right) - \frac{U^2}{U_C^2} + 4\left(\frac{r_c}{r} + \ln(r / r_c)\right) = C \qquad U_c \doteq U(r_c) = \sqrt{\frac{2k_B T}{m_H}} \ \text{(critical speed)}$$



- Manifold of solutions
- U monotonically from sub-sonic to super-sonic in SW → branch **A**
- For the SW: r_c ~ 10 R_{Sun} ~ 0.05 AU
- U → constant for $r \gg r_c$

Observed profile of SW speed



Observations (difference images from SOHO LASCO) of plasma traces

Fitted model given by Sheeley et al.[1997]

Figure from McComas et al., Rev. of Geophysics [2007]

Velocities in agreement with in situ observations (Helios S/C) near 0.3 AU

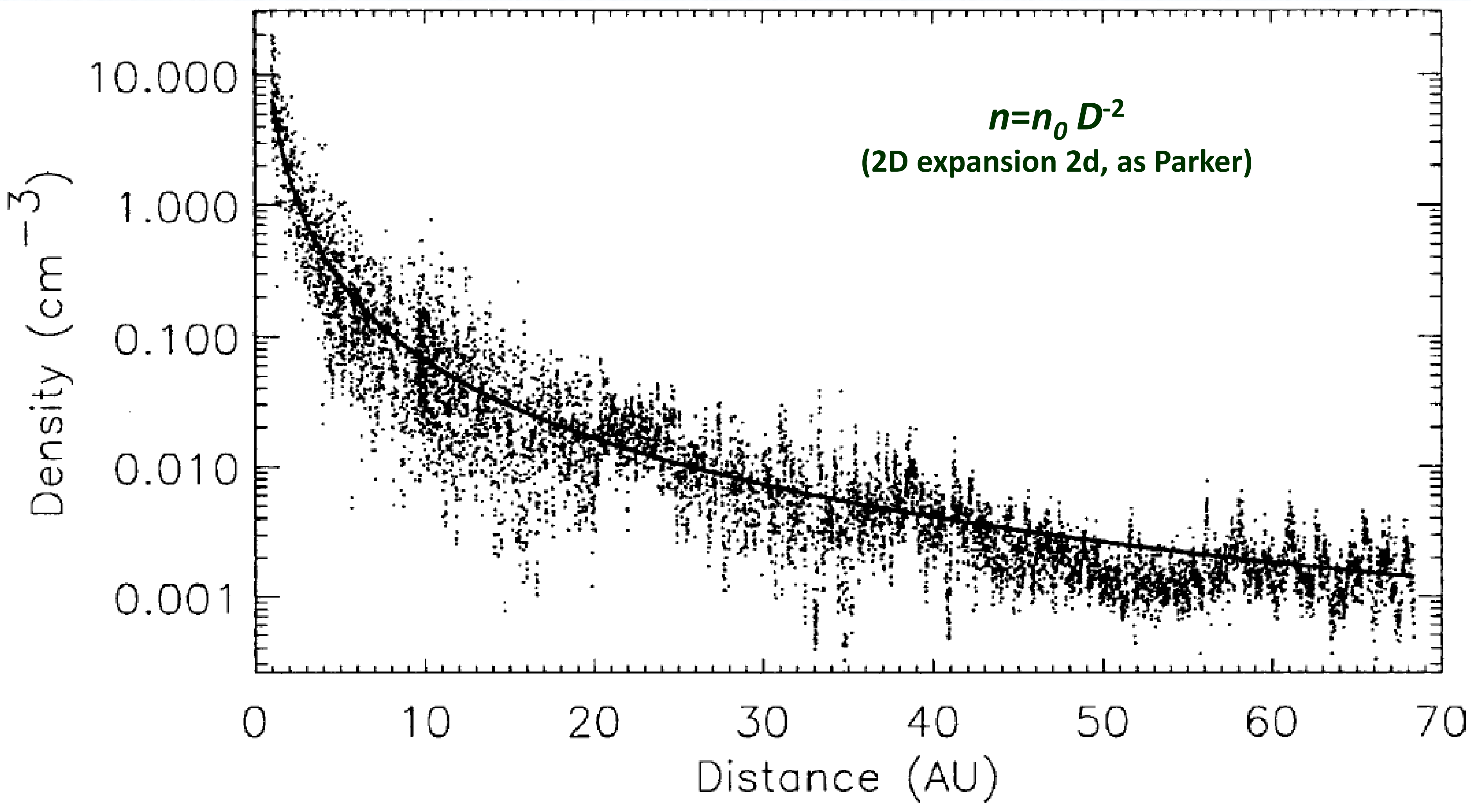
Stationary simplified Solar Wind

Assuming V_r=cte (2D expansion)

Conservation of mass → $n_p \sim D^{-2}$

[From Richardson et al., ASR, 2004]

Observations from Voyager



Stationary simple Solar Wind at ecliptic Assuming ideal MHD and V_r=constant

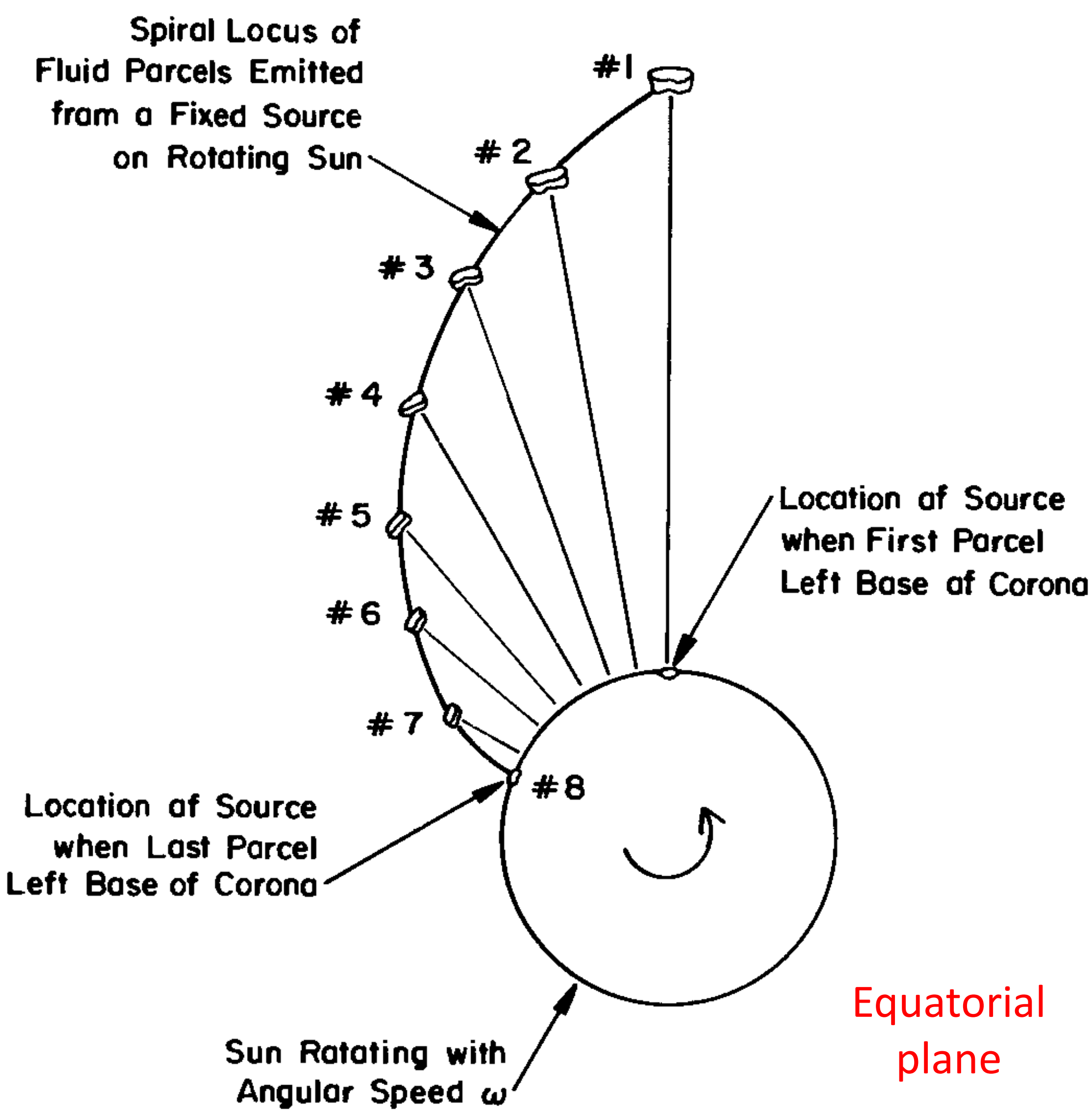
Conservation of magnetic flux in an elementary fluid parcel

→ $B_r \sim D^{-2}$ & $B_\phi \sim D^{-1}$

Then $B \sim \mathrm{sqrt}(D^{-2} + D^{-1})$

angle (**B**, radial from Sun): $\tan(\alpha)=B_\phi/B_r \sim D$

Note that at ecliptic plane $B_z \sim 0$

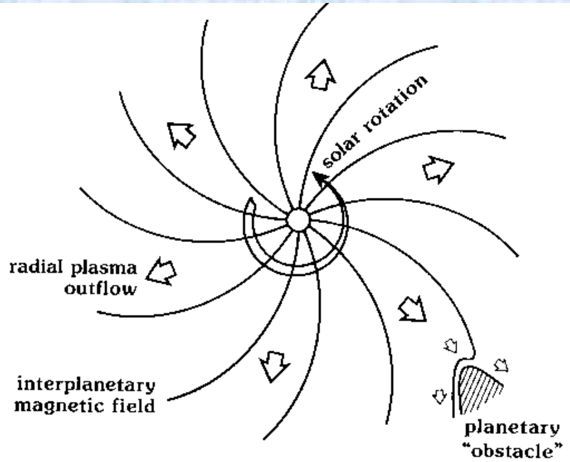


Equatorial plane

Parker Spiral from:

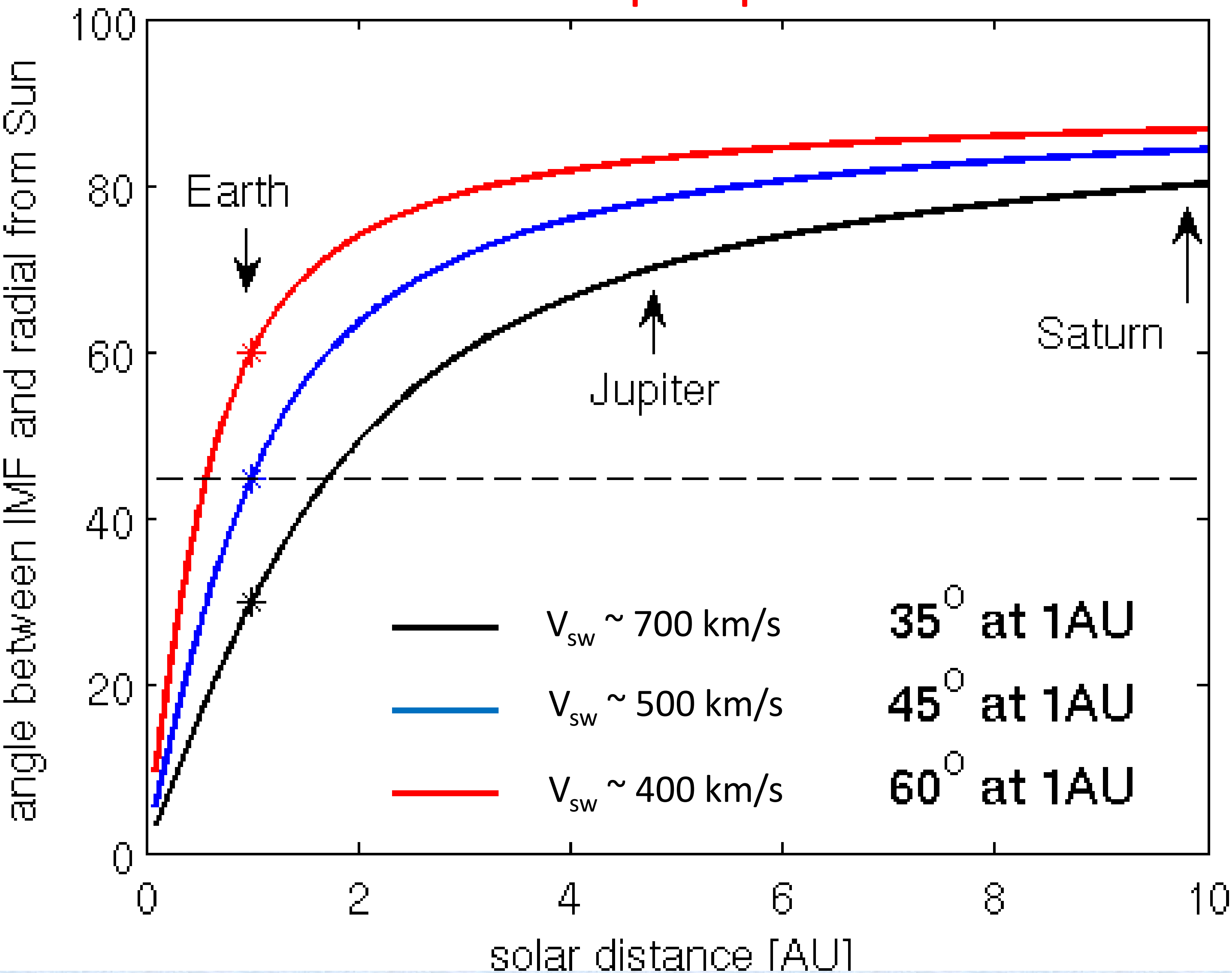
- Solar rotation
- Radial flow
- 'Frozen-in' condition

α~45° for 1AU



$$\frac{B_\phi}{B_r} = \tan(\alpha) = \frac{\Omega\, D}{U_{sw}}$$

At the ecliptic plane

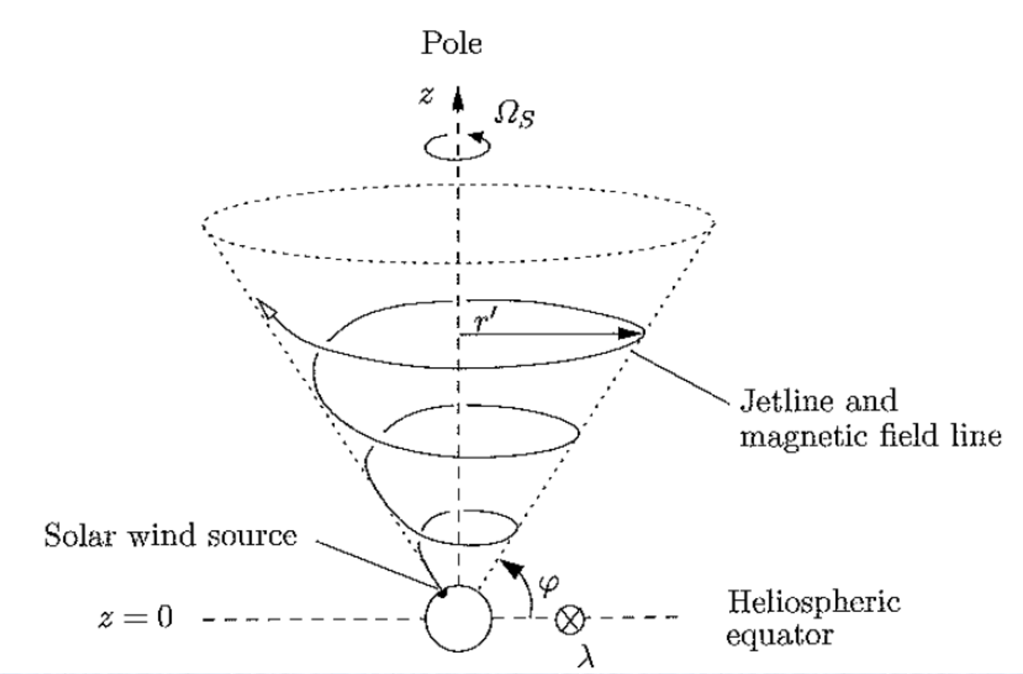


Interplanetary Magnetic Field (3D) in stationary Solar Wind (simple model)

$$\mathbf{B} = B_r(r)\hat{\mathbf{r}} + B_\lambda(r)\hat{\boldsymbol{\lambda}}$$

$$B_r(r) = B_0\left(\frac{r_0}{r}\right)^2$$

$$B_\lambda(r) = -B_0 \frac{r_0\,\Omega_{Sun}}{U_{sw}}\left(\frac{r_0}{r}\right)\cos(\varphi)$$



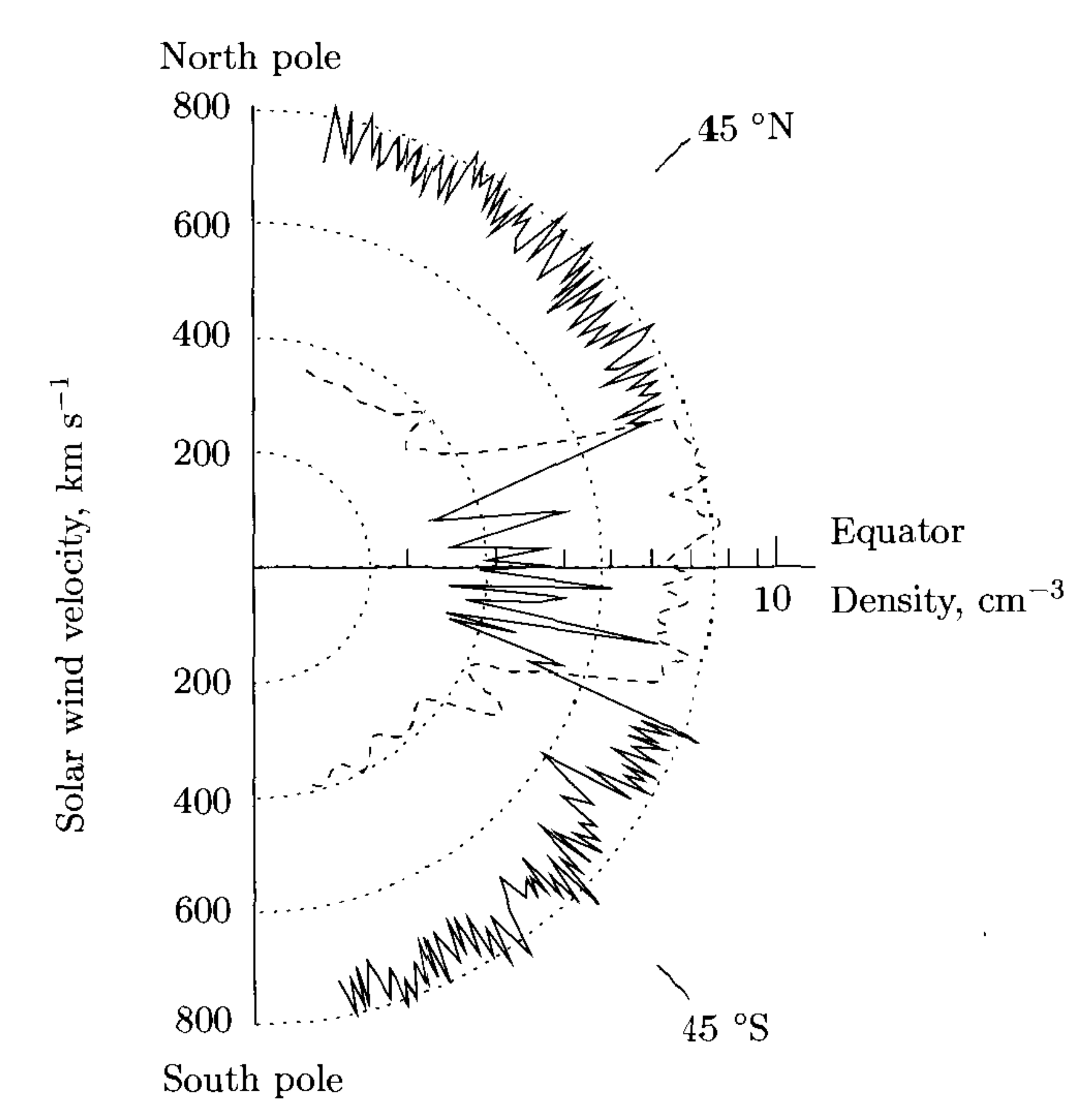
$$B(r) = B_0\left(\frac{r_0}{r}\right)^2\sqrt{1+\frac{r^2\,\Omega_{Sun}{}^2\cos^2(\varphi)}{U_{sw}{}^2}} \xrightarrow[r>>1AU]{} \frac{B_0 r_0{}^2\Omega_{Sun}\cos(\varphi)}{rU_{sw}}$$

Estructura del Viento solar en latitud:

viento rápido

y

viento lento

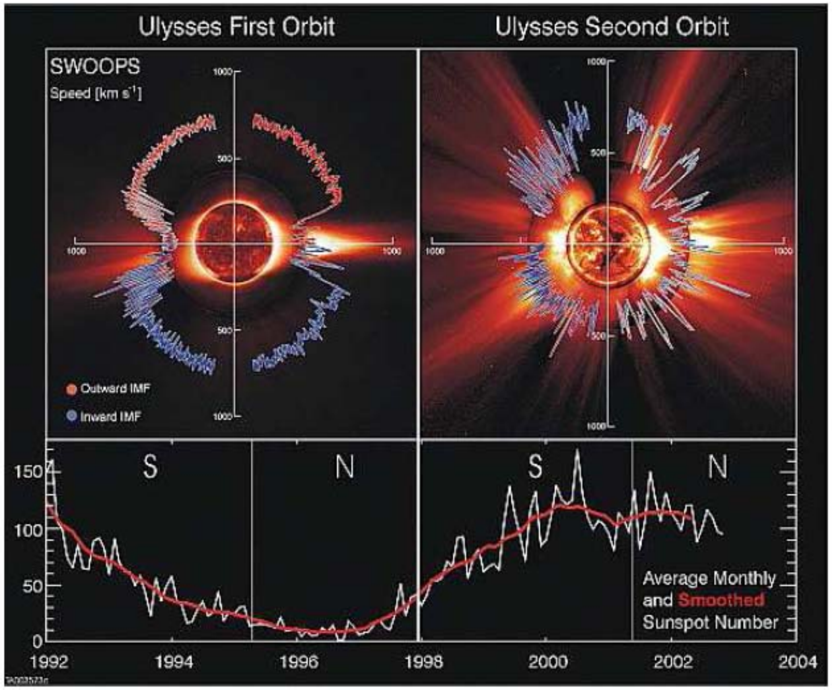


Differences of Slow and Fast SW properties

Slow SW

v ~ 250 - 400 Km/s
$n \sim 10 - 40\ cm^{-3}$
$T \sim 10^3 - 10^4\ {}^0K$

From [McComas et al., 2003]



Fast SW

v ~ 600 - 800 Km/s
$n \sim 1 - 4\ cm^{-3}$
$T \sim 10^4 - 10^5\ {}^0K$

- Higher density
- Cooler

- Lower density
- Hotter

- Lower level of fluctuations
- $\delta \mathbf{b}$ poorly correlated with $\delta \mathbf{u}$
- Fluctuations of $\delta\rho$

(but incompressibility remains as good assumption)

- High level of $\delta|\mathbf{b}|$ ($\delta|\mathbf{b}| \sim B_0$)

- Higher level of fluctuations
- High level of $\delta \mathbf{b}$ and $\delta \mathbf{u}$

($|\delta \mathbf{b}| \sim B_0$, $|\delta \mathbf{u}| \sim U_0$)

- $\delta \mathbf{b}$ highly correlated with $\delta \mathbf{u}$
- Low level of $\delta\rho$ ($\delta\rho \ll \rho_0$)
- Low level of $\delta|\mathbf{b}|$ ($\delta|\mathbf{b}| \ll B_0$)

Modelo dinámico para flujo de Viento Solar

Conservación de la masa
(Ley de Lavoisier)

$$\frac{\partial}{\partial t}\rho + \nabla \bullet (\rho \mathbf{U})$$

Conservación del momento lineal
(2^{da} ley de Newton)

$$\rho \frac{D}{Dt}\mathbf{U} = -\nabla p + \mathbf{J} \times \mathbf{B} - \frac{\rho G M_{Sun}}{r^2}\hat{\mathbf{r}} + \rho \mathbf{F}$$

Conservación de la energía interna,
aplicada a un elemento de fluido
(1^{era} ley de la termodinámica)

$$\frac{D}{Dt}\delta E = -p\frac{D}{Dt}\delta V + \delta M\, Q - \delta V\, \nabla \bullet \mathbf{q}$$

Modelo radial para Viento Solar estacionario

Conservación masa

$$r^2 \rho(r) U(r) = c$$

Conservación momento (desprecio fuerza magnética, ya que B es radial cerca del Sol y la inercia gana lejos del Sol)

$$U \frac{d}{dr} U = -\frac{1}{\rho} \frac{d}{dr} p - \frac{G M_{Sun}}{r^2} + F_r$$

Conservación energía

$$E = \frac{f \rho k_B T \delta V}{2\mu} \ , \ \ p = \frac{\rho k_B T}{\mu} \ , \ \ \mu = \frac{\sum n_i m_i}{\sum n_i}$$

$$\frac{f}{2} \frac{d}{dr} T - T \frac{d}{dr} \ln(\rho) = \frac{\rho}{T^{f/2-1}} \frac{d}{dr} (\frac{T^{f/2}}{\rho}) = \frac{\mu}{k_B} \left(\frac{Q}{U} - \frac{d}{dr} (\frac{q}{\rho U}) \right)$$

Modelo radial para Viento Solar estacionario

Conservación masa

$$r^2\rho(r)U(r) = c$$

Conservación momento (desprecio fuerza magnética, ya que B es radial cerca del Sol y la inercia gana lejos del Sol)

$$U\frac{d}{dr}U = -\frac{1}{\rho}\frac{d}{dr}p - \frac{GM_{Sun}}{r^2} + F_r$$

Conservación energía

$$E = \frac{f\rho k_B T\delta V}{2\mu} \;, \;\; p = \frac{\rho k_B T}{\mu} \;, \;\; \mu = \frac{\sum n_i m_i}{\sum n_i}$$

$$\frac{f}{2}\frac{d}{dr}T - T\frac{d}{dr}\ln(\rho) = \frac{\rho}{T^{f/2-1}}\frac{d}{dr}\left(\frac{T^{f/2}}{\rho}\right) = \frac{\mu}{k_B}\left(\frac{Q}{U} - \frac{d}{dr}\left(\frac{q}{\rho U}\right)\right)$$

Viento Solar Esférico, radial, estacionario, *U=U₀*

Conservación masa $\rho(r) = c\, r^{-2}$

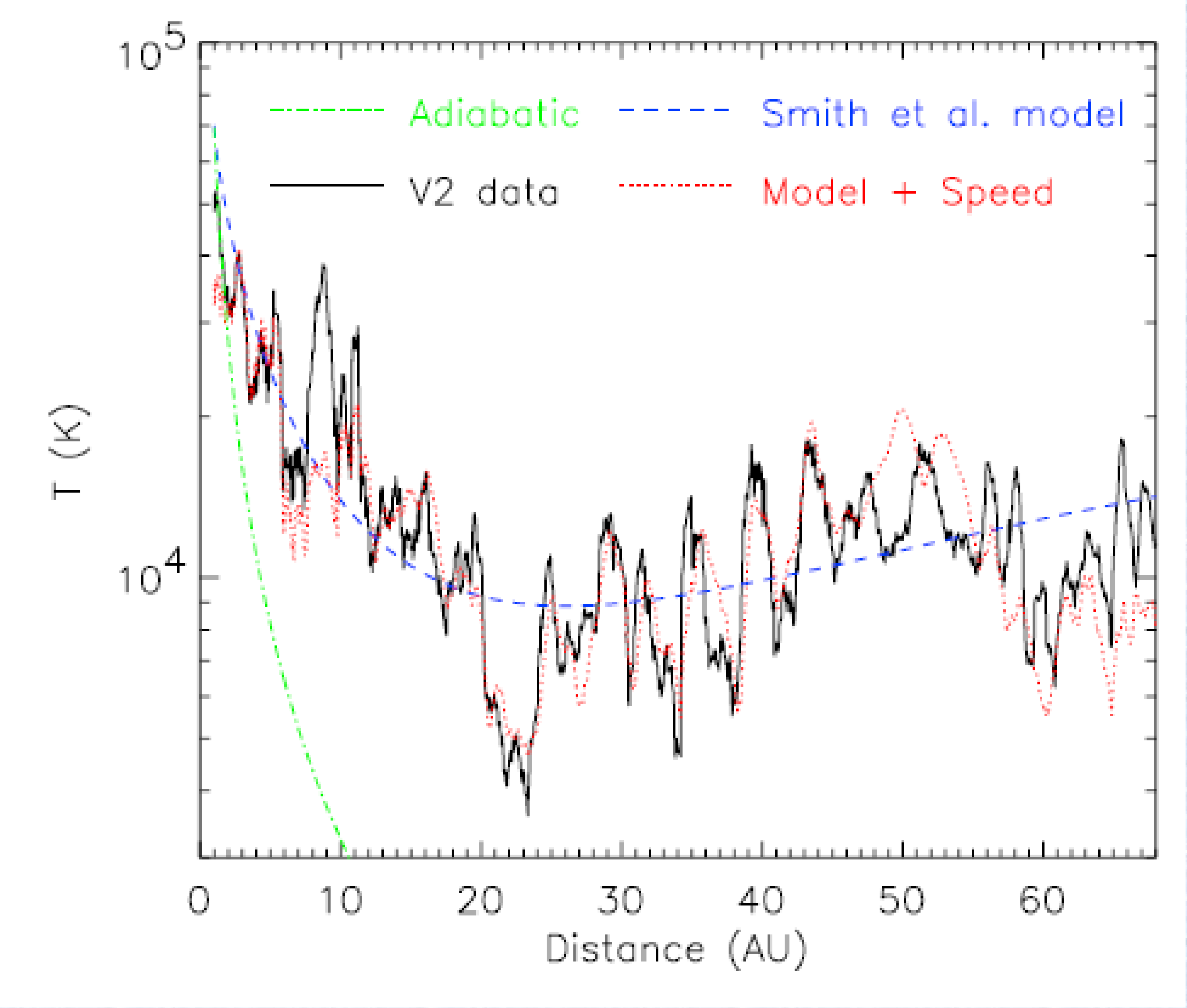
Conservación momento lineal $$-\frac{1}{\rho}\frac{d}{dr}p - \frac{GM_{Sun}}{r^2} + F_r = 0$$

Conservación energía: perfil T(r) $$\frac{r^{-2}}{T^{f/2-1}}\frac{d}{dr}\left(\frac{T^{f/2}}{r^{-2}}\right) = \frac{\mu}{k_B}\left(\frac{Q}{U} - \frac{d}{dr}\left(\frac{q}{cr^{-2}U}\right)\right)$$

Sin flujo de calor ni calentamiento (q=0=Q)
(3 grados de libertad por partícula: f=3)

$$\frac{r^{-2}}{T^{f/2-1}}\frac{d}{dr}\left(\frac{T^{f/2}}{r^{-2}}\right) = 0 \longrightarrow T(r) = T_0\left(\frac{r}{r_0}\right)^{-4/3}$$

Local heating in the Solar Wind



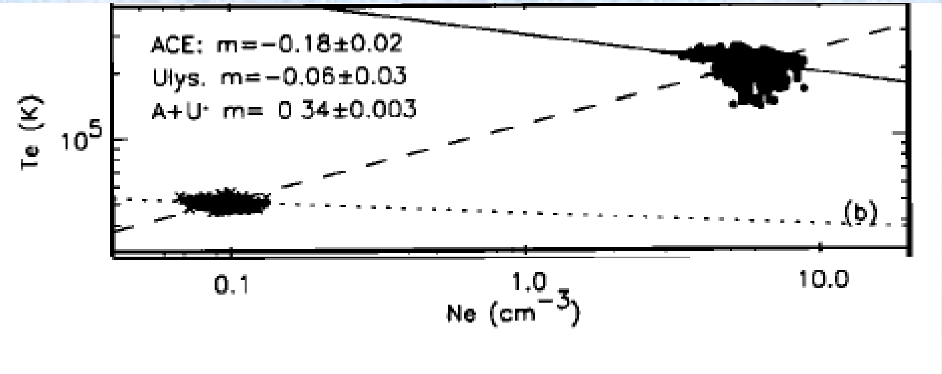
Presence of Turbulence in SW:
Turbulent dissipation !!

[From Richardson & Smith, GRL, 2003]

Multi-spacecraft study of one single MC

For a perfect gas $T \sim N^{\gamma-1}$ (γ the polytropic index, associated with heating of the gas)
$\gamma=1 \rightarrow$ isothermal expansion & $\gamma=5/3 \sim 1.67 \rightarrow$ adiabatic expansion

From observations of the same MC (March 1998) at 1AU (ACE) and ~5AU (Ulysses), possible to get an estimation of γ



[From Skoug et al., JGR 2000]

$T_e \sim N_e^{0.34}$ ($\gamma \sim 1.34$)

A very different result from a non-correct estimation of γ using single S/C observations

However, a real theoretical approach needs more ingregients (e.g., kinetic effects and anomalous heat fluxes)

Fin clase 2