

Solar wind

- First ideas on non-electromagnetic Sun-Earth connections in 19th century
- Chapman (1929): solar flares emit plasma clouds?
 - cause of magnetic disturbances
 - how would they escape from the solar g-field?
 - escape velocity 618 km/s → proton energy 2 keV ~ 20 MK!
- Bierman: comet tails deflected a bit from the anti-sunward direction → corpuscular radiation with speed $\ll c$
- Alfvén: flow has to be magnetized
- In-situ discovery of the solar wind
 - Lunik III and Venus I
 - Mariner II

Chapman's static coronal model

- Assume:
 - gas is at rest
 - heat flux $4\pi r^2 \kappa \frac{dT}{dr}$ constant. Thermal conductivity $\kappa = \kappa_0 T^{5/2}$
- Solution: $T(r) = T_0 (r/r_0)^{-2/7}$
- Hydrostatic equilibrium: $\frac{dp}{dr} = -\frac{Gm_\odot mn}{r^2}$
- IDG $\rightarrow p = p_0 \exp \left\{ \frac{7Gm_\odot mn_0}{5p_0 r_\odot} \left[\left(\frac{r_\odot}{r} \right)^{5/7} - 1 \right] \right\} \rightarrow p_0 \exp \left(\frac{-7U}{5k_B T_0} \right)$
- Too large compared to p_{is} \rightarrow expansion

Parker's model of the solar wind

- Radial, isothermal expansion:

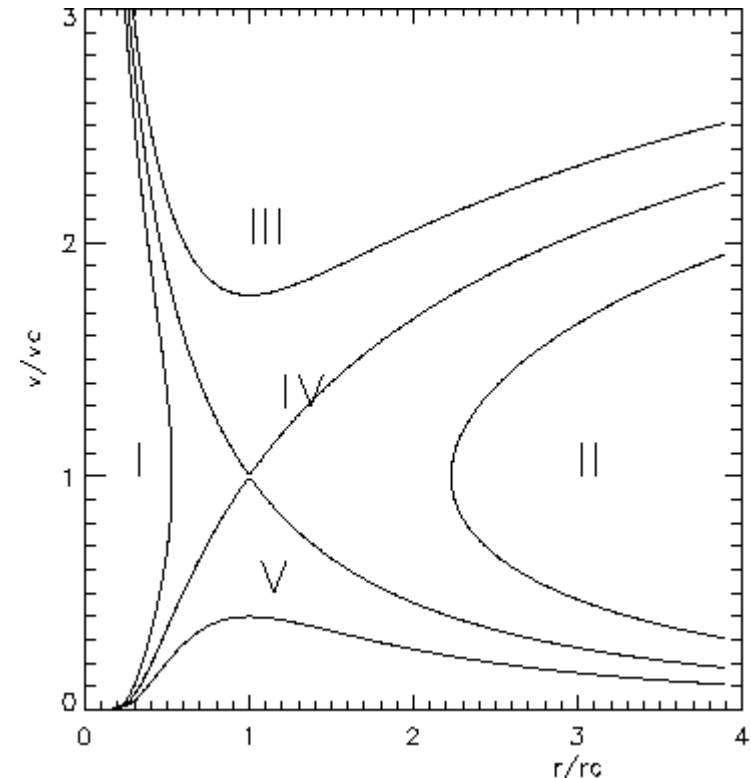
$$\frac{1}{r^2} \frac{d}{dr} (r^2 n v) = 0$$

$$m n v \frac{dv}{dr} = - \frac{dp}{dr} - \frac{GM_{\odot} m n}{r^2}$$

$$p = n k_B T$$

$$= m n v_c^2; \quad v_c = \sqrt{k_B T / m} \quad \text{sound speed}$$

$$\left(v - \frac{v_c^2}{v} \right) \frac{dv}{dr} = \frac{2v_c^2}{r} - \frac{GM_{\odot}}{r^2}$$



- Critical point at $v = v_c, r = r_c = \frac{GM_{\odot}}{2v_c^2}$
 - for $T = 1 \text{ MK}, v_c = 130 \text{ km/s}, r_c = 5.8 R_{\odot}. (m = \frac{1}{2} m_p)$

$$\left(\frac{v}{v_c} \right)^2 - \ln \left(\frac{v}{v_c} \right)^2 = 4 \ln \frac{r}{r_c} + 4 \frac{r_c}{r} + C$$

Energy balance

- Steady-state: divergence of energy flux vanishes

$$\nabla \cdot \left[\mathbf{v} \left(\frac{1}{2} \rho v^2 + \underset{\uparrow}{H} - \frac{Gm_{\odot}\rho}{r} \right) - \kappa \nabla T + \underset{\uparrow}{\mathbf{F}_R} + \underset{\uparrow}{\mathbf{F}_H} \right] = 0$$

enthalpy = $\rho(U + p/\rho)$ radiative losses heating sources

- Inner corona:
 - below T-maximum, heat flux inwards
 - balanced by radiative losses (H-alpha)
- Outer corona:
 - above T-maximum, heat flux outwards
 - Chapman: only this part included
 - Parker: neglect of T-gradients altogether

Energy considerations

$$n = n(r), \quad T = T(r), \quad n_e \approx n_i \approx n$$

$$p = n_e k_B T + n_i k_B T = 2n k_B T$$

$$U = \frac{3}{2}(n_e + n_i)k_B T V = 3n k_B T V \quad H = U + pV = 5n k_B T V$$

$$\Phi = -\frac{Gm_\odot mnV}{r} \quad T = 2 \times 10^6 \text{ K} \quad \rightarrow \quad \frac{H}{|\Phi|} \approx 0.5$$

SW observations: $H + Q = 1.25|\Phi|$

Solar wind energy far from the Sun:

$$nmvr^2 \left(\frac{1}{2}v^2 + \frac{\gamma}{\gamma - 1} \frac{p}{nm} - \frac{Gm_\odot}{r} \right) = r^2 \kappa \frac{dT}{dr} + F_\infty \quad \gamma = 5/3$$

- 1) $T \sim r^{-2/7}$ heat conduction dominates in the far region
- 2) $T \sim r^{-2/5}$ kinetic flux dominates in the far region
- 3) $T \sim r^{-2/3}$ adiabatic expansion

Parker's model for the IMF

- Magnetic field easy to describe in the corotating frame K''
- Velocity components:

$$V_r = \dot{r}; \quad V_\varphi = r \sin \theta \dot{\varphi} = \frac{r_0^2 \Omega_\odot \sin \theta}{r}; \quad V_\theta = r \dot{\theta} = 0$$

$$r'' = r, \quad \theta'' = \theta, \quad \varphi'' = \varphi - \Omega_\odot t \quad \Rightarrow$$

$$V_r'' = V_r; \quad V_\varphi'' = \frac{(r_0^2 - r^2) \Omega_\odot \sin \theta}{r}; \quad V_\theta'' = 0.$$

- In the corotating frame, flow radial at the source surface

$$\Rightarrow \vec{V}''(r_0, \theta, \varphi'') \parallel \vec{B}(r_0, \theta, \varphi'')$$

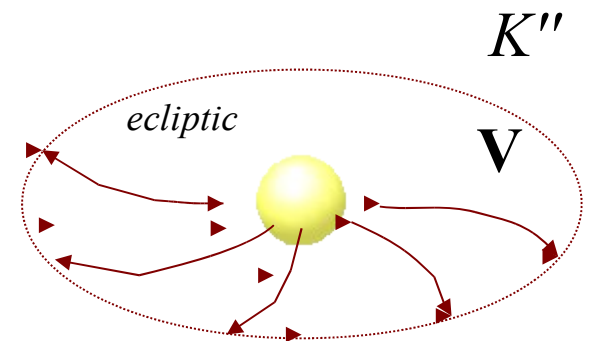
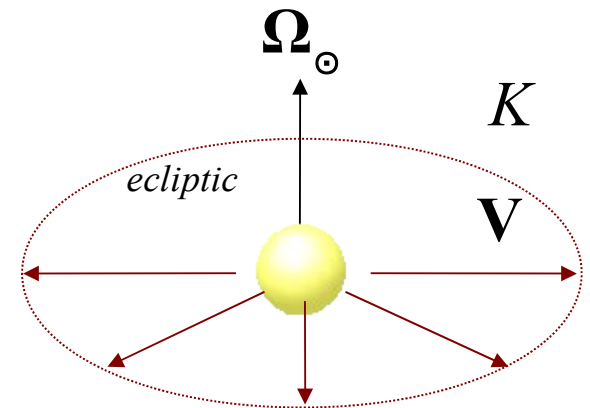
\Rightarrow

Plasma elements emitted from the same corotating point at the source surface are initially connected by a field line.

- High conductivity \Rightarrow connection maintained (flux freezing)

\Rightarrow

$$\vec{B} \parallel \vec{V}'' \text{ everywhere}$$



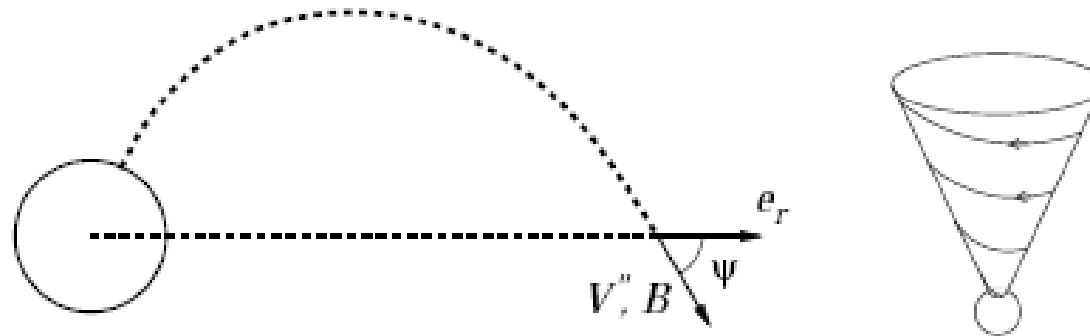
- Therefore, $B_\theta = 0$ and

$$\Rightarrow \boxed{\tan \psi \equiv \frac{B_\varphi}{B_r} = \frac{V_\varphi''}{V_r''} = \frac{(r_0^2 - r^2)\Omega_\odot \sin \theta}{rV_r}} \quad (\psi)$$

- Assume, that $\partial B_\varphi / \partial \varphi = \partial B_r / \partial \varphi = 0$. Thus,

$$0 = \nabla \cdot \vec{B} = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 B_r) \Rightarrow \boxed{B_r = B_0(\theta) \left(\frac{r_0}{r} \right)^2}$$

- Field lines at $\theta = \frac{\pi}{2}$, $r^2 \gg r_0^2$ form an *Archimedean spiral*.



- $B \rightarrow r^{-1}$ in the equatorial plane (the spiral becomes tightly wound)
- $B \rightarrow r^{-2}$ in the direction of the poles

Angular momentum and torque

- Above, we considered the motion of a free plasma parcel and made use of the conservation of angular momentum
- In reality, $\mathbf{J} \times \mathbf{B}$ force exerts a torque to the plasma parcel

$$\mathbf{B} = (B_r, 0, B_\phi), \quad \mathbf{v} = (v_r, 0, v_\phi) \quad \text{functions of } r.$$

$$\nabla \cdot \mathbf{B} = 0 \rightarrow B_r = B_0(r_\odot/r)^2$$

$$\rho(\mathbf{v} \cdot \nabla \mathbf{v})_\phi = (\mathbf{J} \times \mathbf{B})_\phi \quad (\nabla p)_\phi = 0$$

$$\rightarrow r^2 \rho v_r \frac{d}{dr}(r v_\phi) = \frac{1}{\mu_0} r^2 B_r \frac{d}{dr}(r B_\phi) \quad r^2 \rho v_r \text{ and } r^2 B_r \text{ constants}$$

integrate this equation to get

angular momentum per unit mass

$$L = r v_\phi - \frac{r B_r B_\phi}{\mu_0 \rho v_r}$$

← time-integrated torque exerted by the Sun on the SW via the magnetic field

Alfvén radius and magnetic breaking

- We derived

$$B_\phi = \frac{V_\phi - r\Omega}{V_r} B_r \quad L = rv_\phi - \frac{rB_r B_\phi}{\mu_0 \rho v_r}$$

- Define **Alfvénic Mach number** as

$$M_A = \frac{v_r}{v_A} = \frac{v_r \sqrt{\mu_0 \rho}}{B_r} \Rightarrow$$

$$v_\phi = \Omega r \frac{M_A^2 \left(\frac{L}{r^2 \Omega} \right) - 1}{M_A^2 - 1} = \frac{v_r/v_A - 1}{(v_r r^2)/(v_A r_A^2) - 1} \Omega r$$

Critical point, $M_A = 1$, at **Alfvén radius** $r = r_A \Rightarrow L = \Omega r_A^2$

- Close to the Sun $v_\phi \simeq r\Omega$ corotation
- Far from the Sun $v_\phi \simeq r_A^2 \Omega / r$
- Thus, r_A is an effective lever arm for **magnetic breaking**

Solar wind types I

1. Fast wind in high-speed streams

| | |
|-------------------|--|
| High speed | 400 - 800 kms ⁻¹ |
| Low density | 3 cm ⁻³ |
| Low particle flux | 2 x 10 ⁸ cm ⁻² s ⁻¹ |
| Helium content | 3.6 %, stationary |
| Source | coronal holes |
| Signatures | stationary for long times (weeks!) |

2. Low-speed wind near activity minimum

| | |
|--------------------|--|
| Low speed | 250 - 400 km s ⁻¹ |
| High density | 10 cm ⁻³ |
| High particle flux | 3.7 x 10 ⁸ cm ⁻² s ⁻¹ |
| Helium content | below 2 %, highly variable |
| Source | helmet streamers near current sheet |
| Signatures | sector boundaries embedded |

Solar wind types II

3. Low speed wind near activity maximum

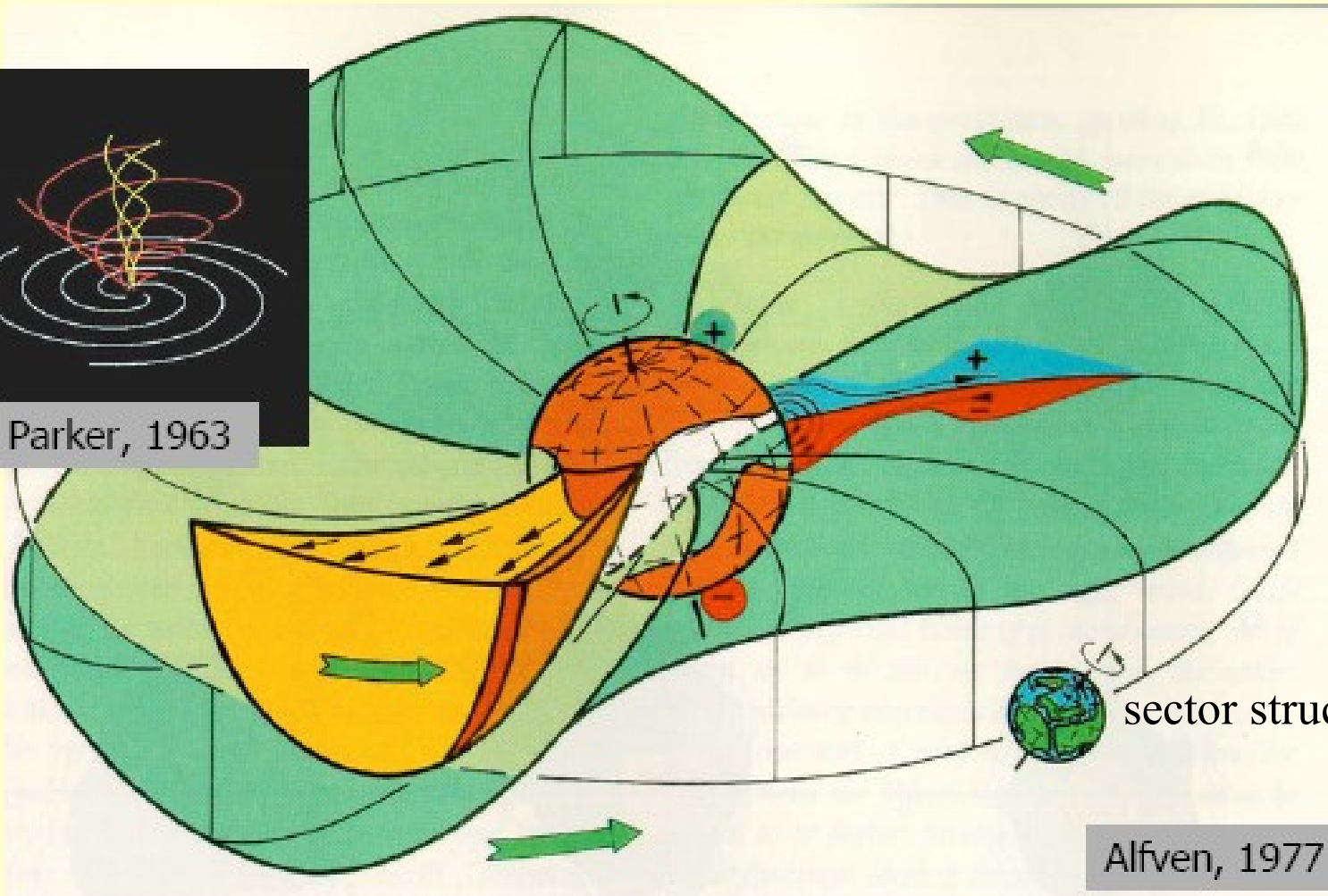
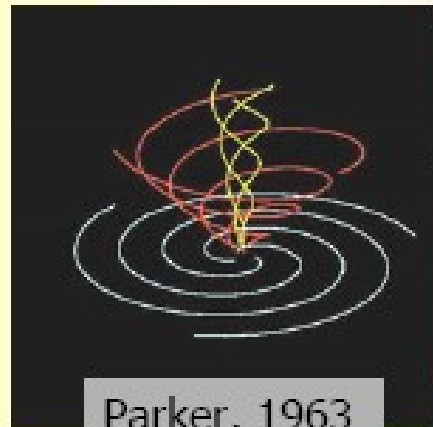
Similar characteristics as 2., except for

| | |
|----------------|----------------------------|
| Helium content | 4%, highly variable |
| Source | related to active regions |
| Signatures | shock waves often imbedded |

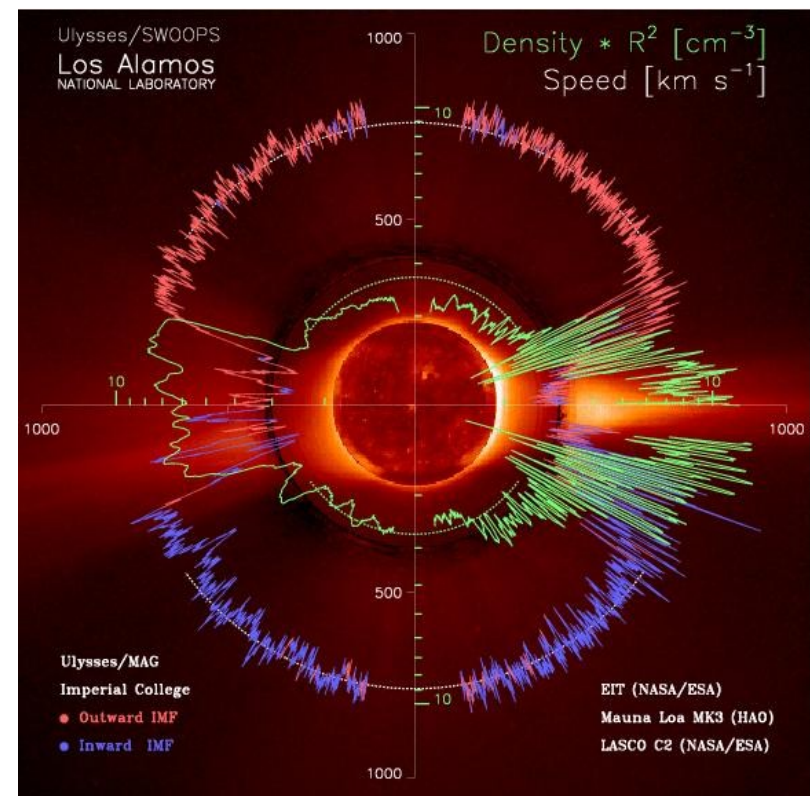
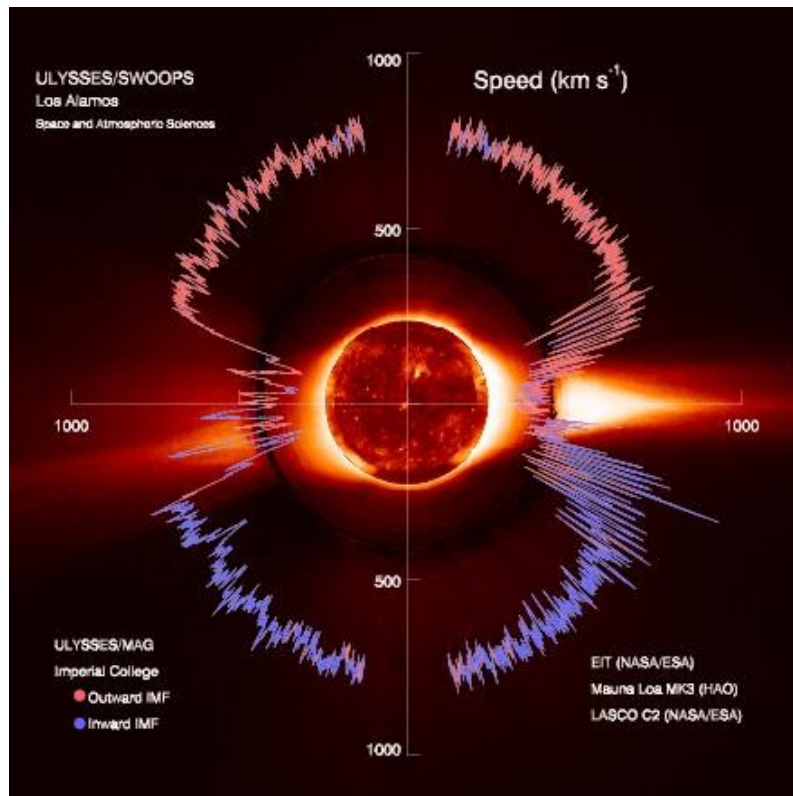
4. Ejecta following interplanetary shocks

| | |
|-------------------------------|---|
| High speed | 400 - 2000 kms ⁻¹ |
| Helium content | up to 30% |
| Other constituents | often Fe ¹⁶⁺ ions; in rare cases He ⁺ |
| Signatures of magnetic clouds | in about 30% of cases |
| Sources | erupting prominences |

Solar wind stream structure and heliospheric current sheet

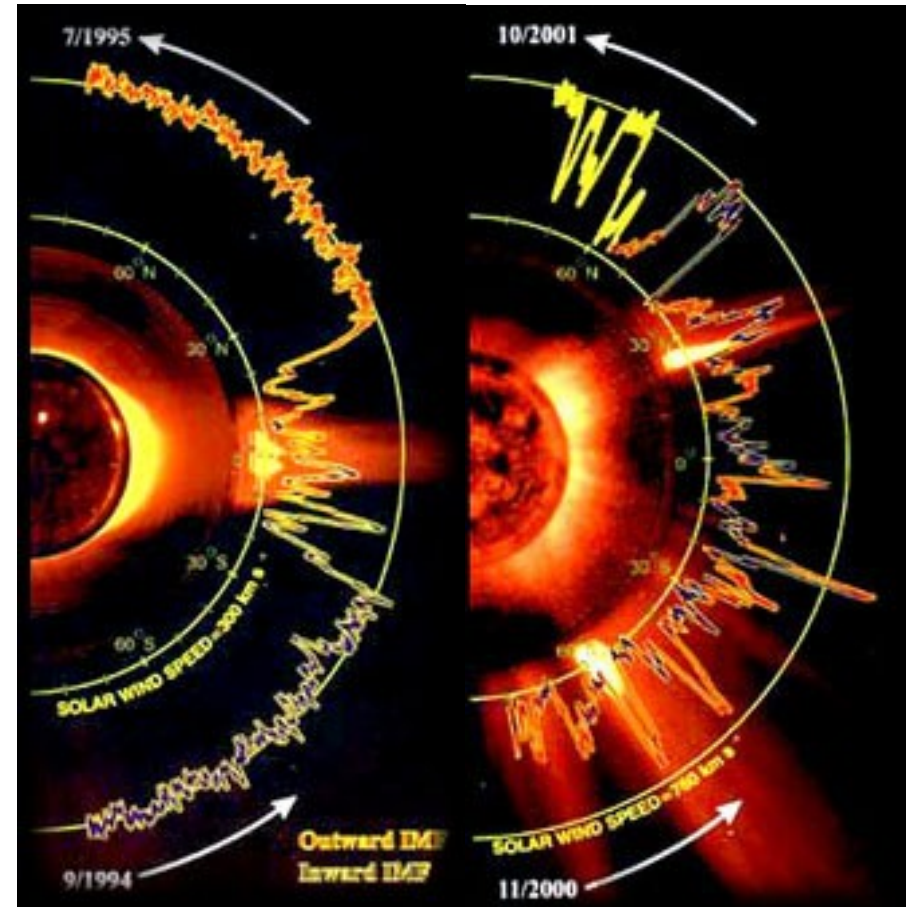


Ulysses observations of fast and slow solar wind (solar minimum)

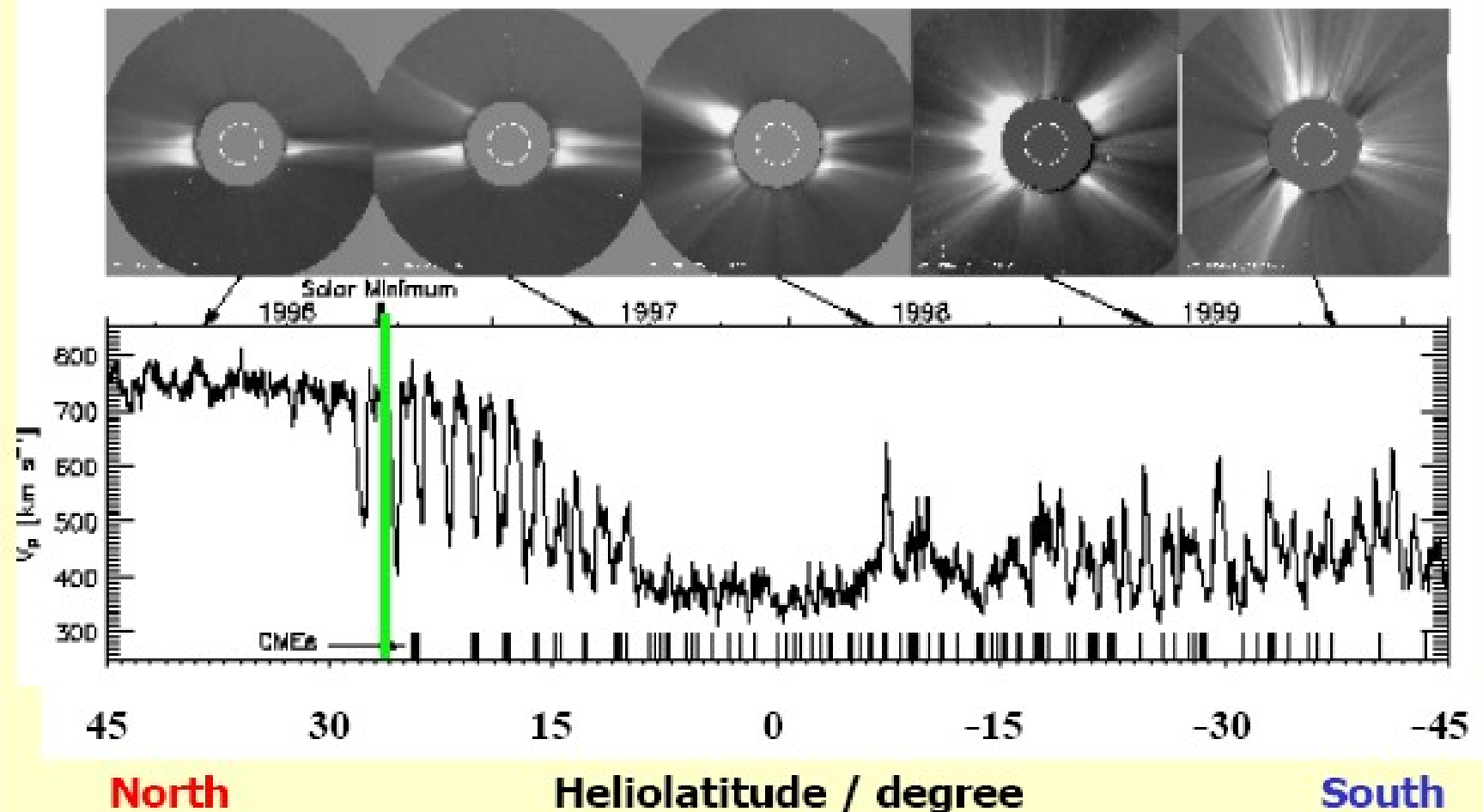


Solar wind structure from minimum to maximum

- The stream structure with fast and slow wind is very clear during solar minimum
 - large polar corona holes →
 - large regions of fast wind
- During solar maximum, clean fast streams are much rarer
 - coronal holes smaller in size and distributed more randomly on the solar surface



Changing corona and solar wind

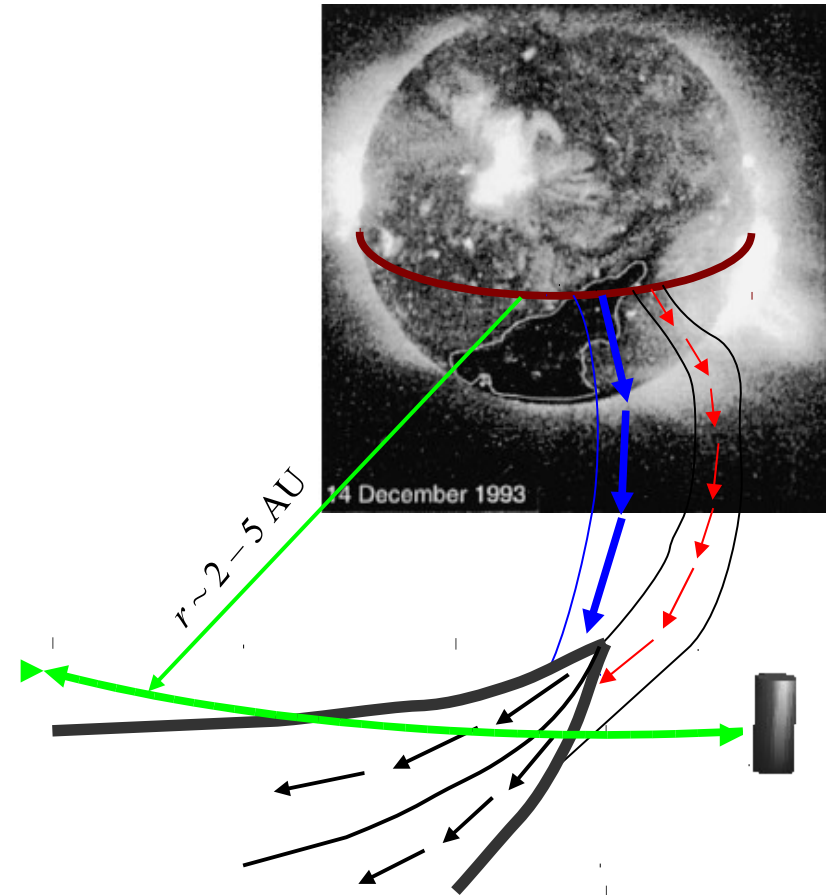


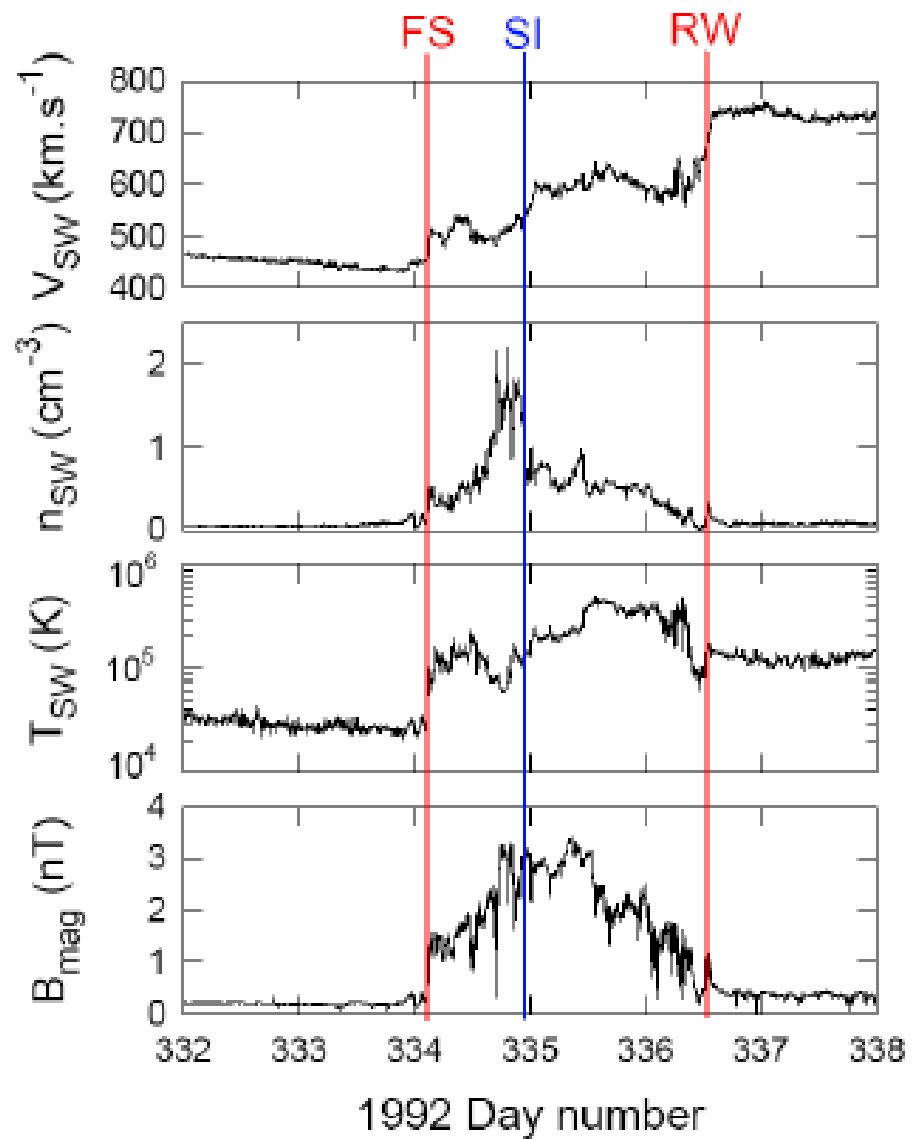
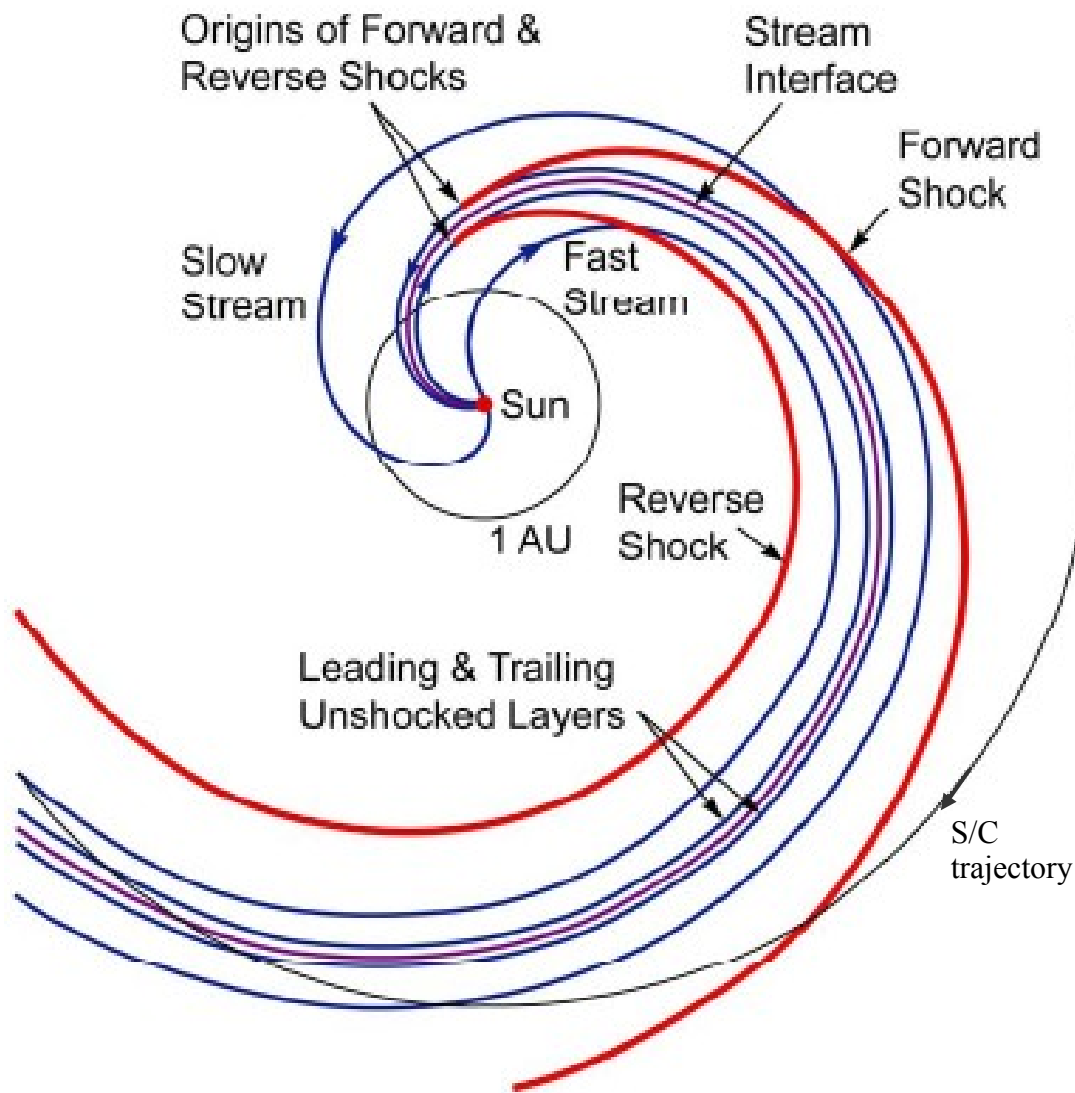
McComas et al., 2000

LASCO/Ulysses

Corotating interaction regions

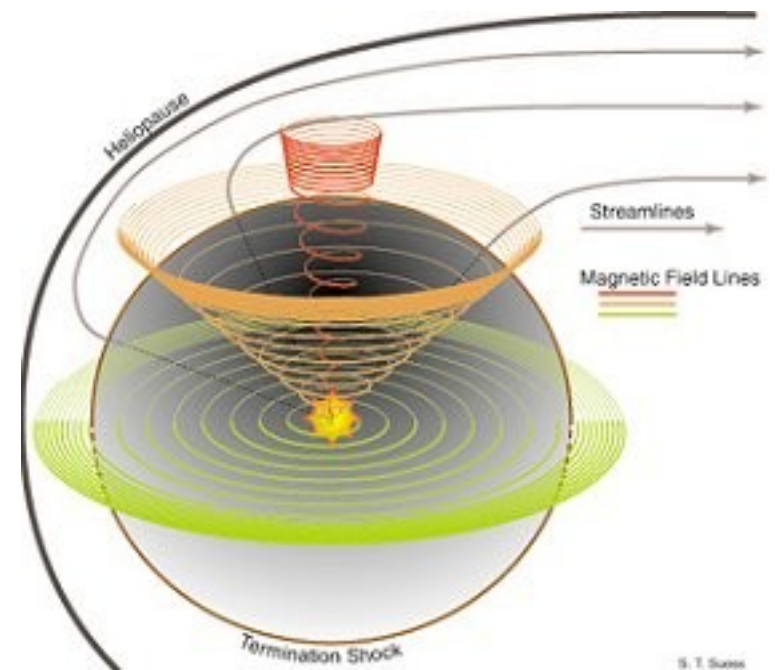
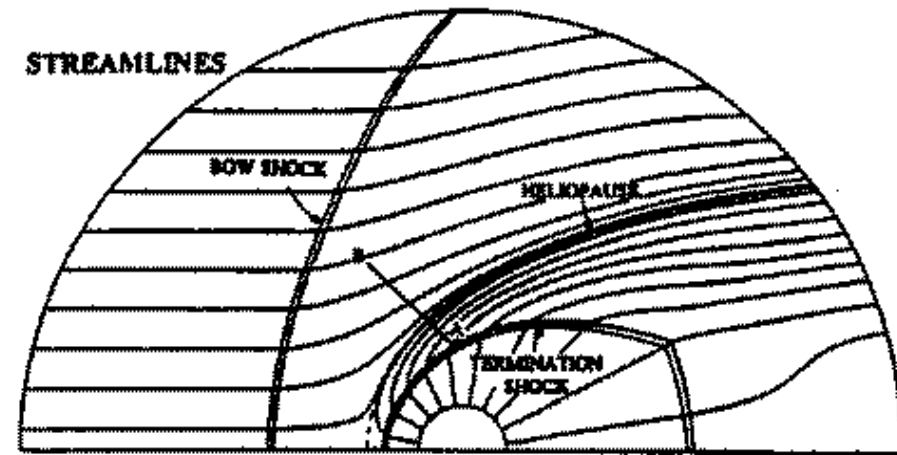
- Coronal hole boundaries are not aligned with latitudes
 - slow solar wind is caught up by a trailing faster stream
 - two shock waves (forward and reverse) form
- the region between the shocks called a corotating interaction region (CIR)
- structure is stable for many solar rotations in the frame co-rotating with the Sun
- CIRs form at radial distances between 2 – 5 AU from the Sun





Heliospheric structure

- The solar wind expands up to $r \sim 90$ AU as a supersonic radial flow
 - supersonic flow can have no feeling of the surrounding interstellar medium \rightarrow termination shock
 - Voyager 1 crossed it in Dec 2004, V2 in Sep 2007
- Heliopause
 - surface separating the sub-sonically flowing solar and interstellar (IS) plasmas
- Bow shock
 - as the heliosphere probably has a supersonic velocity wrt. the LISM, a bow shock is formed



Heliopause position – an estimation

$$\rho_S v_S^2 + \frac{B_S^2}{2\mu_0} = \rho_G v_G^2 + p_G + \frac{B_G^2}{2\mu_0}$$

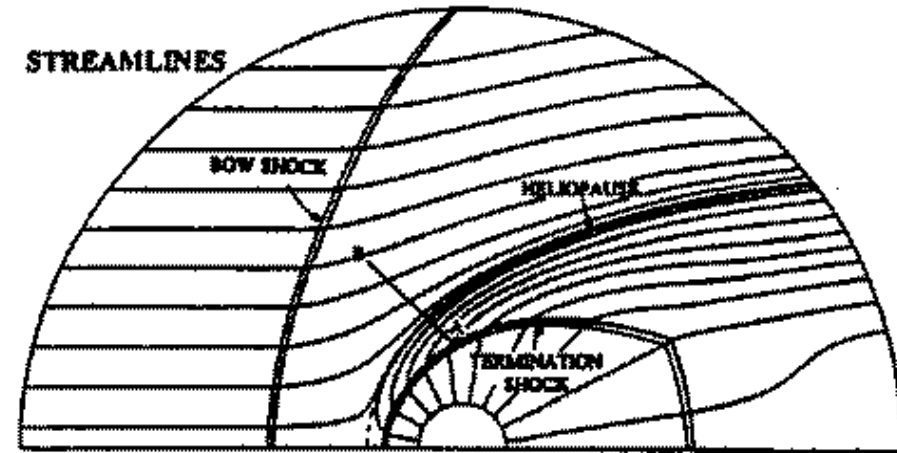
$$B_G \leq 0.5 \text{ nT} \rightarrow 10^{-13} \text{ N/m}^2 \text{ (i.e., 0.1 pPa)}$$

$$n_{pG} < 0.1 \text{ cm}^{-3}, V_G \sim 25 \text{ km/s}$$

dynamic pressure also of the order of 0.1 pPa

total pressure at most 0.1 pPa.

$$\rho_S = \rho_{1\text{AU}} (1 \text{ AU}/r_{\text{HP}})^2 \rightarrow r_{\text{HP}} = 115 \text{ AU}; \text{ Too large? (MHD: } r_{\text{TS}} = 2/3 r_{\text{HP}} \text{)}$$



Thus, probably total pressure in the IS medium is less than 0.1 pPa!