Lecture #20 The Structure of the Heliosphere

I. Solar and Stellar Winds:

Refs: 1. Weber & Davis, 1967, ApJ. 148, 127.
2. Lamers & Cassinelli, Introduction to Stellar Winds, Cambridge Univ Press, 1999.

A. Equatorial Stellar Wind Model

1. Consider a model for the solar wind in spherical coords, (r,θ,ϕ)

$$\underset{\sim}{U} = U_r(r)\,\hat{\underset{\sim}{r}} + U_\phi(r)\,\hat{\underset{\sim}{\phi}}$$
$$\underset{\sim}{B} = B_r(r)\,\hat{\underset{\sim}{r}} + B_\phi(r)\,\hat{\underset{\sim}{\phi}}$$

2. By symmetry on equatorial plane, $U_\theta = 0$ and $B_\theta = 0$.
3. Assume steady state conditions, $\frac{\partial}{\partial t} = 0$
4. From MHD, let's determine the global structure of the Interplanetary Magnetic Field (IMF) emerging from the rotating sun with the solar wind flow.

5. Conservation of Mass:
   a. Continuity Equation: $\cancel{\frac{\partial \rho}{\partial t}} + \nabla\cdot(\rho \underset{\sim}{U}) = 0$
   b. In spherical coordinates, $\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 \rho U_r) = 0$
   c. Thus $\boxed{r^2 \rho U_r = \text{constant}}$ ① $\boxed{4\pi r^2 \rho U_r = \dot{M}}$

   where $\dot{M} = \frac{\text{Mass Flux}}{\text{time}}$

6. Zero Magnetic Divergence:
   a. $\nabla \cdot \underset{\sim}{B} = 0$
   b. Thus, $\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 B_r) = 0$
   c. So, $r^2 B_r = \text{constant} \rightarrow \boxed{B_r = B_\odot\left(\frac{R_\odot}{r}\right)^2}$ ②

   $B_\odot$ is radial magnetic field at surface $r = R_\odot$

2.A. (Continued)

7. Magnetic Induction Equation:

a. $\cancel{\frac{\partial \underset{\sim}{B}}{\partial t}}^{0} = \nabla \times (\underset{\sim}{U} \times \underset{\sim}{B})$

b. Consider the θ-component of curl: $\frac{1}{r}\frac{\partial}{\partial r}\left[r\,(\underset{\sim}{U}\times\underset{\sim}{B})_\theta\right] = 0$

c. Thus, $\frac{1}{r}\frac{\partial}{\partial r}\left[r(U_r B_\phi - U_\phi B_r)\right] = 0$

d. $r(U_r B_\phi - U_\phi B_r) = \text{constant}$

At solar surface, $U_\phi \gg U_r$, and $U_\phi = R_\odot \Omega_\odot$, so

$\text{constant} = -R_\odot^2 \Omega_\odot B_\odot$ where $\Omega_\odot = 2.85\times 10^{-6}\ \frac{\text{rad}}{\text{s}}$

e. Since $r^2 B_r = R_\odot^2 B_\odot$, we obtain $\text{constant} = -r^2 \Omega_\odot B_r$

f. Substituting this result above and simplifying,

$$\boxed{\frac{B_\phi}{B_r} = \frac{U_\phi - r\Omega_\odot}{U_r}} \quad (3)$$

8. Conservation of Angular Momentum:

a. $$\rho\frac{\partial \underset{\sim}{U}}{\partial t} + \rho \underset{\sim}{U}\cdot\nabla\underset{\sim}{U} = -\nabla\left(p + \frac{B^2}{2\mu_0}\right) + \frac{B\cdot\nabla B}{\mu_0} - \rho\frac{GM}{r^2}\hat{\underset{\sim}{r}}$$

b. The azimuthal component gives, in steady state & spherical coords,

$$\rho U_r \frac{\partial}{\partial r}(r U_\phi) = \frac{B_r}{\mu_0}\frac{\partial}{\partial r}(r B_\phi)$$

c. $$\frac{\partial}{\partial r}(r U_\phi) - \underbrace{\frac{B_r}{\mu_0 \rho U_r}}\frac{\partial}{\partial r}(r B_\phi) = 0$$

from DE (3), $\frac{B_r}{\rho U_r} = \left(\frac{4\pi r^2}{\dot{M}}\right)\left(\frac{B_\odot R_\odot^2}{r^2}\right) = \frac{4\pi B_\odot R_\odot^2}{\dot{M}} = \text{constant}$

d. $$\frac{\partial}{\partial r}\left(r U_\phi - \frac{r B_r B_\phi}{\mu_0 \rho U_r}\right) = 0$$

I. A. 8. (Continued)

e. $$\boxed{\mathcal{L} = r U_\phi - \frac{r B_r B_\phi}{\mu_0 \rho U_r}}$$ ④ Conservation of Angular Momentum, where $\mathcal{L} = \frac{\text{Angular Momentum}}{\text{unit mass}}$

9. Therefore, we have

a.
① $4\pi r^2 \rho U_r = \dot{M}$
② $B_r = B_\odot \left(\frac{R_\odot}{r}\right)^2$
③ $\frac{B_\phi}{B_r} = \frac{U_\phi - r\Omega_\odot}{U_r}$
④ $\mathcal{L} = r U_\phi - \frac{r B_r B_\phi}{\mu_0 \rho U_r}$

b. If $U_r(r)$ is known, we can solve for $\rho(r)$, $B_r(r)$, $B_\phi(r)$, and $U_\phi(r)$

c. Constants: $\dot{M}, B_\odot, \Omega_\odot, \mathcal{L}$

c. We can continue, using Conservation of Energy and Radial Momentum Equation to obtain a fully self-consistent (and complicated) system, but for now we'll focus on the structure of $\underline{B}$.

B. The Parker Spiral Magnetic Field

1. At distances $r \gg R_\odot$, $U_\phi \ll r\Omega_\odot$, so ③ can be simplified to
$$\frac{B_\phi}{B_r} \simeq \frac{-r\Omega_\odot}{U_r}$$

2. Substituting ②, $$B_\phi \simeq \frac{-r\Omega_\odot B_\odot R_\odot^2}{U_r \quad r^2} = -B_\odot \frac{R_\odot^2 \Omega_\odot}{r U_r}$$

3. Therefore, we see that $B_r \propto \frac{1}{r^2}$ and $B_\phi \propto \frac{1}{r}$, so the magnetic field begins primarily radial and eventually becomes more and more azimuthal.

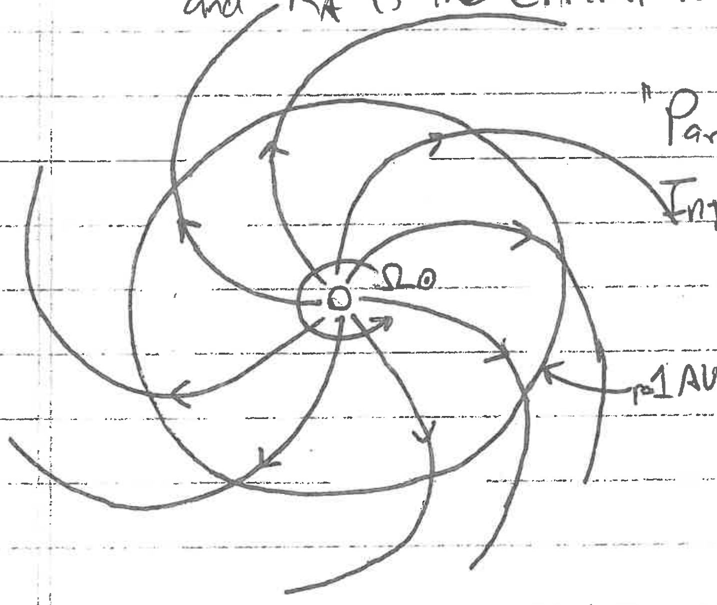
I. B. (Continued)

4. One may obtain a function $\phi(r)$ the describes a magnetic field line,

$$\boxed{\phi(r) = \phi_0 - \frac{\Omega_\odot}{V_{sw}}(r - R_A)}$$ Archimedean Spiral

where ϕ_0 is angle of "foot" of field line at $r = R_A$

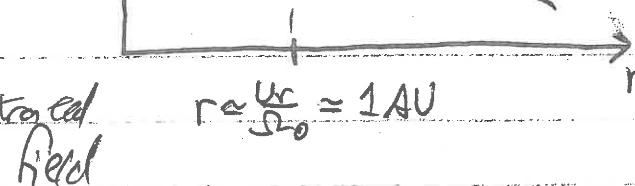
and R_A is the critical radius for Alfvén waves, $R_A \simeq 10 R_\odot$.



"Parker Spiral" of the Interplanetary Magnetic Field.

4. Magnetic Field Magnitude, $B = (B_r^2 + B_\phi^2)^{\frac{1}{2}}$

$$\boxed{B = B_\odot\left(\frac{R_\odot}{r}\right)^2\sqrt{1 + \frac{r^2\Omega_\odot^2}{U_r^2}}}$$

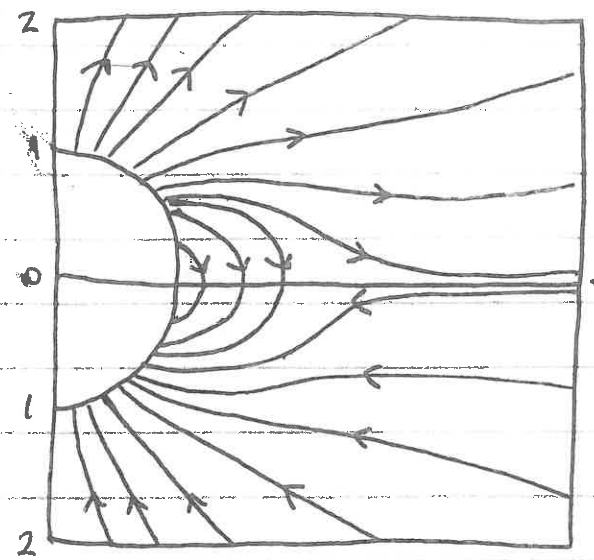


C. Loss of Angular Momentum

1. Weber & Davis (1967) first demonstrated that the solar wind magnetic field significantly enhanced the loss of angular momentum (spin down) of the sun. (in addition spin down by mass loss alone).
2. "Effective corotation" of solar wind with the sun out to the Alfvén radius $r_A \simeq 10 R_\odot$.

II. The Heliospheric Current Sheet

A. 1. Pneuman & Kopp (1971) computed a self-consistent steady state solution of MHD equations with Parker transonic solution along each flow line.



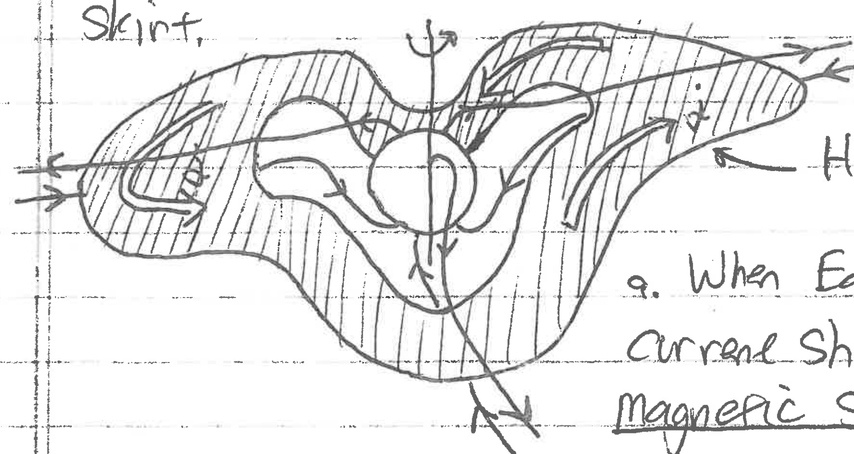
Typical of Solar Minimum

Heliospheric Current Sheet $\otimes j$

2. Open field lines from the poles eventually spread out to cover 4π solid angle beyond $\sim 3R_\odot$.

3. Along the equator, oppositely directed field lines from opposite poles come close together, leading to the Heliospheric Current Sheet required to support the jump in IMF field direction from sunward to anti-sunward.

4. Because the magnetic and rotation axes of the sun do not coincide, this current sheet becomes rippled, like a ballerina skirt.



Heliospheric current sheet

a. When Earth's orbit passes through current sheet, it moves from a magnetic sector of sunward IMF to a sector of anti-sunward IMF.

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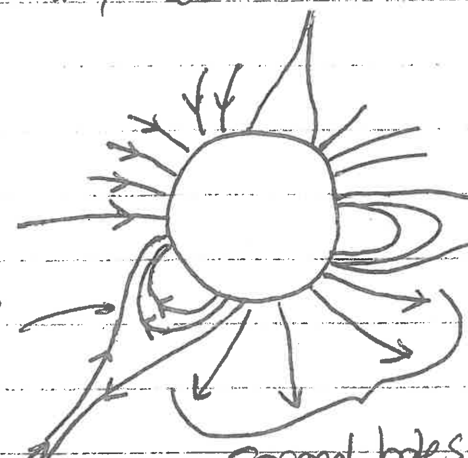
II. B. Coronal Holes and Coronal Helmet Streamer Belt

1. The simplified picture above is reasonably accurate for solar minimum,

2. Coronal Holes: low density regions of open magnetic field lines that appear dark on coronagraphs.

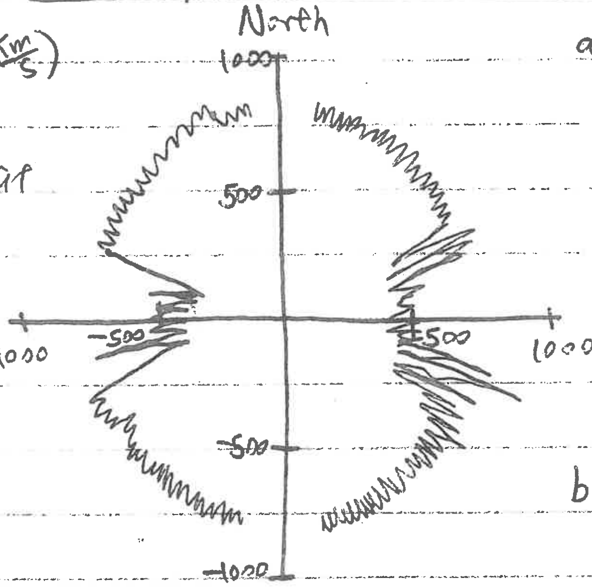
Solar Maximum



3. Coronal Streamer Belt: Bright teardrop shaped region (coronal helmet streamers) that appear to straddle field line reversals. Generally presumed to create a belt around the sun where the heliospheric current sheet meets the corona, but may be more geometrically complicated during solar maximum.

4. Connection to Solar Wind Speed:

Ulysses measurements at solar minimum (1992 to 1997)



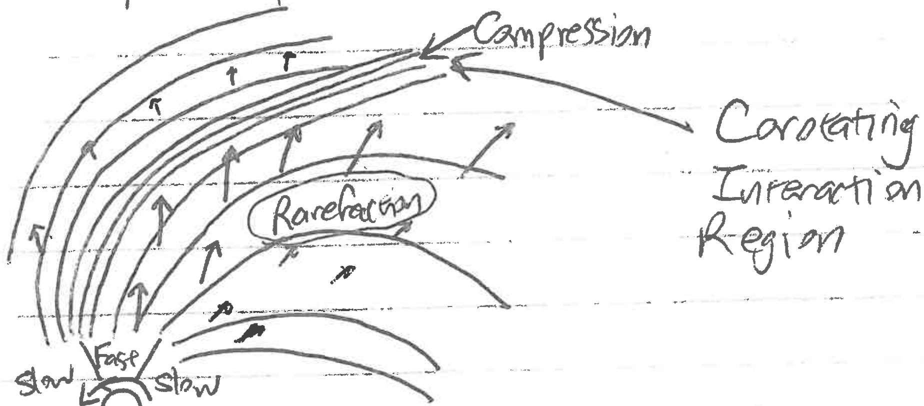
a. Ulysses spacecraft went to high heliographic latitude, and at solar minimum found fast solar wind ($\sim 700-800$ km/s) at high latitudes, and slow solar wind (< 500 km/s) at low latitudes $\lesssim 30°$ N/S.

b. Fast solar wind is assumed to originate at coronal holes

c. Slow solar wind is believed to originate at the outer regions of coronal streamers.

III. Corotating Interaction Regions

A. 1. Because the sun is rotating, regions of fast solar wind can emerge from the sun at a position radially behind previously emitted slow solar wind streams.



2. The fast radial flow in fast streams catches up with and compresses the slow solar wind radially beyond it.
3. Since the regions of fast & slow solar wind persist for several solar rotations, this pattern of compression and rarefaction repeats at each solar rotation.
4. The region of compression are known as corotating interaction regions, or CIRs.

IV. Global Structure of the Heliosphere

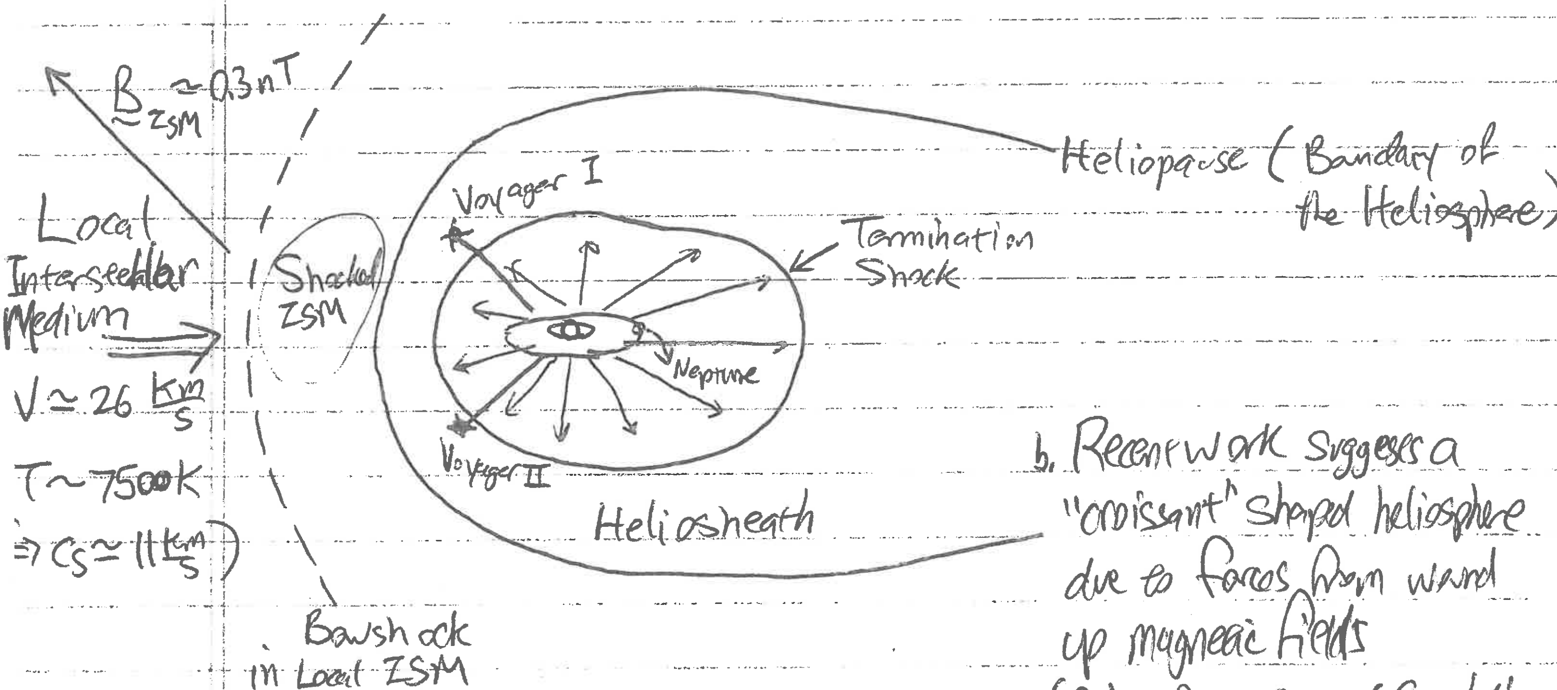
A. The Termination Shock

1. The supersonic solar wind at large heliocentric radius connects to a boundary condition $p \to 0$ at $r \to \infty$ (Lec #18)
2. But, if a finite pressure exists in the surrounding Local Interstellar Medium (LISM), the coronal expansion must eventually stop when solar wind pressure becomes smaller than LISM pressure.

IV. A. (Continued)

3. A termination shock must develop to transition from supersonic flow to subsonic flow to enable the solar wind flow to stop.

4.a. Beyond this is the heliopause, the tangential discontinuity separating plasma and magnetic field of solar origin from that of the local ISM.



b. Recent work suggests a "croissant" shaped heliosphere due to forces from wound up magnetic fields (Opher, Drake, Zieger, & Gombosi, ApJL, 2015)

5. Neptune's orbit is at $R \sim 30 AU$

6.a. Voyager I crossed the termination shock in the Northern heliospheric hemisphere at $R \simeq 94\ AU$ in December 2004

b. Voyager II crossed the termination shock in the Southern hemisphere at $R \sim 84\ AU$ in August 2007.

7. The Interstellar Boundary Explorer (IBEX) mission, launched in October 2008, uses measurements of energetic neutral atoms to map the heliospheric boundaries, showing that the direction of the local ISM magnetic field $\underline{B}_{ISM}$ may influence the shape of the heliosphere.

~121 AU 8. From Plasma oscillation measurements, Voyager I crossed heliopause on 25 AUG 2012.