Open magnetic structures -
Coronal holes and fast solar wind

- The solar corona over the solar cycle
- Coronal and interplanetary temperatures
- Coronal holes and fast solar wind
- Origin of solar wind in magnetic network
- Multi-fluid modelling of the solar wind
Corona of the active sun

Fe XIV
5303 Å

EIT - LASCO C1/C2

1998
Solar wind speed and density

McComas et al., GRL, 25, 1, 1998
Electron density in the corona


+ Current sheet and streamer belt, closed

- Polar coronal hole, open magnetically

Heliocentric distance / $R_s$

Skylab coronagraph/ Ulysses in-situ
Electron temperature in the corona

David et al., A&A 336, L90, 1998

Streamer belt, closed
Coronal hole, open magnetically

Heliocentric distance
SUMER/ CDS    SOHO
Temperature profiles in the corona and fast solar wind

Fast solar wind speed profile

Radial distance / $R_s$

$V$ (km s$^{-1}$) mass flux continuity

Lyman Doppler dimming

IPS

Ulysses

Speed profile of the slow solar wind


Outflow starts at about $3 \, R_S$


Consistent with Helios data
Changing corona and solar wind

McComas et al., 2000

SOHO/Ulysses

Slow latitude scan (2-5 AU)
Solar wind fast and slow streams

Helios 1976

Alfvén waves and small-scale structures

Marsch, 1991
Solar wind stream structure and heliospheric current sheet

Parker, 1963

Alfven, 1977
Rotation of the sun and corona

Schwenn, 1998
Rotation of solar corona

Fe XIV 5303 Å

Time series: 1 image/day (24-hour averages)

LASCO / SOHO

Syodic Rotation Period (days)

Long-lived coronal patterns exhibit uniform rotation at the equatorial rotation period!

Stenborg et al., 1999
Sun’s loss of angular momentum carried by the solar wind

Induction equation:
\[ \nabla \times (V \times B) = 0 \quad \rightarrow \quad r (V_r B_\phi - B_r V_\phi) = -r_0 B_0 \Omega_0 r_0 \]

Momentum equation:
\[ \rho V_\phi \nabla V_\phi = \frac{1}{4 \pi} B_0 \nabla B_\phi \quad \rightarrow \quad r (\rho V_r V_\phi - B_r B_\phi) = 0 \]

\[ L = \Omega_0 r_A^2 \] (specific angular momentum)

\[ V_\phi = \Omega_0 r (M_A^2 (r_A/r)^2 - 1)/(M_A^2 - 1) \]

\[ M_A = V_r (4\pi \rho)^{1/2}/B_r \]

Alfvén Mach number

Helios: \( r_A = 10-20 \, R_S \)

(Parker) spiral interplanetary magnetic field

$$\text{rot}(E) = \text{rot}(V \times B) = 0$$
Solar wind types

1. Fast wind near activity minimum
   
   High speed            400 - 800 kms\(^{-1}\)
   Low density           3 cm\(^{-3}\)
   Low particle flux     2 \times 10^8 cm\(^{-2}\) s\(^{-1}\)
   Helium content        3.6\%, stationary
   Source                coronal holes
   Signatures            stationary for long times (weeks!)

2. Slow wind near activity minimum
   
   Low speed             250 - 400 km s\(^{-1}\)
   High density          10 cm\(^{-3}\)
   High particle flux    3.7 \times 10^8 cm\(^{-2}\) s\(^{-1}\)
   Helium content        below 2\%, highly variable
   Source                helmet streamers near current sheet
   Signatures            sector boundaries embedded

Schwenn, 1990
Solar wind types

3. Slow wind near activity maximum

Similar characteristics as 2., except for

- Helium content: 4%, highly variable
- Source: active regions and small CHs
- Signatures: shock waves, often imbedded

4. Solar ejecta (CMEs), often associated with shocks

- High speed: 400 - 2000 kms\(^{-1}\)
- Helium content: high, up to 30%
- Other heavy ions: often Fe\(^{16+}\) ions, in rare cases He\(^+\)
- Signatures: often magnetic clouds, about 30% of the cases related with erupting prominences

Schwenn, 1990
Solar wind data from Ulysses

McComas et al., 2000

September 3, 1999 - September 2, 2000

Latitude: -65°
Energetics of the fast solar wind

- Energy flux at 1 R$_S$: $F_E = 5 \times 10^5$ erg cm$^{-2}$ s$^{-1}$
- Speed beyond 10 R$_S$: $V_p = (700 - 800)$ km s$^{-1}$
- Temperatures at
  - 1.1 R$_S$: $T_e \approx T_p \approx 1.2 \times 10^6$ K
  - 1 AU: $T_p = 3 \times 10^5$ K; $T_\alpha = 10^6$ K; $T_e = 1.5 \times 10^5$ K
- Heavy ions: $T_i \approx \frac{m_i}{m_p} T_p$; $V_i - V_p = V_A$

$$\frac{\gamma}{(\gamma-1)} 2k_B T_S = \frac{1}{2m_p} (V_\infty^2 + V^2)$$

$\gamma = \frac{5}{3}$, $V_\infty = 618$ km s$^{-1}$, $T_S = 10^7$ K for $V_p = 700$ km s$^{-1}$

$\rightarrow 5$ keV
Solar wind models I

Assume heat flux, $Q_e = -\kappa \nabla T_e$, is free of divergence and thermal equilibrium: $T = T_p = T_e$. Heat conduction: $\kappa = \kappa_0 T^{5/2}$ and $\kappa_0 = 8 \times 10^8$ erg/(cm s K); with $T(\infty) = 0$ and $T(0) = 10^6$K and for spherical symmetry:

$$4\pi r^2 \kappa(T) \frac{dT}{dr} = \text{const} \quad \rightarrow \quad T = T_0 \left(\frac{R}{r}\right)^{2/7}$$

Density: $\rho = n_p m_p + n_e m_e$, quasi-neutrality: $n = n_p = n_e$, thermal pressure: $p = n_p k_B T_p + n_e k_B T_e$, then with hydrostatic equilibrium and $p(0) = p_0$:

$$\frac{dp}{dr} = - \frac{GM m_p n}{r^2}$$

$$p = p_0 \exp\left[ \frac{(7GM m_p)}{(5k_B T_0 R)} \left( \left(\frac{R}{r}\right)^{5/7} - 1 \right) \right]$$

Problem: $p(\infty) > 0$, therefore corona must expand!

Chapman, 1957
Density: \( \rho = n_p m_p + n_e m_e \), quasi-neutrality: \( n = n_p = n_e \), ideal-gas thermal pressure: \( \rho = n_p k_B T_p + n_e k_B T_e \), thermal equilibrium: \( T = T_p = T_e \), then with hydrodynamic equilibrium:

\[
mn_p V \frac{dV}{dr} = - \frac{dp}{dr} - \frac{GMm_p n}{r^2}
\]

Mass continuity equation:

\[
mn_p V r^2 = J
\]

Assume an isothermal corona, with sound speed \( c_0 = (k_B T_0 / m_p)^{1/2} \), then one has to integrate the DE:

\[
[(V / c_0)^2 - 1] \frac{dV}{V} = 2 \left(1 - \frac{r_c}{r}\right) \frac{dr}{r}
\]

With the critical radius, \( r_c = GMm_p / (2k_B T_0) = (V_\infty / 2c_0)^2 R \), and the escape speed, \( V_\infty = 618 \text{ km/s} \), from the Sun’s surface.

Parker, 1958
Solar wind models III

Introduce the sonic Mach number as, \( M_s = \frac{V}{c_0} \), then the integral of the DE (C is an integration constant) reads:

\[
(M_s)^2 - \ln(M_s)^2 = 4 \left( \ln\left(\frac{r}{r_c}\right) + \frac{r_c}{r} \right) + C
\]

For large distances, \( M_s \gg 1 \); and \( V \sim (\ln r)^{1/2} \), and \( n \sim r^{-2}/V \), reflecting spherical symmetry.

Only the "wind" solution IV, with \( C=-3 \), goes through the critical point \( r_c \) and yields: \( n \to 0 \) and thus \( p \to 0 \) for \( r \to \infty \). This is Parker's famous solution: the solar wind.

Parker, 1958

V, solar breeze; III accretion flow
Funnels merging in coronal hole

Cranmer and van Ballegoijen, ApJS, 2005

Field lines in (c) are plotted at 2.1° intervals at the solar surface, and thus each pair encompasses 1–2 funnels.

On the source regions of the fast solar wind in coronal holes

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

Image: EIT Corona in Fe XII 195 Å at 1.5 M K

Insert: SUMER Ne VIII 770 Å at 630 000 K

Chromospheric network
Doppler shifts
Red: down
Blue: up

Outflow at lanes and junctions
Loops and funnels in equatorial CH

Field lines: brown open, and yellow closed

Correlation: Field topology and plasma outflow (blue in open field)

Flows and funnels in coronal hole

Tu, Zhou, Marsch, et al., Science, 308, 519, 2005

Colorbar for Z=0Mm  100Gauss
Colorbar for Z=4.0Mm 40Gauss
Colorbar for Z=20.6Mm 8Gauss

Curve lines at 4Mm denote the Sill intensity contour lines at rank 80%; Shaded regions at 20.6Mm denote where NeVIII Doppler shift <-7km/s.
Height profiles in funnel flows

- Heating by wave sweeping
- Steep temperature gradients

- Critical point at 1 $R_S$

Lateral mass and energy supply

Sketch to illustrate the scenario of the solar wind origin and mass supply through reconnection. The supergranular convection is the driver of solar wind outflow in coronal funnels. Sizes and shapes of funnels and loops shown are drawn to scale.

He, Tu and Marsch, Solar Phys., 2008
Modelling of coronal funnel

He, Tu and Marsch, Solar Phys., 2008

Location of mass and energy supply
Fast solar wind acceleration by magnetic flux emergence

\[ \frac{u_f^2}{2} = \frac{\left( \frac{c}{4\pi} (\mathbf{E} \times \mathbf{B}) \right) \cdot ds}{s_i} - \frac{GM_0}{r_i} \]

\[ \frac{u_f^2}{2} = \frac{\bar{B}_i^2}{4\pi \bar{\rho}_i} - \frac{GM_0}{r_i} \]

Fisk et al., JGR 104, 19765, 1999
Fluid equations

- **Mass flux:** \( F_M = \rho \ V \ A \) \( \rho = n_p m_p + n_i m_i \)

- **Magnetic flux:** \( F_B = B \ A \)

- **Total momentum equation:**

\[
V \frac{d}{dr} V = - \frac{1}{\rho} \frac{d}{dr} (\rho \ V \ A) - \frac{GM_s}{r^2} + a_w
\]

- **Thermal pressure:** \( p = n_p k_B T_p + n_e k_B T_e + n_i k_B T_i \)

- **MHD wave pressure:** \( p_w = (\delta B)^2/(8\pi) \)

- **Kinetic wave acceleration:** \( a_w = (\rho_p a_p + \rho_i a_i)/\rho \)

- **Stream/flux-tube cross section:** \( A(r) \)
Magnetic flux tube expansion factor

Wang & Sheeley (1990) defined the expansion factor $f(r)$ between “coronal base” and the source-surface radius $\sim 2.5 \, R_s$. 

- **Polar coronal holes**: $f \approx 4$
- **Equatorial streamers**: $f \approx 9$
- **“Active regions”**: $f \approx 25$
Model of the fast solar wind


Low density, $n \approx 10^8 \text{ cm}^{-3}$, consistent with coronagraph measurements

- hot protons, $T_{\text{max}} \approx 5 \text{ M K}$
- cold electrons
- small wave temperature, $T_w$

Radial distance / $R_s$
Four-fluid model for turbulence driven heating of coronal ions

- Four-fluid 1-D corona/wind model
- Quasi-linear heating and acceleration by dispersive ion-cyclotron waves
- Rigid power-law spectra with index: $-2 \leq \gamma \leq -1$
- No wave absorption
- Turbulence spectra not self-consistent

Hu, Esser & Habbal, JGR, 105, 5093, 2000
Coronal line broadenings

Limits on Alfvén wave amplitude $\delta v$: 10 – 30 km/s in solar transition region

Cranmer and van Ballegooijen (2005) solved the transport equations for a grid of “monochromatic” periods (3 s to 3 days), then renormalized using a photospheric power spectrum.

One free parameter: base “jump amplitude” (0 to 5 km/s allowed; ~3 km/s is best)
Coronal ion temperature profiles

$T_{\text{eff}} = T + \langle V_{\phi,k}^2 \rangle \frac{A m_p}{2 k_b}$

Wave-driven wind

Three-fluid model

Ofman, JGR, 2004
MHD equations for the 3-D solar wind

\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \]

\[ \frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[ \rho \mathbf{v} \mathbf{v} + \left( P + \frac{\mathcal{E}}{2} + \frac{B^2}{8\pi} \right) \mathbf{I} - \frac{\mathbf{BB}}{4\pi} \right] + \rho \left[ \frac{GM_\odot}{r^2} \mathbf{\hat{r}} + 2\Omega \times \mathbf{v} + \Omega \times (\Omega \times \mathbf{r}) \right] = 0, \]

\[ \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}), \]

\[ \frac{\partial}{\partial t} \left[ \frac{\rho}{2} \left( v^2 - |\Omega \times r|^2 \right) + \frac{P}{\gamma - 1} + \frac{B^2}{8\pi} - \frac{\rho GM_\odot}{r} + \mathcal{E} \right] + \nabla \cdot \left\{ \left[ \frac{\rho}{2} \left( v^2 - |\Omega \times r|^2 \right) + \frac{\gamma P}{\gamma - 1} - \frac{\rho GM_\odot}{r} \right] \mathbf{v} \right. \]

\[ + \frac{B}{4\pi} \times (\mathbf{v} \times \mathbf{B}) + \left( \frac{3}{2} \mathbf{v} + \mathbf{V}_A \right) \mathcal{E} \right\} = 0, \]

\[ \frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot [(\mathbf{v} + \mathbf{V}_A) \mathcal{E}] = -\frac{\mathcal{E}}{2} \nabla \cdot \mathbf{v} - |\mathbf{v} + \mathbf{V}_A| \frac{\mathcal{E}}{L}, \]

The dependent variables are \( \rho, \mathbf{v}, \mathbf{B}, P, \) and \( \mathcal{E}, \) which is the plasma density, flow velocity in the frame rotating with the Sun, magnetic field, thermal pressure, and the Alfvén wave energy density, respectively. \( M_\odot \) is the solar mass, \( \Omega \) the solar angular velocity vector, \( \gamma \) the polytropic index, \( t \) the time, and \( r \) the radial distance. We use \( P \sim n^{-\gamma}. \) \( L \) is the wave damping length, and \( \mathbf{V}_A \) the Alfvén velocity.

Usmanov et al., JGR 105, 12675, 2000
Acceleration of the solar wind

Goldstein et al. (1996)

Ulysses SWOOPS

Goldstein et al. (1996)