Open magnetic structures - Coronal holes and the solar wind

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

EIT - LASCO C1/C2

1998
Solar wind speed and density

McComas et al., GRL, 25, 1, 1998

B outward

B inward

Ecliptic

Density $\times R^2$ [cm$^{-3}$]

Speed [km s$^{-1}$]

Polar diagram

V

Density vs $n R^2$
Structure of the heliosphere

- Basic plasma motions in the restframe of the Sun
- Principal surfaces (wavy lines indicate disturbances)
Heliosphere and local interstellar medium

V = 25 km/s

Bow shock

Heliopause

Hydrogen wall

Heliospheric SW shock

(red) - 0.3 > log(n_e/cm³) > - 3.7 (blue)

Kausch, 1998
Schematic view of the heliosphere

(LISM) Local interstellar medium

V1 at 94 AU
Inventory of the heliosphere

• Interplanetary magnetic field  (sun)
• Solar wind electrons and ions  (corona)
• Solar energetic particles (solar atmosphere)
• Anomalous cosmic rays (planets, heliopause)
• Cosmic rays  (galaxy)
• Pick-up ions  (dust, surfaces)
• Energetic neutrals (heliopause)
• Dust  (interstellar medium, comets, minor bodies)
Heliospheric magnetic field

McComas et al., 1998

Ulysses VHM/FGM
Heliospheric temperatures

\[ T_p \leq T_e \]

McComas et al., 1998
Fast solar wind speed profile

Speed profile of the slow solar wind

Speed profile as determined from plasma blobs in the wind

\[ v_a = 298.3 \text{ km/s}, \quad r_a = 8.1 \text{ Rs} \]
\[ r_1 = 2.8 \text{ Rs} \]

Parker, 1963

Outflow starts at about 3 Rs


Consistent with Helios data
Changing corona and solar wind

McComas et al., 2000

SOHO/Ulysses

North

Heliolatitude / degree

South

McComas et al., 2000

Slow latitude scan (2-5 AU)
Evolution of the current sheet

Stack plot of Carrington rotations from 1983 to 1994, showing the location of the heliospheric current sheet (HCS) on the source surface at 2.5 $R_s$

Negative polarity, dark Neutral line, bold

Hoeksema, Space Sci. Rev. 72, 137, 1995
In situ current sheet crossings

Dense

Slow

Cold

Less Helium

Speeds equal

Temperatures close

Borrini et al., JGR, 1981
Solar wind stream structure and heliospheric current sheet

Parker, 1963

Alfven, 1977
Solar wind fast and slow streams

Helios 1976

Alfvén waves and small-scale structures

Marsch, 1991
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$^{6+}$ 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 \( 10^6 \) 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:** \( T_i \approx m_i / m_p T_p; \ V_i - V_p = V_A\)

\[
\gamma/(\gamma-1) \ 2k_B T_S = 1/2m_p (V_\infty^2 + V^2)
\]

\(\gamma = 5/3, \ V_\infty = 618 \) kms\(^{-1}\), \( T_S = 10^7 \) K for \( V_p = 700 \) kms\(^{-1}\) \(\rightarrow 5 \) 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 \( p(0) = p_0 \):

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

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

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

Chapman, 1957
Solar wind models II

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

$$m n_p V \frac{dV}{dr} = - \frac{dp}{dr} - \frac{GM m_p n}{r^2}$$

Mass continuity equation:

$$m n_p V r^2 = J$$

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, $r_c = GM m_p / (2k_B T_0) = (V_\infty / 2c_0)^2$, and the escape speed, $V_\infty = 618$ 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, $M_s >> 1$; 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
On the source regions of the fast solar wind in coronal holes

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

Hassler et al., Science 283, 811-813, 1999
Detailed source region

Tu, Zhou, Marsch, et al., SW11, 2005
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
Height profiles in funnel flows

- Heating by wave sweeping
- Steep temperature gradients

- Critical point at 1 $R_S$

Sketch to illustrate the scenario of the solar wind origin and mass supply. The plot is drawn to show that supergranular convection is the driver of solar wind outflow in coronal funnels. The sizes and shapes of funnels and loops shown are drawn according to the real scale sizes of the magnetic structures.
Rotation of the sun and corona

Schwenn, 1998
Long-lived coronal patterns exhibit uniform rotation at the equatorial rotation period!

LASCO / SOHO

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

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

Momentum equation:
\[ \rho \mathbf{V} \cdot \nabla V_\phi = \frac{1}{4\pi} \mathbf{B} \cdot \nabla B_\phi \quad \Rightarrow \quad r (\rho V_r V_\phi - B_r B_\phi) = 0 \]

\[ L = \Omega_0 r_A^2 \quad \text{(specific angular momentum)} \]

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

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

Alfvén Mach number

Helios: \[ r_A = 10-20 \ R_S \]

(Parker) spiral interplanetary magnetic field

\[ \text{rot}(E) = \text{rot}((V \times B)) = 0 \]
Fluid equations

• Mass flux: \( F_M = \rho \, V \, A \) \quad \rho = n_p m_p + n_i m_i

• Magnetic flux: \( F_B = B \, A \)

• Total momentum equation:
  \[ V \frac{d}{dr} V = -\frac{1}{\rho} \frac{d}{dr} (p + p_w) - \frac{GM_S}{r^2} + a_w \]

• 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, \( T_w \)

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

Preferential heating of heavy ions by waves
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)
Acceleration of the solar wind

Goldstein et al. (1996)

Ulysses SWOOPS

Goldstein et al. (1996)
The future: Solar Orbiter

A high-resolution mission to the Sun and inner heliosphere

Exploring the Sun-Earth connection

ESA 2017