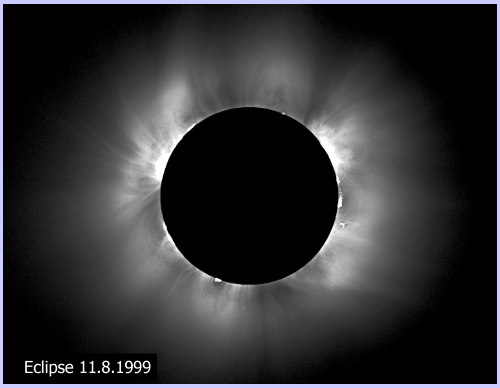
Coronal expansion and solar wind

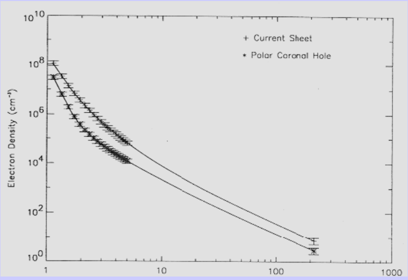
- The large solar corona
- Coronal and interplanetary temperatures
- Coronal expansion and solar wind
- The heliosphere
- Origin of solar wind in magnetic network
- Multi-fluid models of the solar wind

The visible solar corona



Eclipse 11.8.1999

Electron density in the corona



+ Current sheet and streamer belt, closed

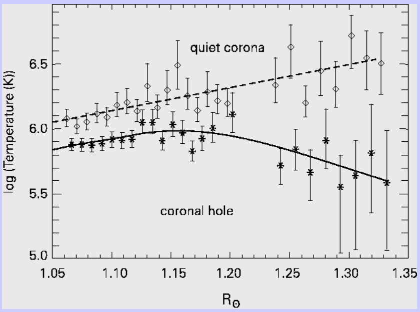
• Polar coronal hole, open magnetically

Heliocentric distance / R_s

Guhathakurta and Sittler, 1999, Ap.J., **523**, 812

Skylab coronagraph/Ulysses in-situ

Electron temperature in the corona



Streamer belt, closed

Coronal hole, open magnetically

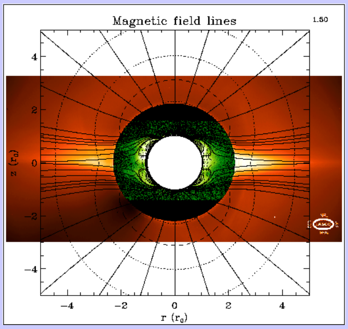
David et al., A&A, **336**, L90, 1998

Heliocentric distance

SUMER/CDS SOHO

Coronal magnetic field and density

Dipolar, quadrupolar, current sheet contributions



Polar field: B = 12 G

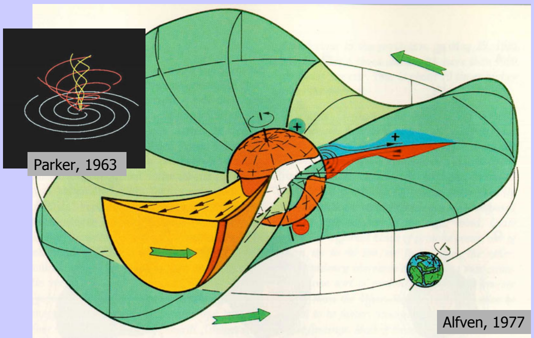
Current sheet is a symmetric disc anchored at high latitudes !

Banaszkiewicz et al., 1998;

Schwenn et al., 1997

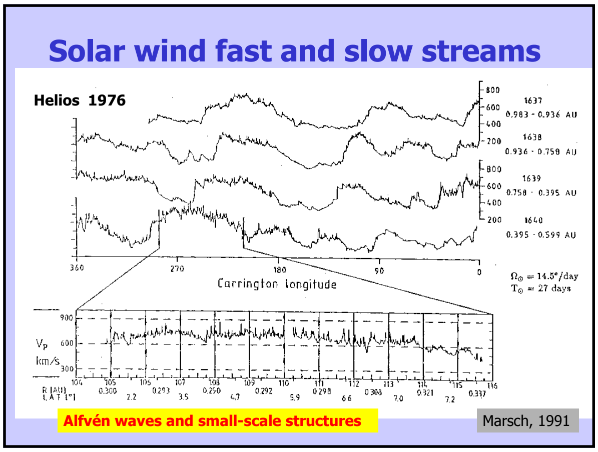
LASCO C1/C2 images (SOHO)

Solar wind stream structure and heliospheric current sheet



Parker, 1963

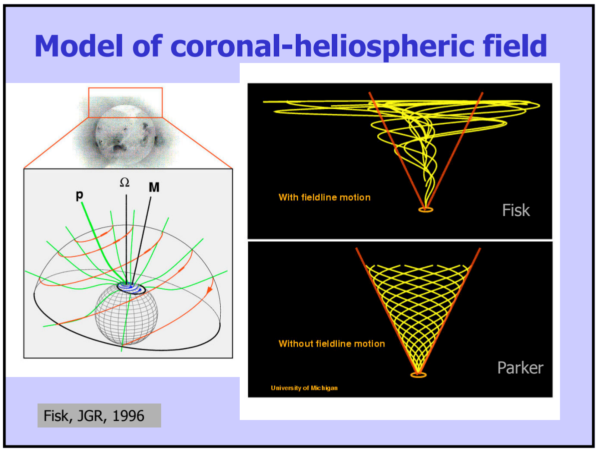
Alfven, 1977



Solar wind fast and slow streams

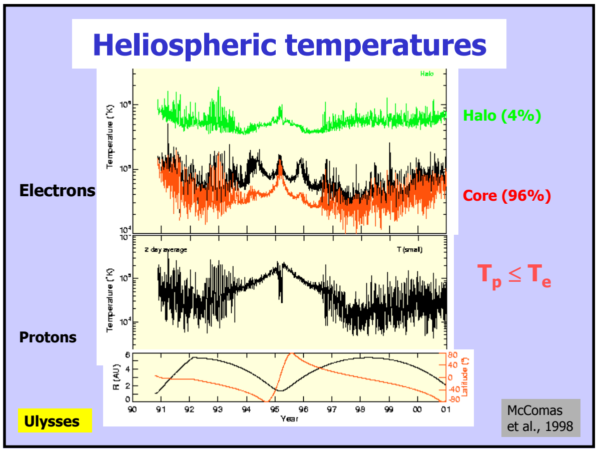
Alfvén waves and small-scale structures

Marsch, 1991



Model of coronal-heliospheric field

Fisk, JGR, 1996



Heliospheric temperatures

Electrons

Halo (4%)

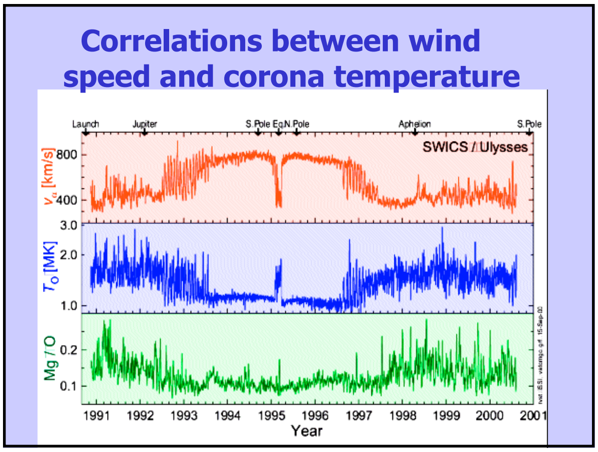
Core (96%)

$T_p \leq T_e$

Protons

Ulysses

McComas et al., 1998



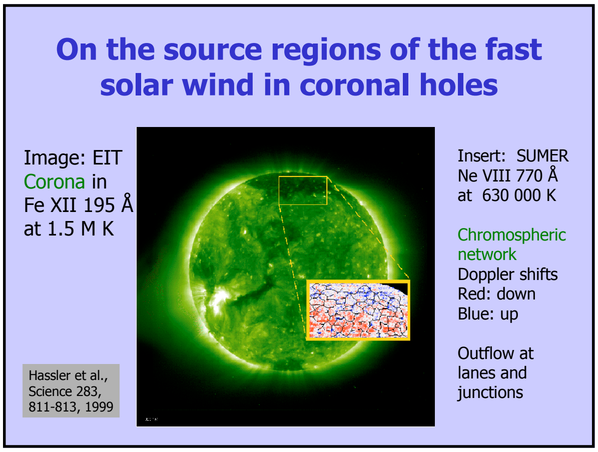
Correlations between wind speed and corona temperature

Fast solar wind parameters

- **Energy flux at 1 R_S: F_E = 5 10^5 erg cm^{-2} s^{-1}**
- **Speed beyond 10 R_S: V_p = (700 - 800) km s^{-1}**
- **Proton flux at 1 AU: $n_p V_p$ = 2 10^8 cm^{-2} s^{-1}**
- **Density at 1 AU: n_p = 3 cm^{-3} ; n_α/n_p = 0.04**
- **Temperatures at 1 AU:**

  T_p = 3 10^5 K ; T_α = 10^6 K ; T_e = 1.5 10^5 K
- **Heavy ions: $T_i \cong m_i / m_p T_p$; $V_i - V_p = V_A$**

Schwenn and Marsch, 1990, 1991



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

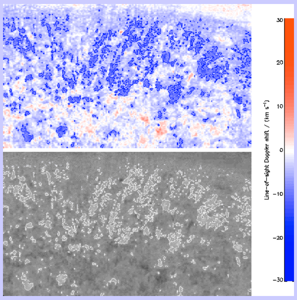
Outflow at lanes and junctions

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

The source regions of the fast solar wind in polar coronal holes

Doppler-shift

map of solar polar cap: 520" × 300" gliding step size: 3"



SUMER
Ne VIII 770 Å
at 630 000 K

Encircled contours: Doppler shift > 5 km/s

Radiance

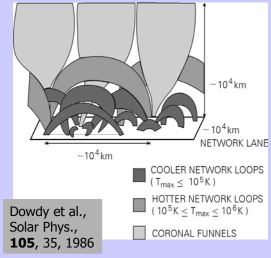
September 21, 1996

Wilhelm et al., A&A, **353**, 749, 2000

Magnetic network loops and funnels

Structure of transition region

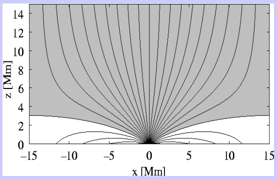
F_B = AB **F_M = ApV**



Dowdy et al., Solar Phys., **105**, 35, 1986

Magnetic field of coronal funnel

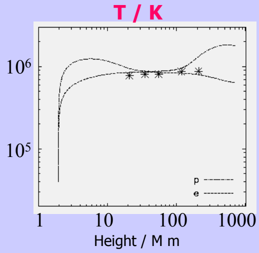
A(z) = flux tube cross section



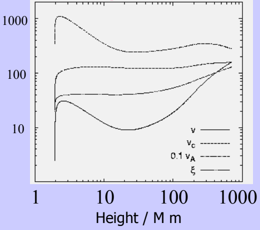
Hackenberg et al., Space Sci. Rev., **87**, 207, 1999

Height profiles in funnel flows

T / K



V / km s⁻¹



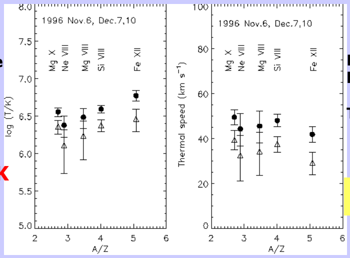
- **Heating by wave sweeping**
- **Steep temperature gradients**

- **Critical point at 1 R_S**

Hackenberg, Marsch, Mann, A&A, **360**, 1139, 2000

Heating and acceleration of ions by cyclotron and Landau resonance

Temperature



Doppler broadening

Thermal speed

T=(2-6) MK

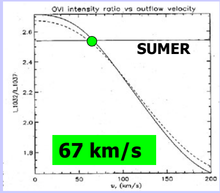
r = 1.15 R_S

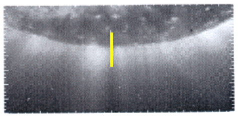
Ω ~ Z/A

Tu et al., Space Sci. Rev., **87**, 331, 1999

Ion heating ~ mass/charge

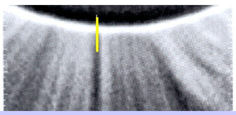
Outflow speed in interplume region at the coronal base





1.05 R_S

EIT FeIX/X



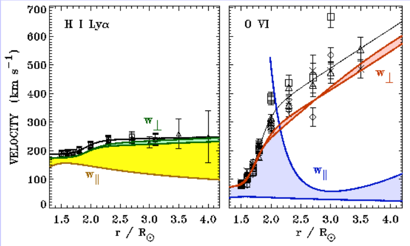
Eclipse 26/02 1998 18:33 UT

O VI 1031.9 Å / 1037.2 Å line ratio; Doppler dimming

$T_e = T_i$ = 0.9 M K, n_e = 1.8 10^7 cm^{-3}

Patsourakos and Vial, A&A, 359, L1, 2000

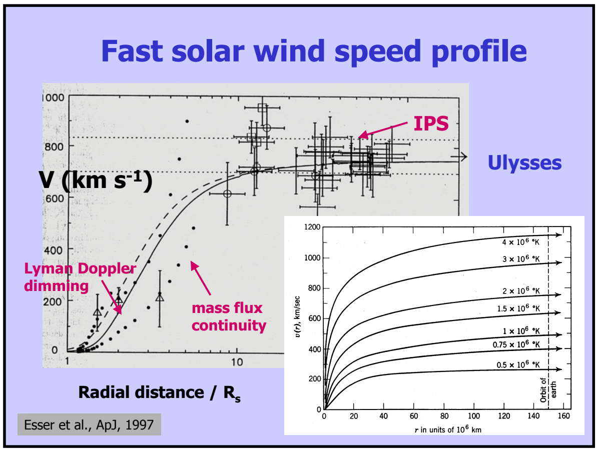
Oxygen and hydrogen thermal speeds in coronal holes



Very Strong perpendicular heating of Oxygen !

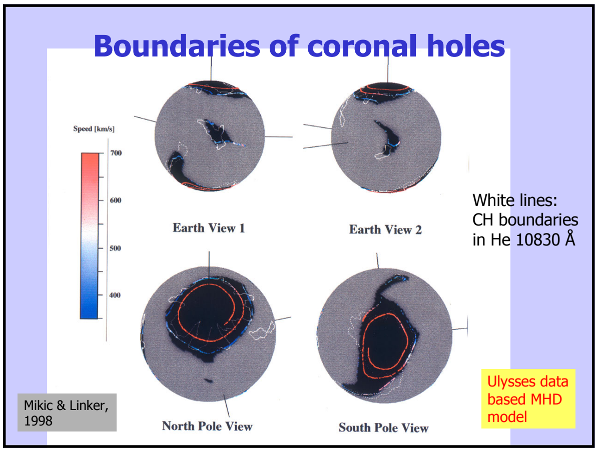
Cranmer et al., Ap. J., **511**, 481, 1998

Large anisotropy: $T_{O\perp}/T_{O\parallel} \ge 10$



Fast solar wind speed profile

Esser et al., ApJ, 1997

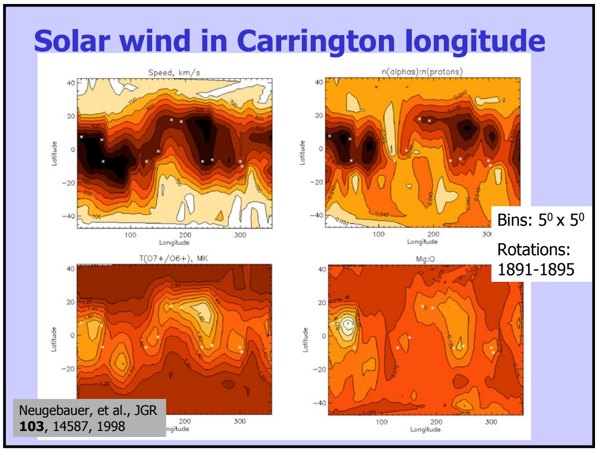


Boundaries of coronal holes

White lines:
CH boundaries
in He 10830 Å

Ulysses data based MHD model

Mikic & Linker, 1998

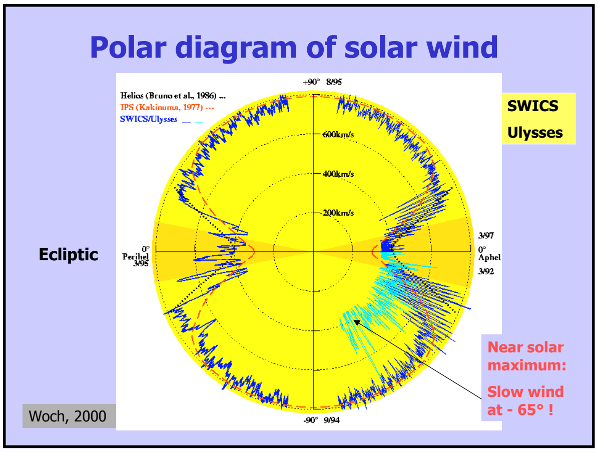


Solar wind in Carrington longitude

Bins: 5^0 x 5^0

Rotations:
1891-1895

Neugebauer, et al., JGR **103**, 14587, 1998



Polar diagram of solar wind

SWICS

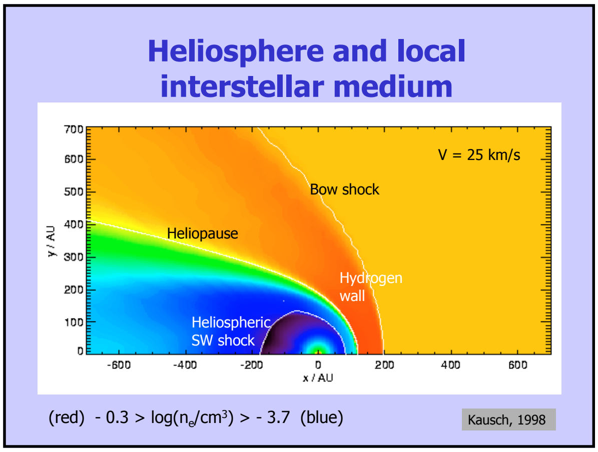
Ulysses

Ecliptic

Near solar maximum:

Slow wind at - 65° !

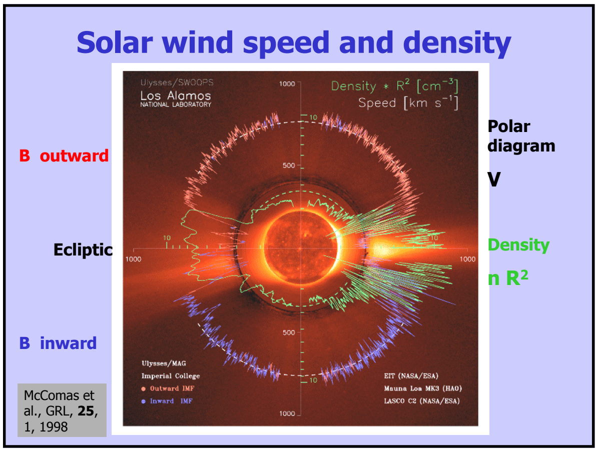
Woch, 2000



Heliosphere and local interstellar medium

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

Kausch, 1998



Solar wind speed and density

B outward

Ecliptic

B inward

Polar diagram

V

Density

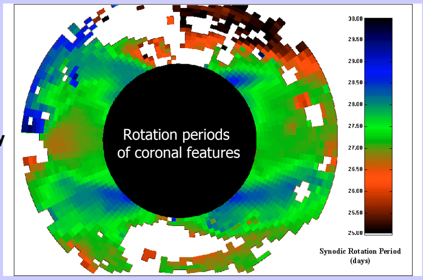
n R²

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

Rotation of solar corona

Fe XIV
5303 Å

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



27.2
days

**LASCO
/SOHO**

Stenborg et al., 1999

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

Sun`s loss of angular momentum carried by the solar wind I

Induction equation:

$\nabla \times (\mathbf{V} \times \mathbf{B}) = 0 \quad \text{-->} \quad r\,(V_r B_\phi - B_r V_\phi) = -\,r_0 B_0 \Omega_0 r_0$

Momentum equation:

$\rho \mathbf{V} \bullet \nabla V_\phi = 1/4\pi\, \mathbf{B} \bullet \nabla B_\phi \quad \text{-->} \quad r\,(\rho\, V_r V_\phi - B_r B_\phi) = 0$

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

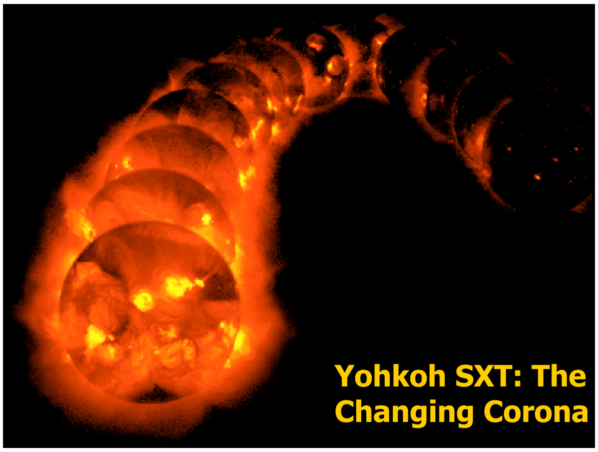
$V_\phi = \Omega_0 r\,(M_A^2\,(r_A/r)^2 - 1)/(M_A^2 - 1)$

$M_A = V_r (4\pi\rho)^{1/2}/B_r$
Alfvén Machnumber

Weber & Davis, ApJ, **148**, 217, 1967

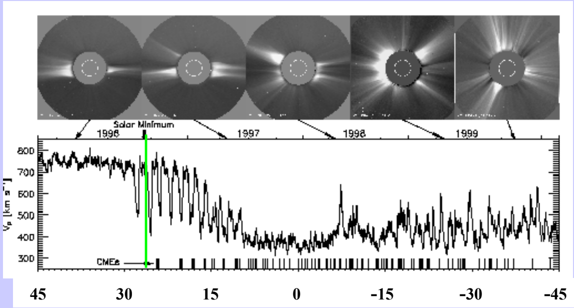
Helios: $r_A = 10\text{-}20\ R_s$

Sun`s loss of angular momentum carried by the solar wind II



Yohkoh SXT: The Changing Corona

Changing corona and solar wind



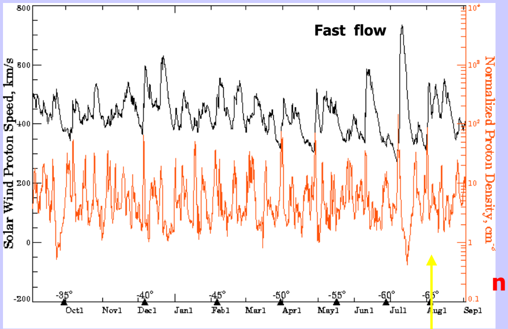
North **Heliolatitude / degree** **South**

McComas et al., 2000

LASCO/Ulysses

New solar wind data from Ulysses

V



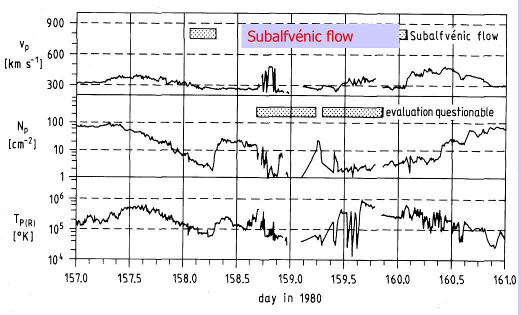
n

McComas et al., 2000

September 3, 1999 - September 2, 2000

Latitude: - 65°

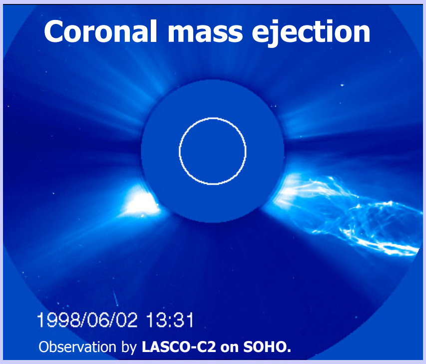
Solar wind dropout



Schwenn, 1980

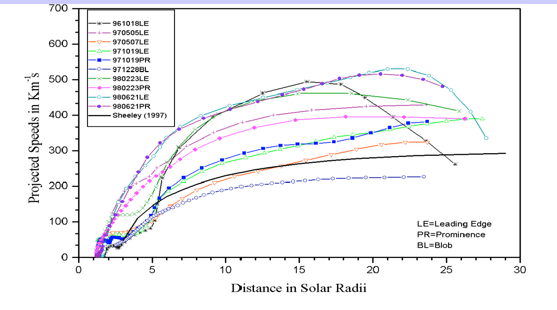
Helios 1 at 0.3 AU

Coronal mass ejection



Note the helical structure of the prominence filaments!

Speed profile of balloon-type CMEs

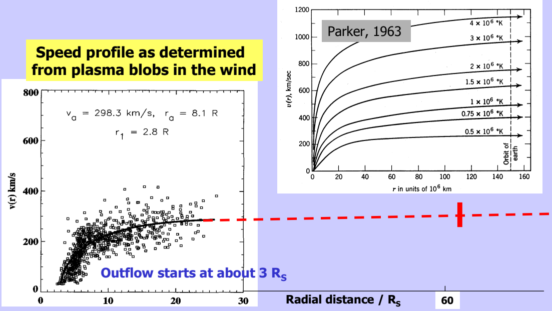


Srivastava et al., 1999

Wide range of initial acceleration: 5-25 ms^{-2}

Speed profile of the slow solar wind

Speed profile as determined from plasma blobs in the wind



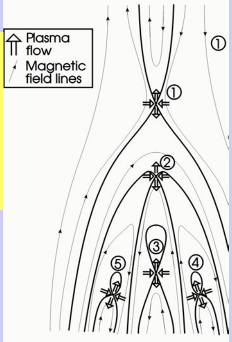
Outflow starts at about 3 R_S

Sheeley et al., Ap.J., **484**, 472, 1998

Consistent with Helios data

Non-stationary slow solar wind

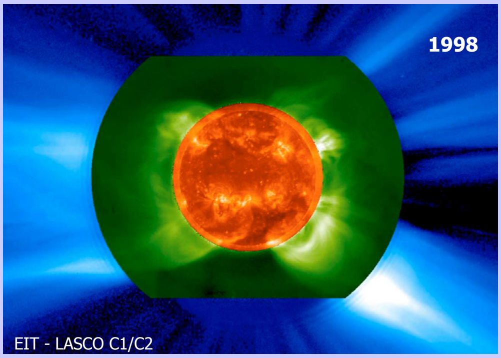
"....small eruptions at the helmet streamer cusp may incessantly accelerate small amounts of plasma without significant changes of the equilibrium configuration and might thus contribute to the non-stationary slow solar wind...."



- **Acceleration of slow wind above cusp (1)**
- **Coronal eruptions by magnetic reconnection inside the streamer (1)**
- **Interaction of three smaller streamers forming a dome (2)**
- **Plasmoids form by reconnection (3,4,5)**

Wiegelmann et al., Solar Phys., 1999

Corona of the active sun



Solar wind models I

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

$$4\pi r^2\kappa(T)dT/dr = \text{const} \quad \text{-->} \quad T = T_0(R/r)^{2/7}$$

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 $p(0) = p_0$:

$$dp/dr = - GMm_p n/r^2$$

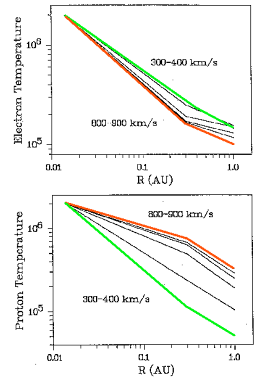
$$p = p_0 \exp[\ (7GMm_p)/(5k_B T_0 R)\ (\ (R/r)^{5/7} -1)\ ]$$

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

Chapman, 1957

Proton and electron temperatures

Electrons are cool!



slow wind
↓
fast wind

Protons are hot!

fast wind
↓
slow wind

Marsch, 1991

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:

$$mn_p V\ dV/dr = - dp/dr - GMm_p n/r^2$$

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:

$$[(V/c_0)^2 -1]\ dV/V = 2\ (1-r_c/r)\ dr/r$$

With the critical radius, $r_c = GMm_p/(2k_B T_0) = (V_\infty/2c_0)^2$, and the escape speed, V_∞ = 618 km/s, from the Sun's surface.

Parker, 1958

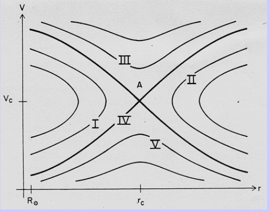
Solar wind models III

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

$$(M_s)^2 - \ln(M_s)^2 = 4\ (\ \ln(r/r_c) + r_c/r\ ) + C$$

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: $n \rightarrow 0$ and thus $p \rightarrow 0$ for $r \rightarrow \infty$. This is Parker's famous solution: the solar wind.



Parker, 1958

V, solar breeze; III accretion flow

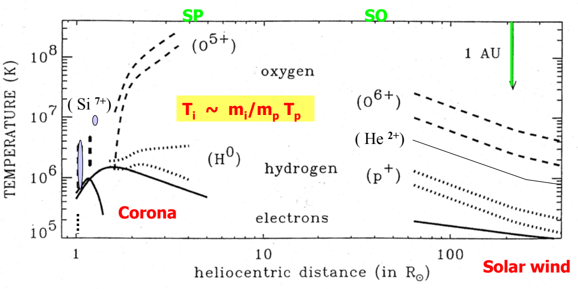
Fluid equations

- **Mass flux:** $F_M = \rho V A \qquad \rho = n_p m_p + n_i m_i$
- **Magnetic flux:** $F_B = B A$
- **Total momentum equation:**

$$V\ d/dr\ V = - 1/\rho\ d/dr\ (p + p_w) - GM_S/r^2 + a_w$$

- **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:** $A(r)$

Temperature profiles in the corona and fast solar wind



Cranmer et al., Ap.J., 2000; Marsch, 1991

Energy equations

Parallel thermal energy

$$\frac{d}{dr}v_{\|j}^2 = -2v_{\|j}^2\left(\frac{1}{u_j}\frac{du_j}{dr}\right) + \frac{2q_{\|j}}{u_j} + (Q_{\|j} + S_{\|j})/u_j$$

w-p terms + sources + sinks

Perpendicular thermal energy

$$\frac{d}{dr}v_{\perp j}^2 = -v_{\perp j}^2\left(\frac{1}{A}\frac{dA}{dr}\right) + \frac{q_{\perp j}}{u_j} + (Q_{\perp j} + S_{\perp j})/u_j$$

Heating functions: $q_{\perp,\|}$ .... ?

Wave energy absorption/emission by wave-particle interactions !

Conduction/collisional exchange of heat + radiative losses

Heating and acceleration of ions by cyclotron and Landau resonance

$$\begin{pmatrix} \frac{\partial}{\partial t}U_{j\|} \\ \frac{\partial}{\partial t}V_{j\|}^2 \\ \frac{\partial}{\partial t}V_{j\perp}^2 \end{pmatrix}$$

$= a_j$ **acceleration**

$= 2\, q_{j\|}$ **parallel heating**

$= q_{j\perp}$ **perpendicular heating**

$$= \frac{1}{(2\pi)^3}\int_{-\infty}^{+\infty} d^3k \sum_M \mathcal{B}_M(\mathbf{k})\left(\frac{\Omega_j}{k}\right)^2 \frac{1}{1-|\hat{\mathbf{k}}\cdot e_M(\mathbf{k})|^2}$$
$$\times \sum_{s=-\infty}^{+\infty} \mathcal{R}_j(\mathbf{k},s)\begin{pmatrix} k_\| \\ 2k_\| w_j(\mathbf{k},s) \\ s\Omega_j \end{pmatrix}$$

Marsch and Tu, JGR, **106**, 227, 2001

Wave spectrum ?
Wave dispersion ?
Resonance function ?

Height profile of turbulence amplitude

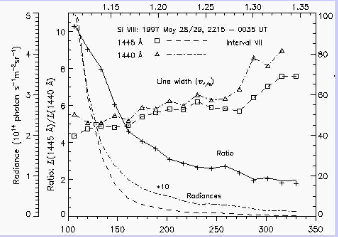
SUMER

Silicon VIII

λλ1440,1445

North polar coronal hole

Heliocentric distance / R_S



Height above limb / arcsec

Doppler velocity

$V_{1/e}$ / km s^{-1}

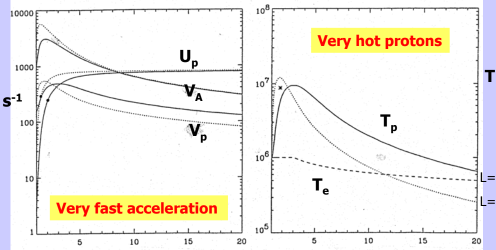
At 1.33 R_S:

$T_{Si} \approx 10^7$ K
$\xi \approx 70$ km s^{-1}
$n_e \approx 10^6$ cm^{-3}

Wilhelm et al., Ap.J., **500**, 1023, 1998

Rapid acceleration of the high-speed solar wind

V / km s^{-1}



T / K

L=0.50 R_S

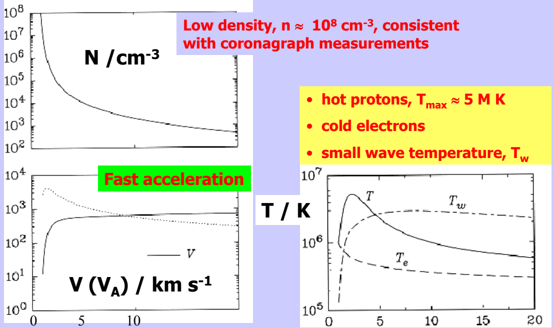
L=0.25 R_S

Radial distance / R_S Radial distance / R_S

McKenzie et al., A&A, **303**, L45, 1995

Heating: $Q = Q_0 \exp(-(r - R_S)/L)$; Sonic point: $r \approx 2\, R_S$

Model of the fast solar wind



Low density, n ≈ 10^8 cm^{-3}, consistent with coronagraph measurements

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

Fast acceleration

T / K

Radial distance / R_S

McKenzie et al., Geophys. Res. Lett., **24**, 2877, 1997

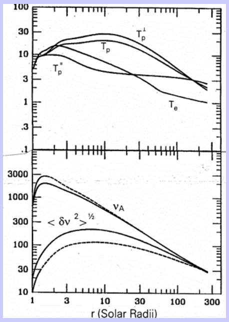
Anisotropic two-fluid model of the fast solar wind

$T_{p\perp} = 3\ 10^6$ K

T / 10^5 K

- Anisotropic heat deposition in 1-D two-fluid model
- Alfvén wave pressure gradient

v / km s^{-1}



- Anisotropy weakly influences dynamics
- Anisotropy needed for perpendicular ion-cyclotron heating and thermodynamics

Coronal base:

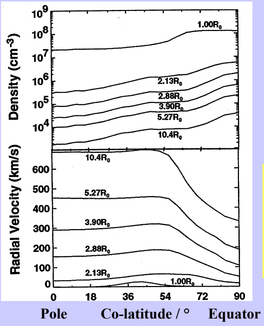
δv ≈ 10-20 km s^{-1}

ξ ≈ 20-30 km s^{-1}

Hu et al., JGR, **102**, 14661, 1997

Two-dimensional two-fluid MHD model of the solar corona

- Time-dependent 2-D model MHD with separate T_e and T_p equations
- Slow outflow at equator, fast over poles after 1 day
- Heating functions Q_e and Q_p latitude-dependent



Suess et al., JGR, **104**, 4697, 1999

Heating function:

$Q_{e,p} = Q_0 f_{e,p}(r,\theta) \exp(-0.1(r-R_s)/R_s)$

$Q_0 = 5\ 10^{-8}$ erg $cm^{-3}\ s^{-1}$

Poles:

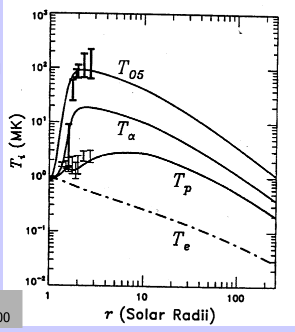
$T_e < T_p$ $\beta \ll 1$

Equator:

$T_e = T_p$ $\beta \geq 1$

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: $-2 \leq \gamma \leq -1$

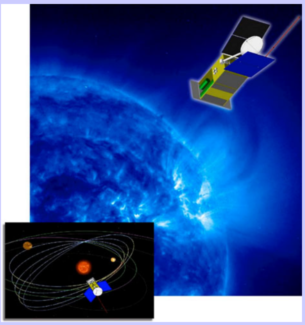


Hu, Esser & Habbal, JGR, **105**, 5093, 2000

- No wave absorption
- Turbulence spectra not self-consistent

Preferential heating of heavy ions by waves

The future: Solar Orbiter

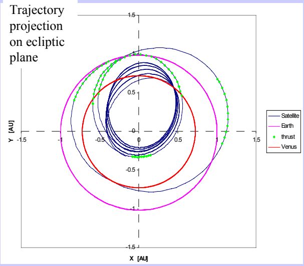


A high-resolution mission to the Sun and inner heliosphere

ESA

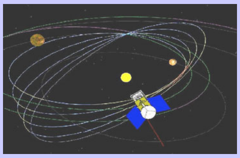
2011 - 2012

Solar Orbiter's novel orbital design



Trajectory projection on ecliptic plane

- **Venus gravity assist**
- **Solar electric propulsion**



- **Closer to the Sun!**
- **Out of the ecliptic!**