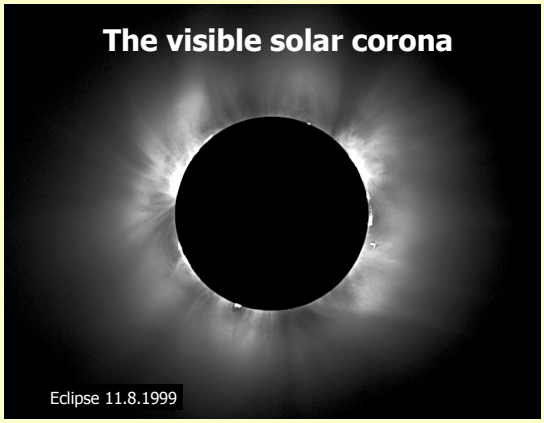
The heliosphere, structure and dynamics

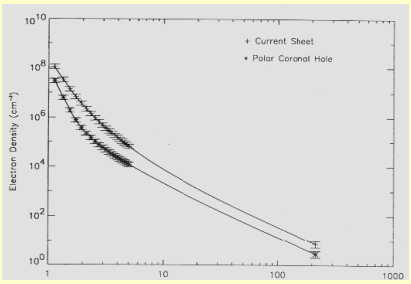
- Solar corona, structure and evolution
- The heliosphere, structure and dynamics
- Solar wind (heliospheric) magnetic field
- Corotating interaction regions
- Interplanetary shock waves
- The outer heliosphere and LISM

The visible solar corona



Eclipse 11.8.1999

Electron density in the corona



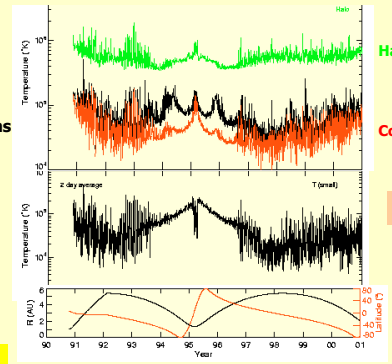
+ Current sheet and streamer belt, closed

• Polar coronal hole, open magnetically

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

Skylab coronagraph/Ulysses in-situ

Heliospheric temperatures



Electrons

Protons

Halo (4%)

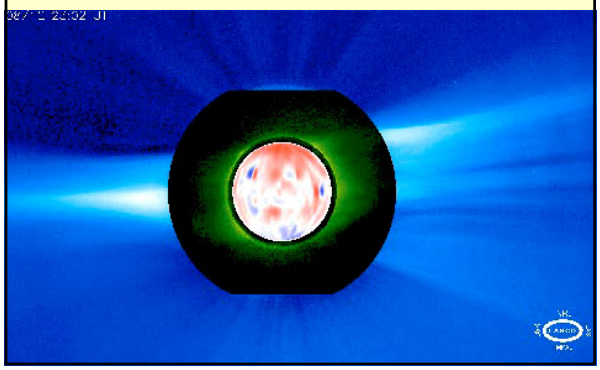
Core (96%)

$T_p \leq T_e$

Ulysses

McComas et al., 1998

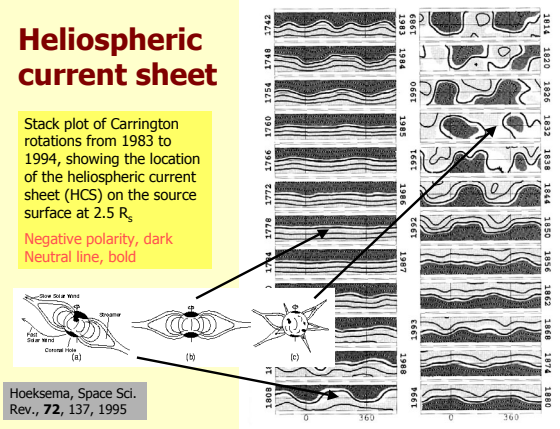
Rotation of the sun and corona



Heliospheric 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

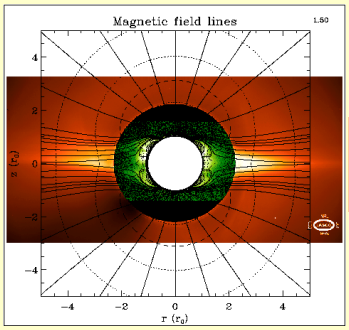
Negative polarity, dark
Neutral line, bold



Hoeksema, Space Sci. Rev., **72**, 137, 1995

Coronal magnetic field and density

Dipolar, quadrupolar, current sheet contributions



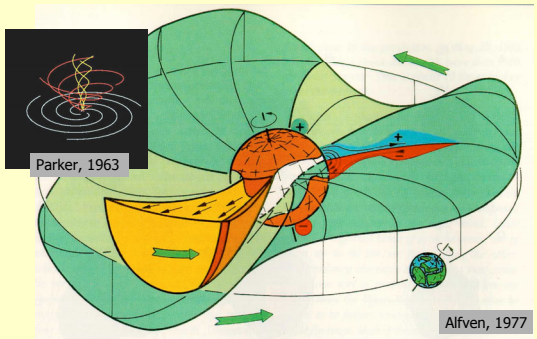
Polar field: B = 12 G

Current sheet is a symmetric disc anchored at high latitudes !

Banaszkiewicz et al., 1998; Schwenn et al., 1997

LASCO C1/C2 images (SOHO)

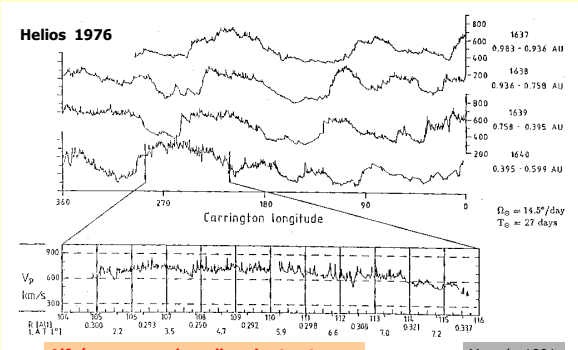
Solar wind stream structure and heliospheric current sheet



Parker, 1963

Alfven, 1977

Solar wind fast and slow streams

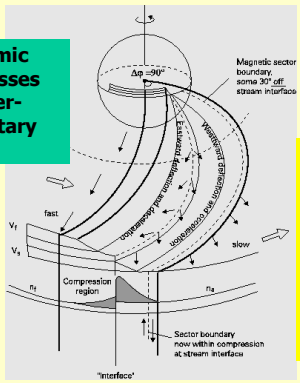


Alfvén waves and small-scale structures

Marsch, 1991

Stream interaction region

Dynamic processes in inter-planetary space



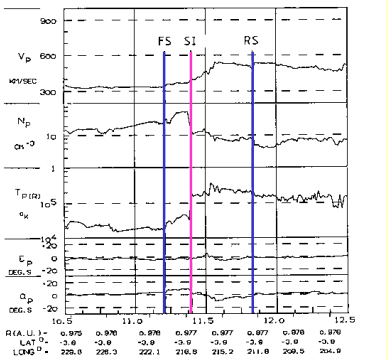
- **Wave amplitude steepening ($n \sim r^{-2}$)**
- **Compression and rarefaction**
- **Velocity shear**
- **Nonlinearity by advection ($\underline{V} \bullet \nabla) \underline{V}$**
- **Shock formation (co-rotating)**

Stream interaction region (Helios)

Forward shock FS

Reverse shock RS

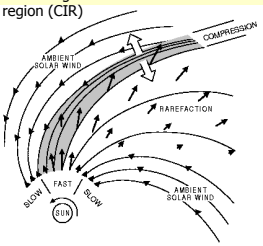
Stream interface SI, tangential discintinuity with T jump



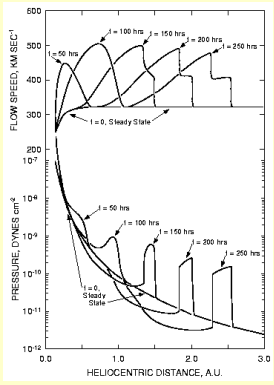
Schwenn, 1990

Solar wind stream interactions

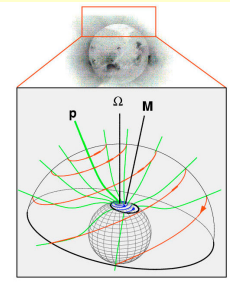
Corotating interaction region (CIR)

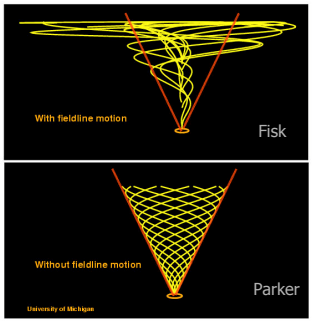


Hundhausen, 1973; Pizzo, 1978



Model of coronal-heliospheric field

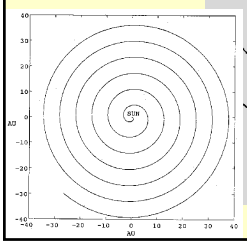


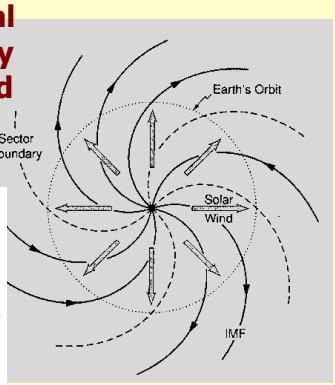


Fisk, JGR, 1996

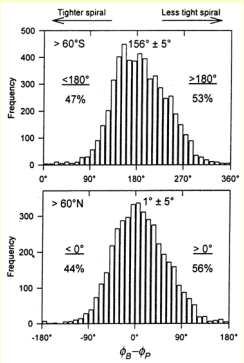
(Parker) spiral interplanetary magnetic field

rot(**E**) = rot(**V**x**B**) = **0**





Heliospheric magnetic field direction

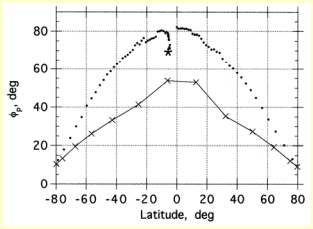


$B_R = B_s\,(R_s/R)^2$ Parker spiral

$B_T = B_R\,\Omega(\theta)R/V\cos\theta$ $\varphi_p = \tan^{-1}(B_T/B_R)$

$B_N = 0$ (R_s = 700000 km)

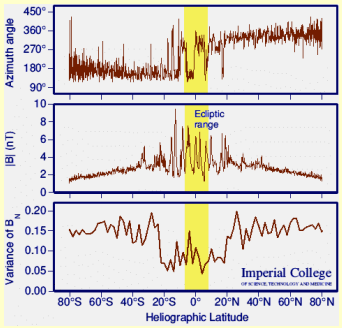
$\Omega(\theta) = 3.101 - 0.464\,\sin(\theta)^2 - 0.328\,\sin(\theta)^4$ [μrad/s]



Forsyth et al., A&A **316**, 287, 1996

Latitudinal variation of the heliospheric magnetic field

Ulysses

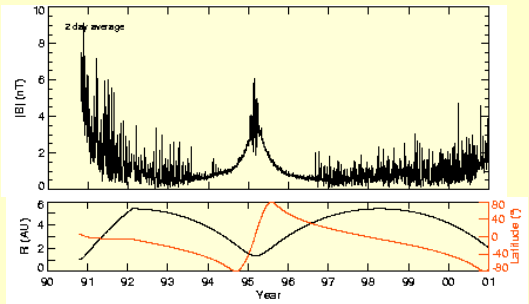


Field polarity

Alfvén waves

Balogh and Forsyth, 1998

Heliospheric magnetic field



McComas et al., 1998

Ulysses SWOOPS

Conservation of radial magnetic flux

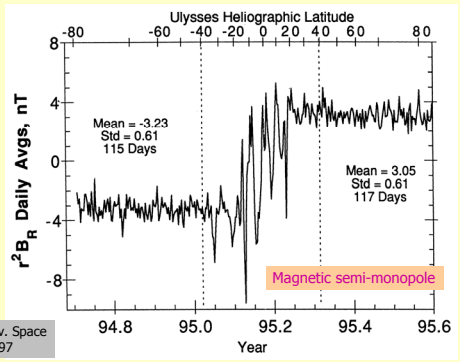
At 1 AU:

Ulysses:

$B_R \approx 3.1$ nT

Helios:

$B_R \approx 3.3$ nT



Magnetic semi-monopole

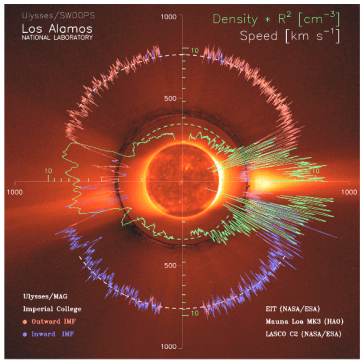
Smith et al., Adv. Space Res. **20**, 47, 1997

Solar wind speed and density

B outward

Ecliptic

B inward



Polar diagram

V

Density

n R²

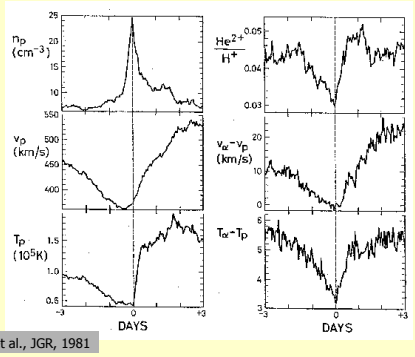
McComas et al., GRL, **25**, 1, 1998

Current sheet crossings

Dense

Slow

Cold



Less Helium

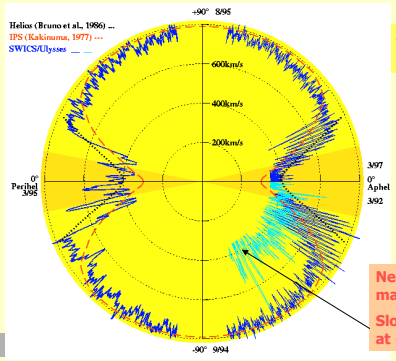
Speeds equal

Temperatures close

Borrini et al., JGR, 1981

Polar diagram of solar wind

Ecliptic



SWICS

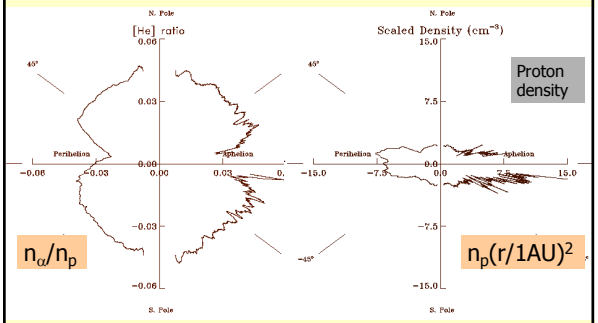
Ulysses

Near solar maximum:

Slow wind at ~ 65° !

Woch, 2000

Polar plot of density and He/H ratio



Proton density

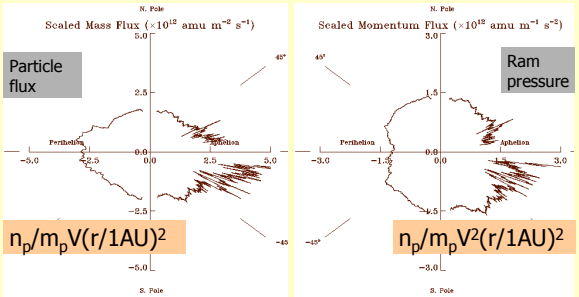
n_α/n_p

$n_p(r/1AU)^2$

McComas et al., 1998; Geiss et al., 1998

Ulysses SWOOPS/SWICS

Polar plot of mass/momentum flux



Particle flux

Ram pressure

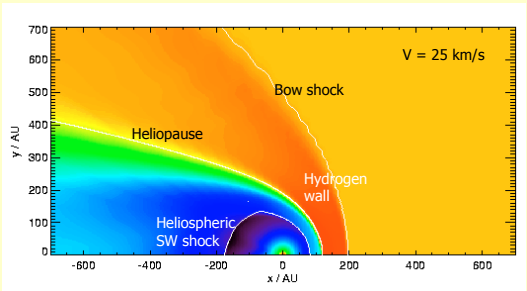
$n_p/m_pV(r/1AU)^2$

$n_p/m_pV^2(r/1AU)^2$

McComas et al., 1998

Ulysses SWOOPS/SWICS

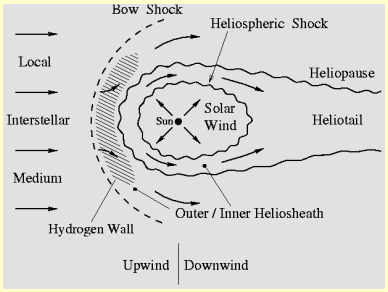
Heliosphere and local interstellar medium



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

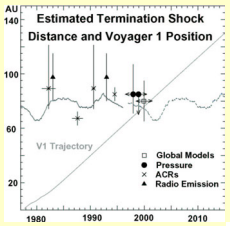
Kausch, 1998

Structure of the heliosphere



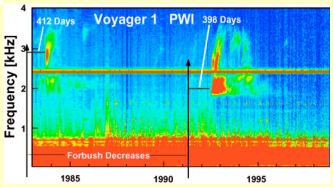
- Basic plasma motions in the restframe of the Sun
- Principal surfaces (wavy lines indicate disturbances)

Heliospheric termination shock



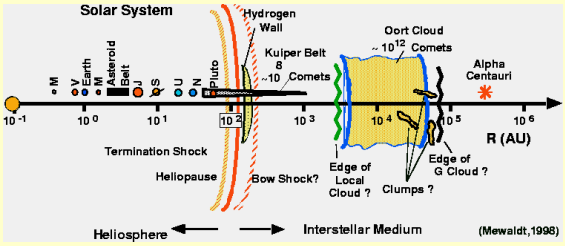
2-3 kHz radio emission generated at the heliopause (compression region); radiation is trapped in heliospheric cavity; source: largest CMEs of solar activity maximum in 1983 and 1993

Shock at 100 AU?



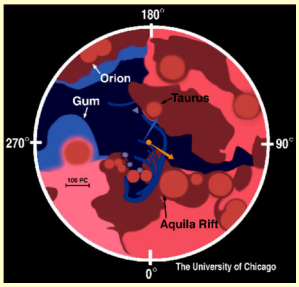
Stone, 1999; Kurth, 1999

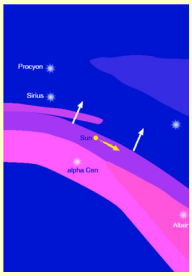
The outer frontier



Termination schock at about 100 AU and Voyager at 80 AU

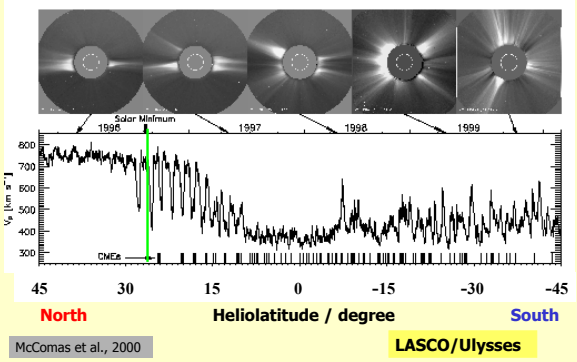
The interstellar neighbourhood





Frisch, Space Sci. Rev. 86, 107, 1998

Changing corona and solar wind



McComas et al., 2000

LASCO/Ulysses

Solar wind types I

1. Fast wind in high-speed streams

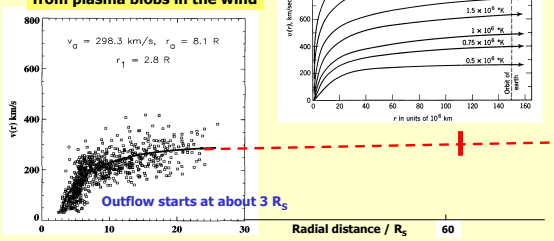
High speed	400 - 800 kms^{-1}
Low density	3 cm^{-3}
Low particle flux	2 x 10^{8} cm^{-2} s^{-1}
Helium content	3.6 %, stationary
Source	coronal holes
Signatures	stationary for long times (weeks!)

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

Speed profile of the slow solar wind

Speed profile as determined from plasma blobs in the wind



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

Consistent with Helios data

Solar wind types II

3. Low speed wind near activity maximum

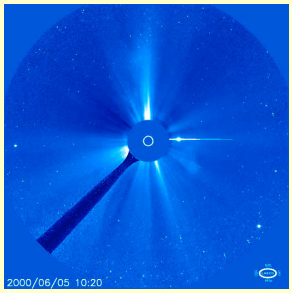
Similar characteristics as 2., except for

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

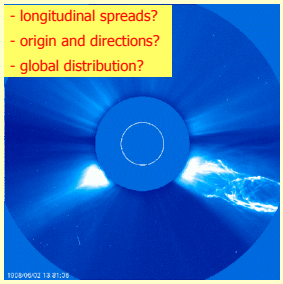
4. Ejecta following interplanetary shocks

High speed	400 - 2000 kms^{-1}
Helium content	up to 30%
Other constituents	often Fe^{6+} ions; in rare cases He^{+}
Signatures of magnetic clouds	in about 30% of cases
Sources	erupting prominences

Coronal mass ejections



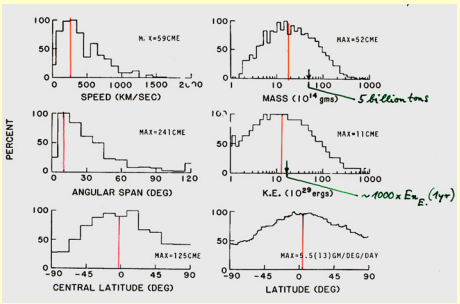
- longitudinal spreads?
- origin and directions?
- global distribution?



Schwenn et al., 1998, 2000

LASCO on SOHO, helical CME

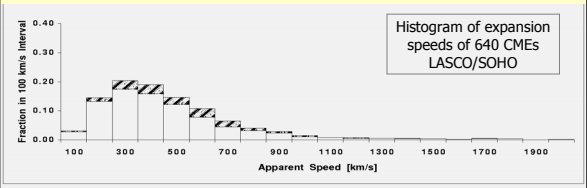
Statistics of CME properties



About 1000 CMEs observed by **SOLWIND**

Howard et al., 1985

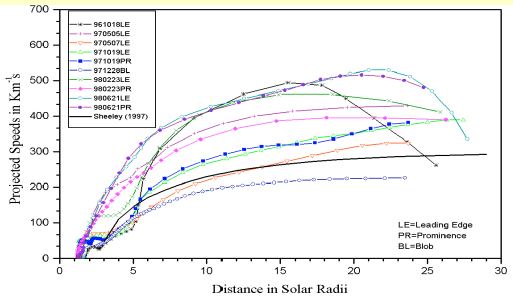
Speeds of CMEs (1996 to 1998)



- **Flare-associated fast CMEs with 0.3 ms^{-2} and initial V > 700 km/s**
- **Eruptive slow CMEs with 0-50 ms^{-2} and initial V = 10-20 km/s**

St.Cyr et al., 2000

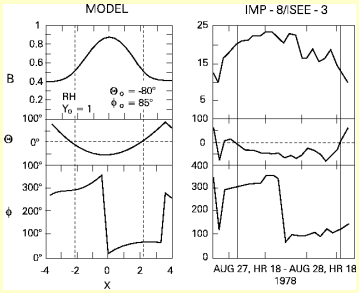
Speed profile of balloon-type CMEs

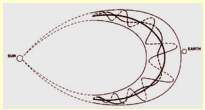


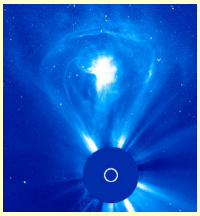
Srivastava et al., 1999

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

Field variation in magnetic cloud

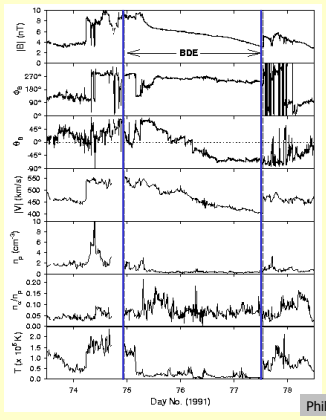






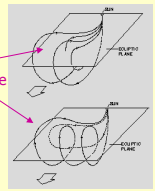
Burlaga, 1980

Interplanetary CME



- Rotation of field vector
- Speed enhancement
- Lower density
- Higher Helium content
- Cooler protons

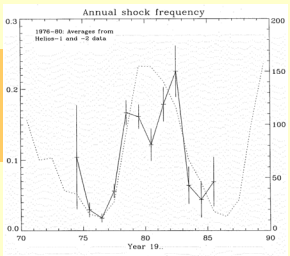
Magnetic loop or flux rope



Philipps, 1997

Daily number of interplanetary shocks in a typical solar cycle

The daily shock rate, based on 400 shocks observed by the **Helios** solar probes in 12 years.



.... Sunspot number

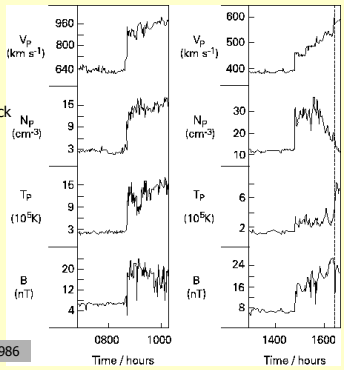
CME rates:
2-3/day (max)
0.2/day (min)

Shock rate in the ecliptic plane is about 10 % of the total CME rate: every tenth CME shock hits the earth!

Khalisi, 1995

Interplanetary shock waves

Quasiparallel (19^0) transient fast-mode shock



Quasiparallel (12^0) corotating fast-mode shock

Note the strong jumps in all parameters!

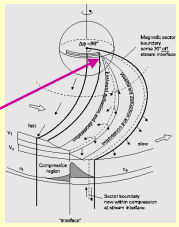
Richter et al., 1986

Solar wind stream dynamics

Fast streams <-------> slow streams

Coronal holes (open) - streamers (closed)

Sharp transitions ≈ 2^0 - 8^0
(20 - 80) kms^{-1}/degree



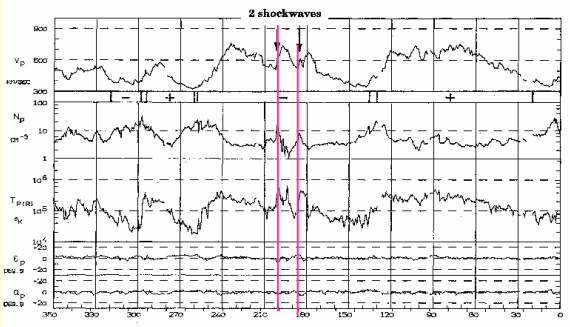
Stream collisions <---> interaction regions

advection <---> compression

$(\underline{V}\bullet\nabla)\,\underline{V} = -\nabla(p + B^2/4\pi)$

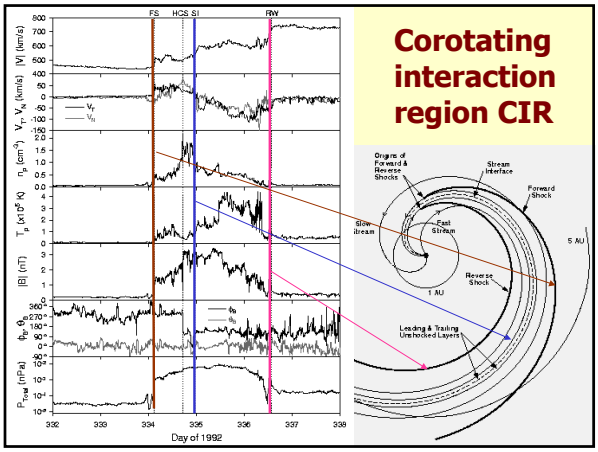
- Colliding transient flows form corotating interaction regions (CIRs)
- Compound streams: - two corotating streams
  - stream and transient ejection
  - two ejecta or clouds or shocks

Solar wind streams and shocks



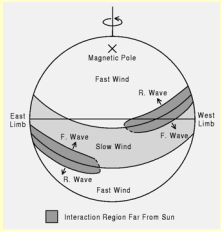
Schwenn, 1990

Corotating interaction region CIR

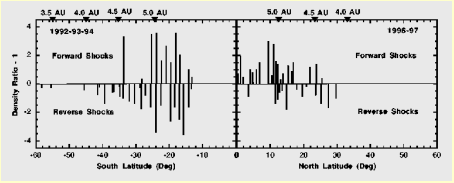


Corotating shocks

Schematic showing how the tilted streamer belt leads equatorward forward (FS) and poleward reverse (RS) shock propagation



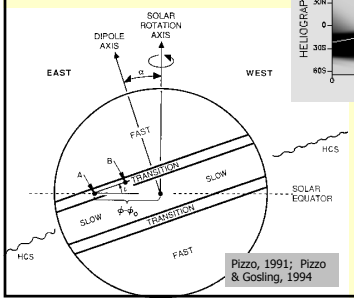
Ulysses shock statistics for northern (right) and southern (left) hemisphere



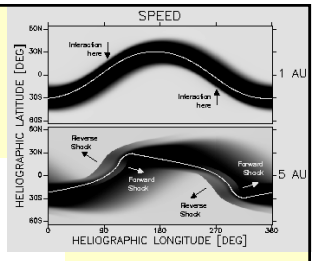
Gosling & Pizzo, Space Sci. Rev. **89**, 21, 1999

CIR simulation

Tilted dipol geometry used at inner boundary



Pizzo, 1991; Pizzo & Gosling, 1994



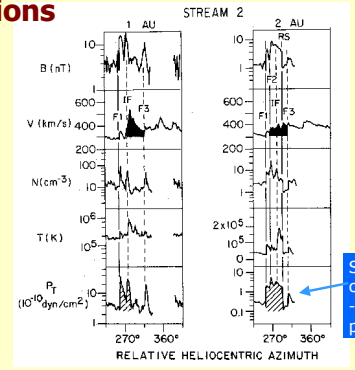
White: fast, black: slow

FS and RS pairs develop

Large-scale 3-D structure of CIRs is intimately linked with slow/fast wind source geometry in solar corona

Merged stream interaction regions

In-situ observation at 1 AU



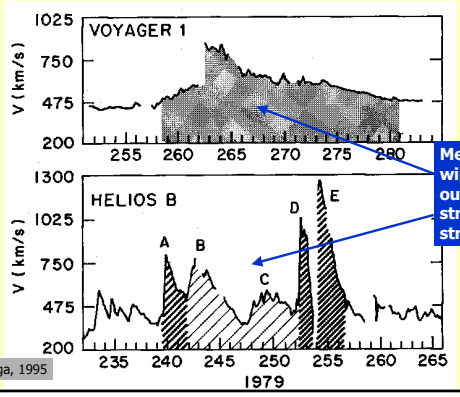
MHD simulation at 2 AU

MIRs

Stream coalescence --> pressure pulse

Burlaga, 1995

Global merged interaction region



Voyager at 6.2 AU

Merging wipes out stream structure

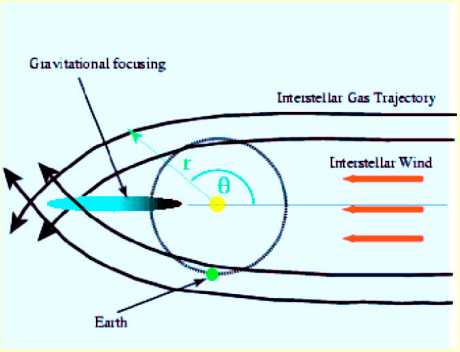
Helios at 0.85 AU

Burlaga, 1995

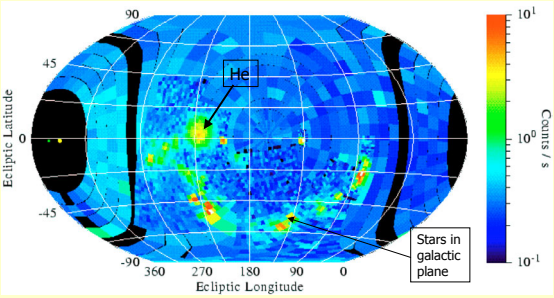
Inventory of the heliosphere

- **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 (solar wind, dust, surfaces)**
- **Energetic neutrals (heliopause)**
- **Dust (interstaller medium, minor bodies)**

Gravitational focussing of interstellar gas



Interstellar neutral gas



Witte et al., Spac. Sci. Rev. **78**, 289, 1996

View from Ulysses, in ecliptic coordinates: $\lambda \approx 225^o$, $\beta \approx 5^o$.