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AUTUMN COLLEGE ON PLASMA PHYSICS

8 October - 2 November 2001

Kinetic Physics of the Solar Corona and Solar Wind - I

E. Marsch

Max Planck Institute for Aeronomy
Lindau, Germany

Kinetic Physics of the Solar Corona and Solar Wind

Eckart Marsch

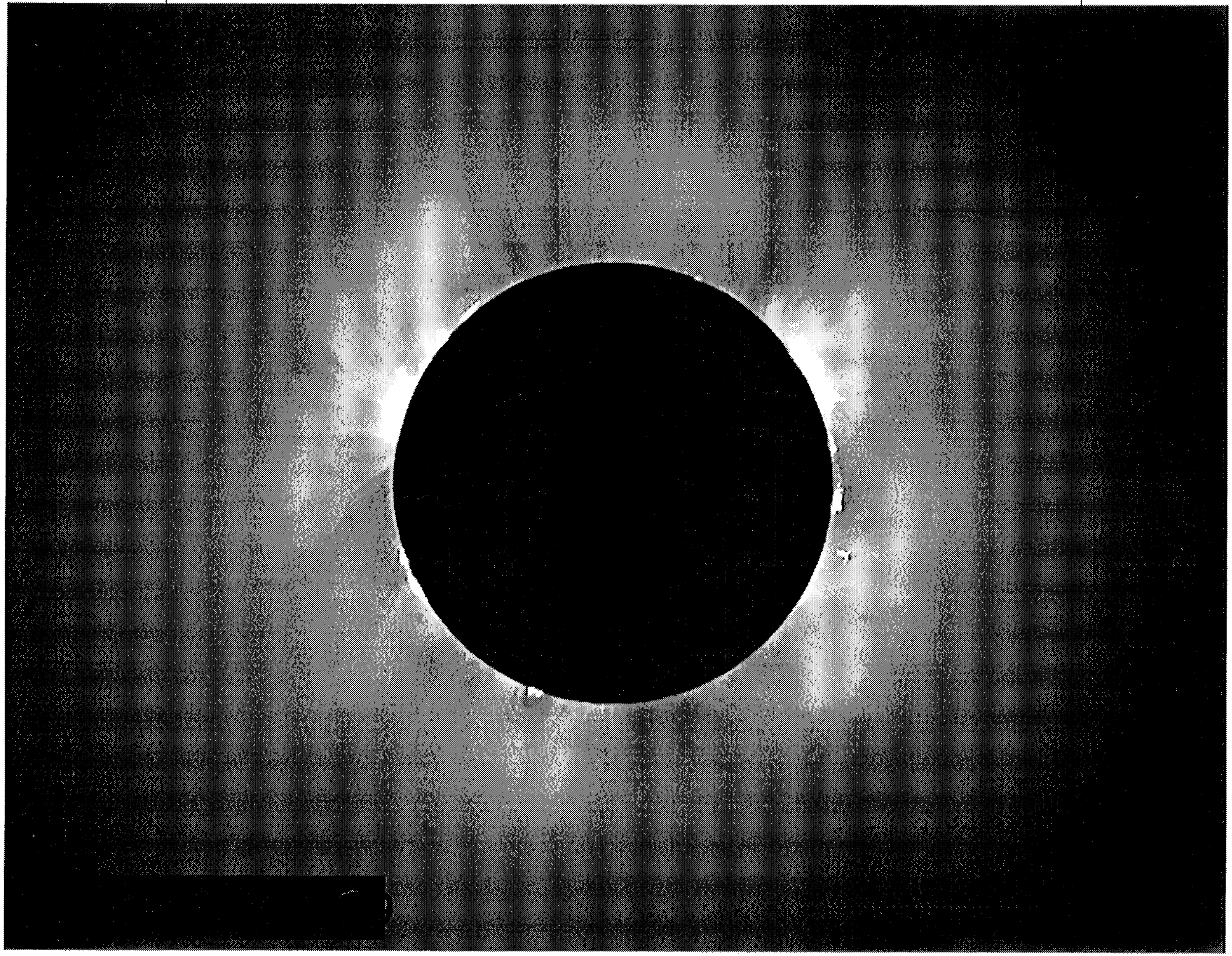
Max-Planck-Institut für Aeronomie

- The Sun's corona and wind – structure, evolution and dynamics
- Ions and electrons – velocity distributions and kinetics
- Waves and turbulence – excitation, transport and dissipation

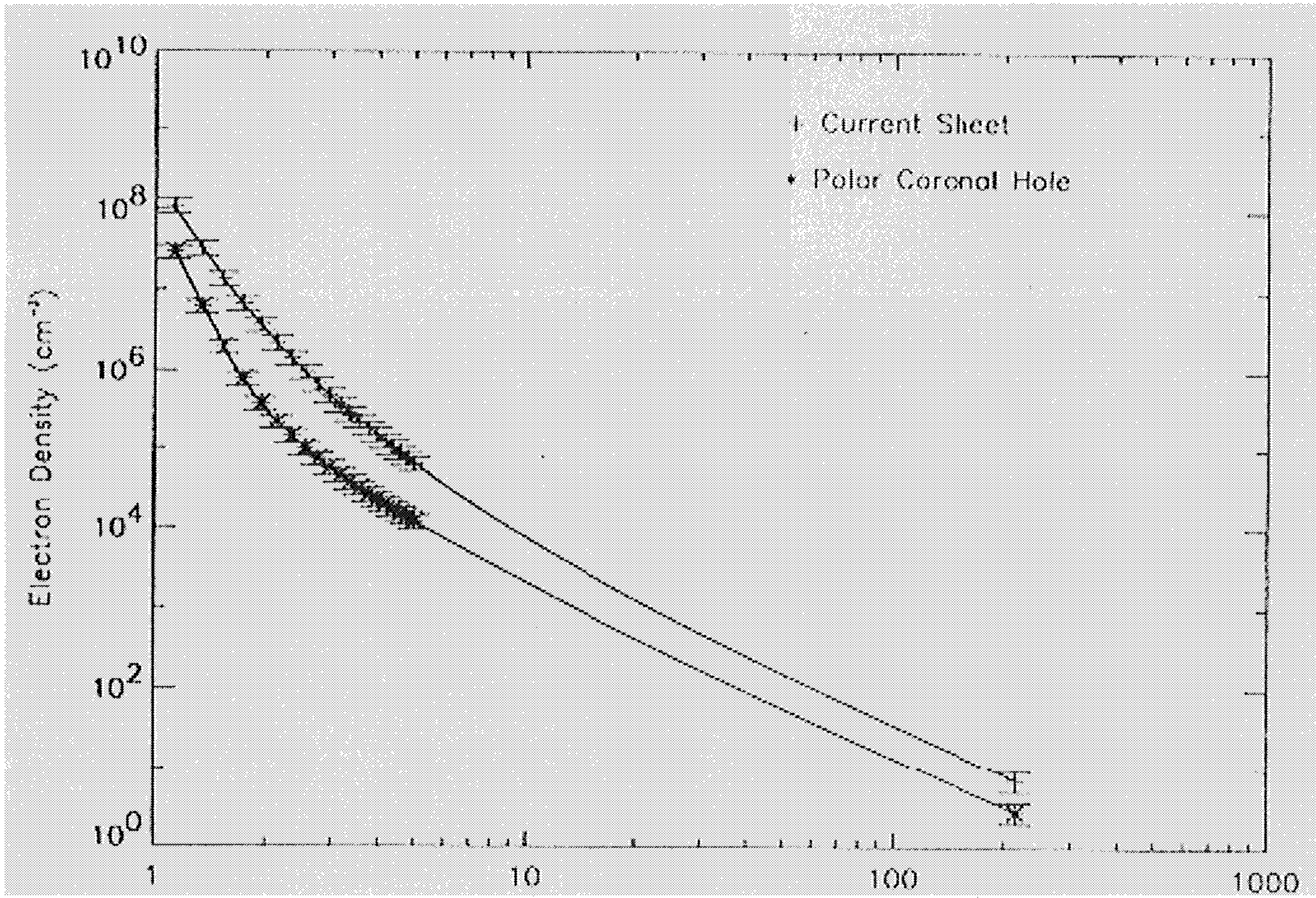
The Sun's corona and wind – structure, evolution and dynamics

- Solar atmosphere
- Coronal plasma state and parameters
- Chromospheric network and corona
- Solar magnetic field and activity
- Coronal temperature distribution
- Origin and types of solar wind
- Sun's loss of mass and angular momentum
- Concept of a wind: Parker's fluid model
- Multi–fluid models of the solar wind
- Spiral magnetic field and Alfven waves
- Dynamic processes in interplanetary space
- Large–scale structure of the heliosphere

The visible solar corona



Electron density in the corona



+ Current sheet and streamer belt, closed

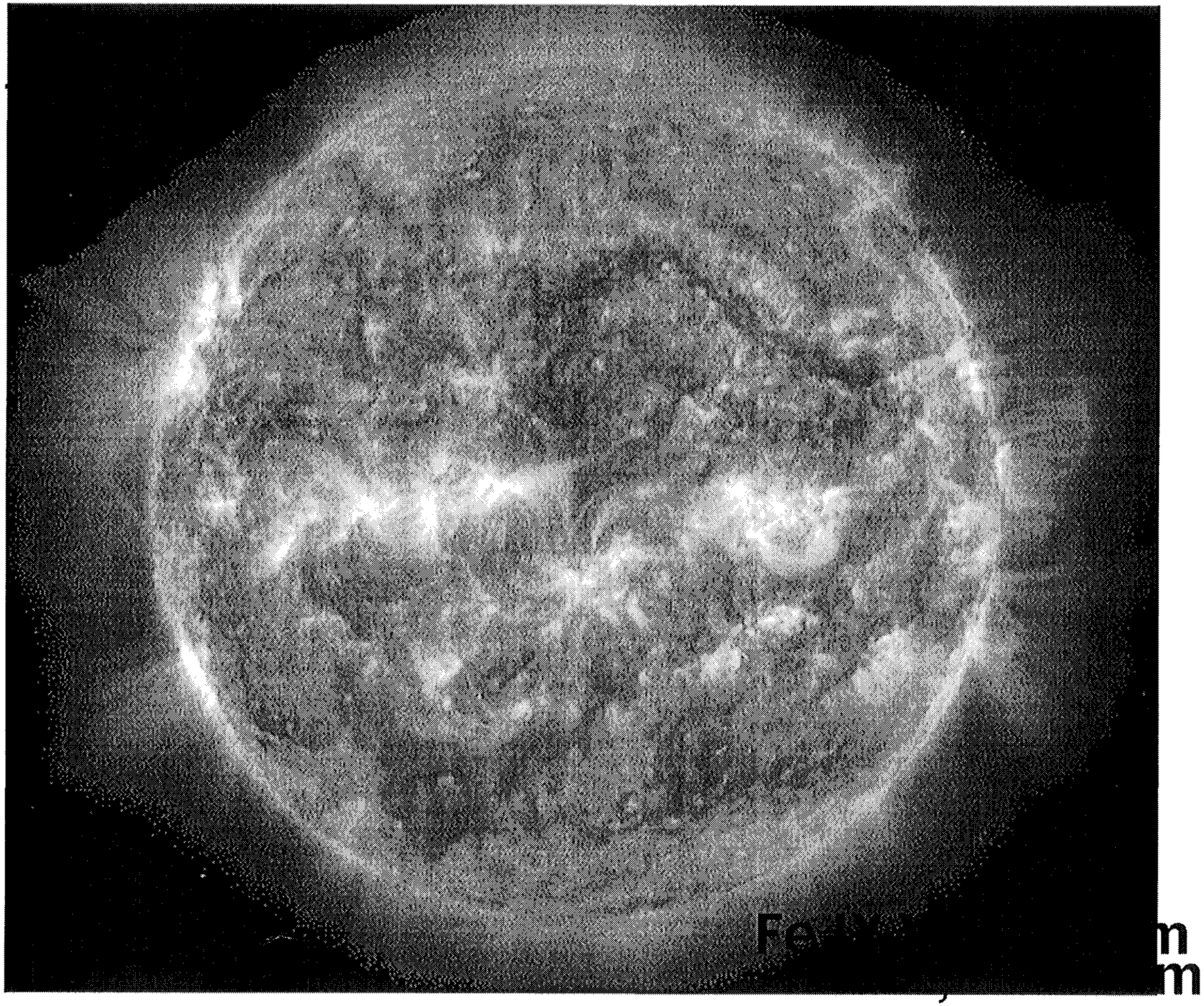
• Polar coronal hole, open magneticall y

Heliocentric distance / R_s

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

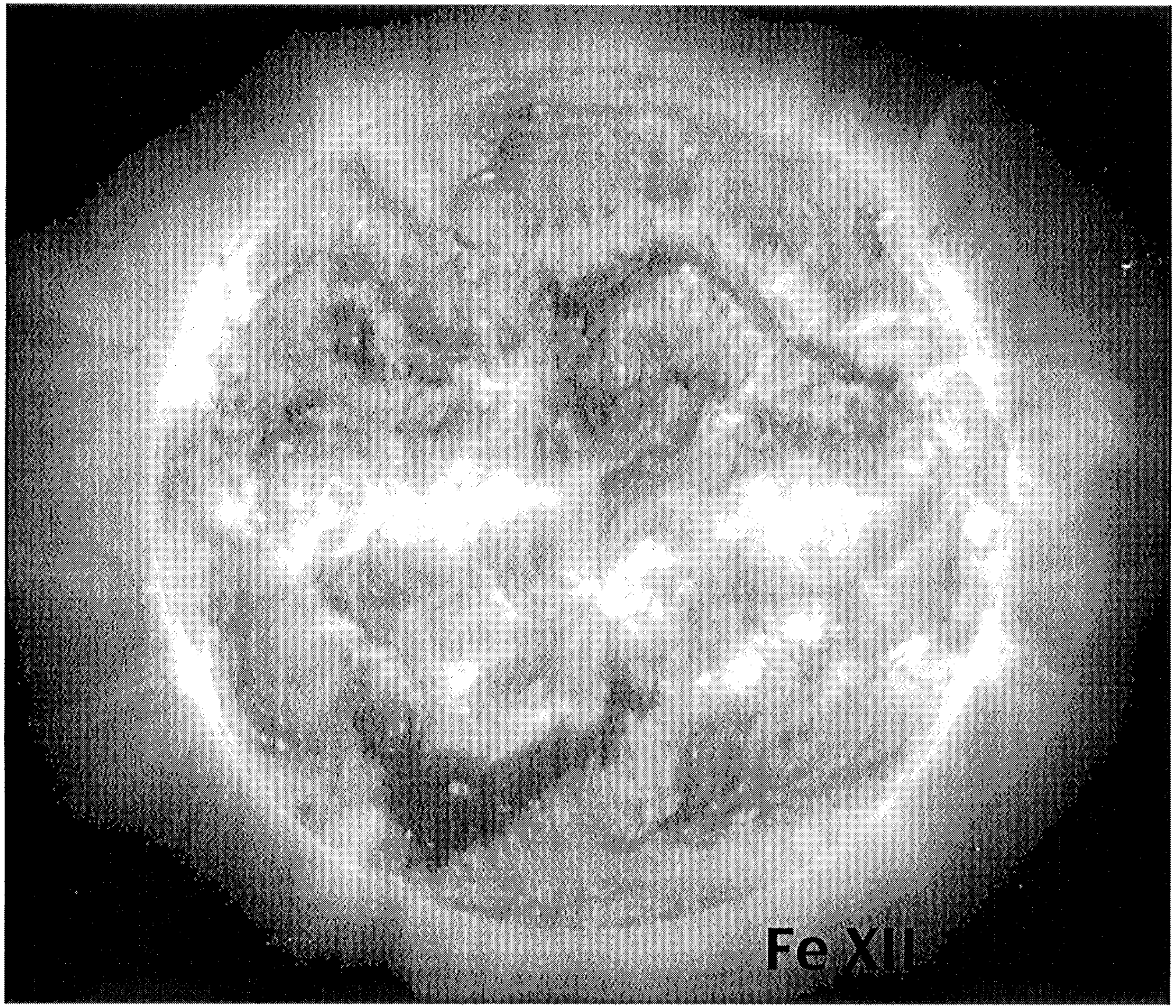
Skylab coronagraph/Ulysses in-situ

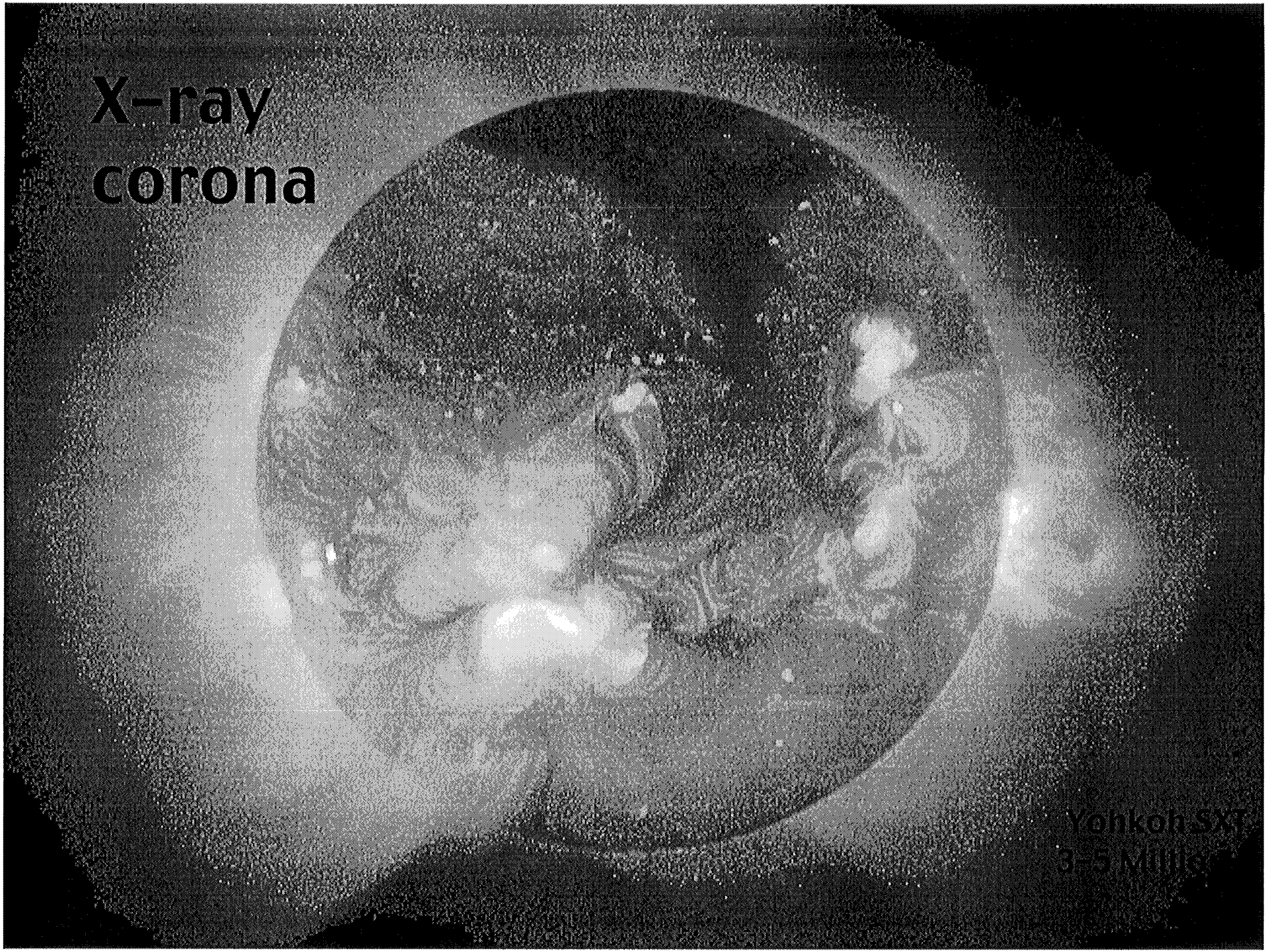
Corona and transition region



1996

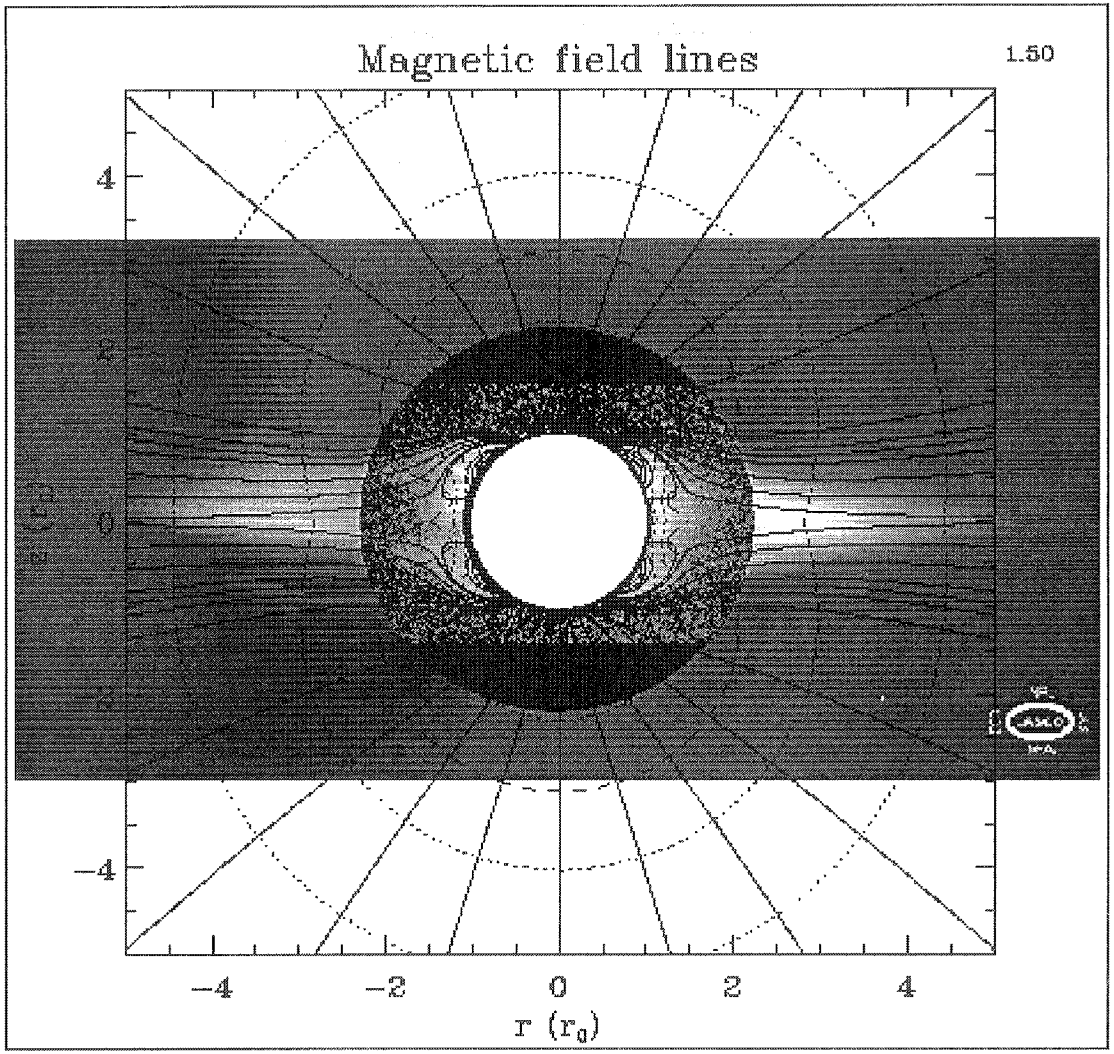
Active regions near maximum




X-ray
corona
Yohkoh SXT

Coronal magnetic field and density

Dipolar, quadrupolar, current sheet contributions



Polar field: B = 12 G

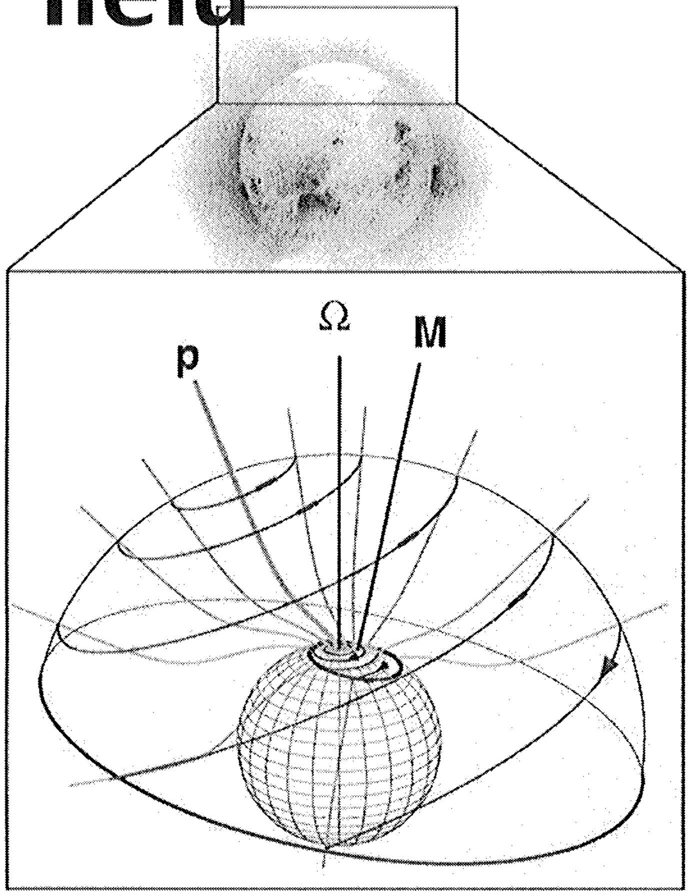
Current sheet is a symmetric disc anchored at high latitudes !

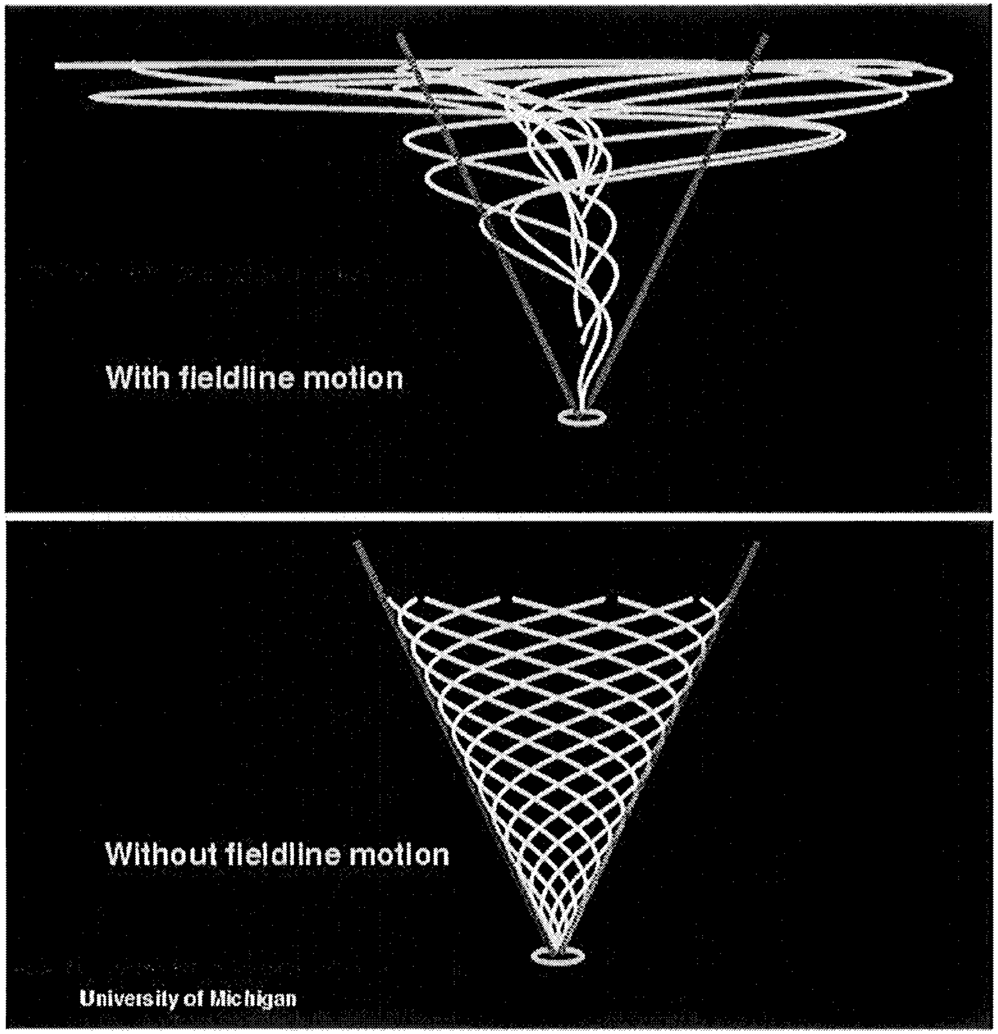
LASCO C1/C2 images (SOHO)

Banaszkiewicz et al., 1998;

Schwenn et al., 1997

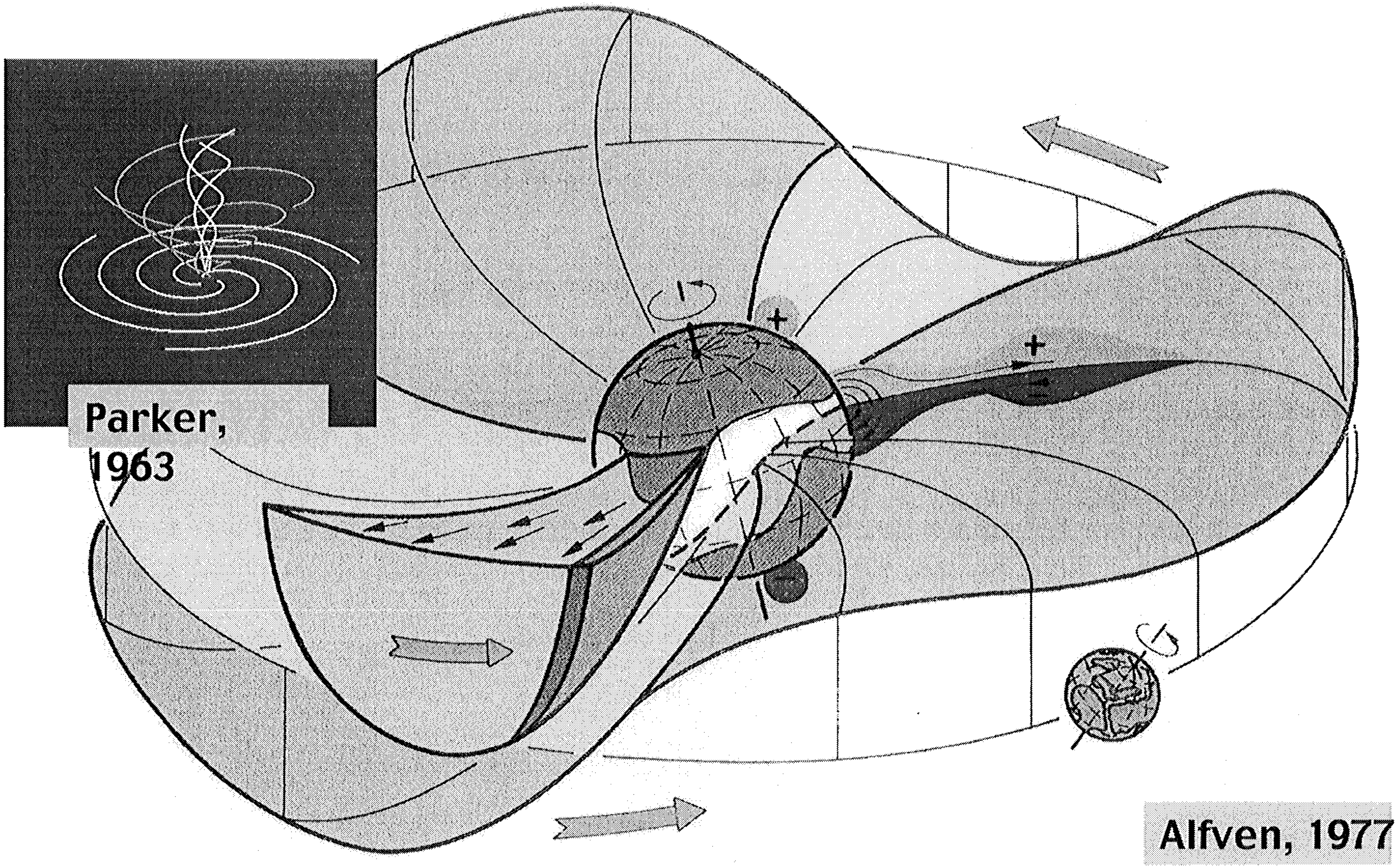
Model of coronal–heliospheric field





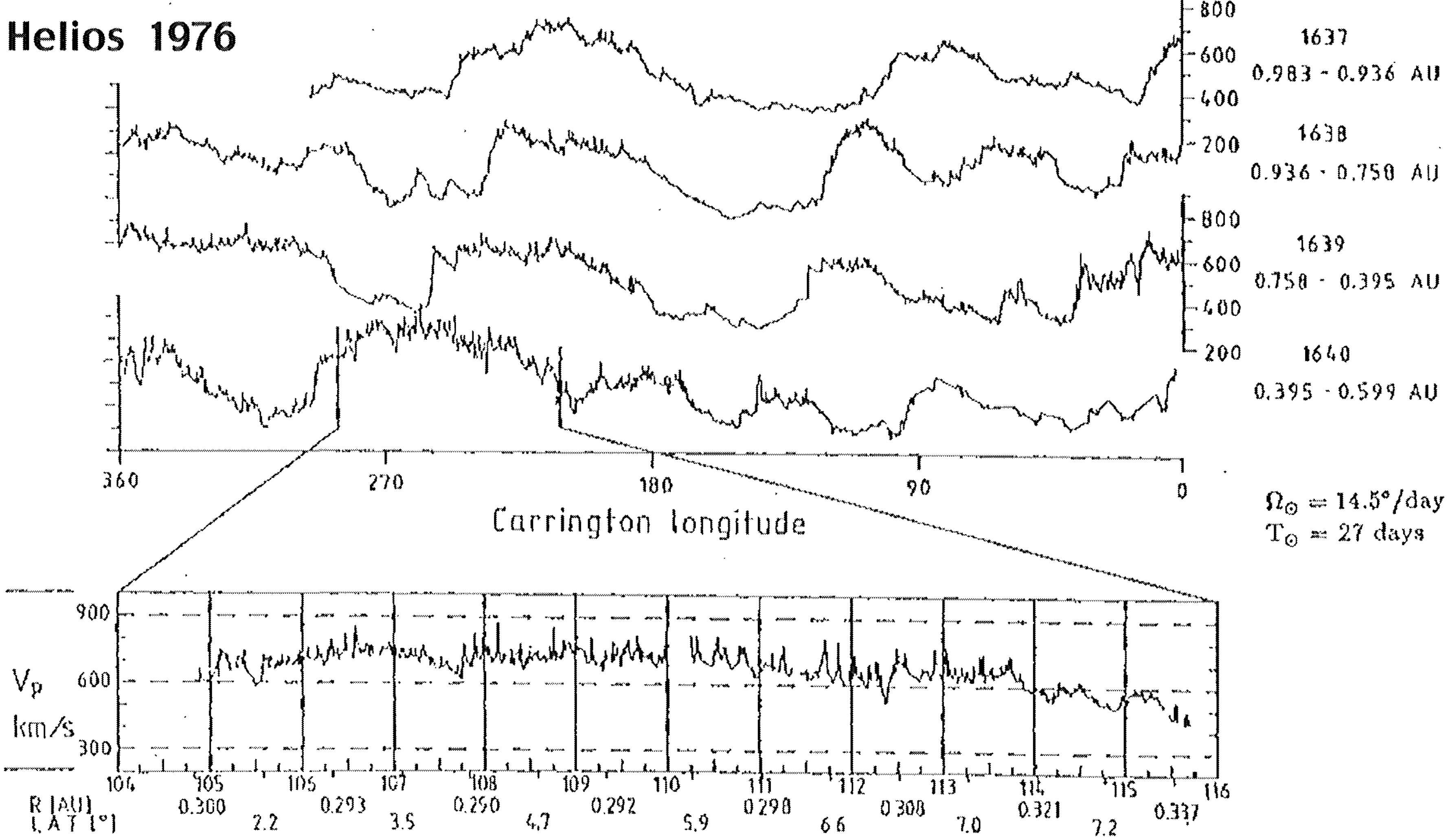
Fisk, JGR, 1996

Solar wind stream structure and heliospheric current sheet



Solar wind fast and slow streams

Helios 1976

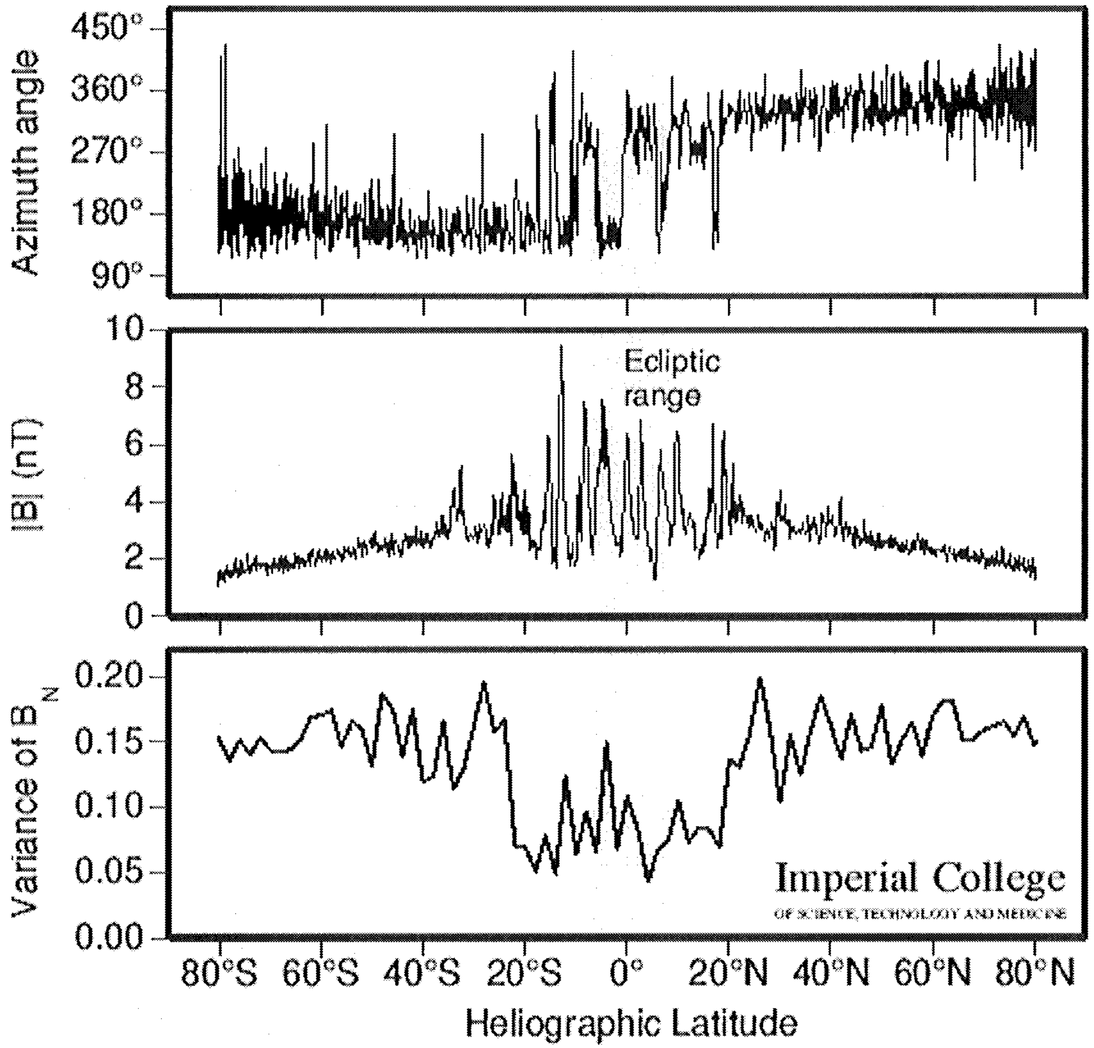


Alfvén waves and small-scale structures

Marsch, 1991

Latitudinal variation of the heliospheric magnetic field

Ulysses



Field polarity

Alfvén waves

Balogh and Forsyth, 1998

Fast solar wind parameters

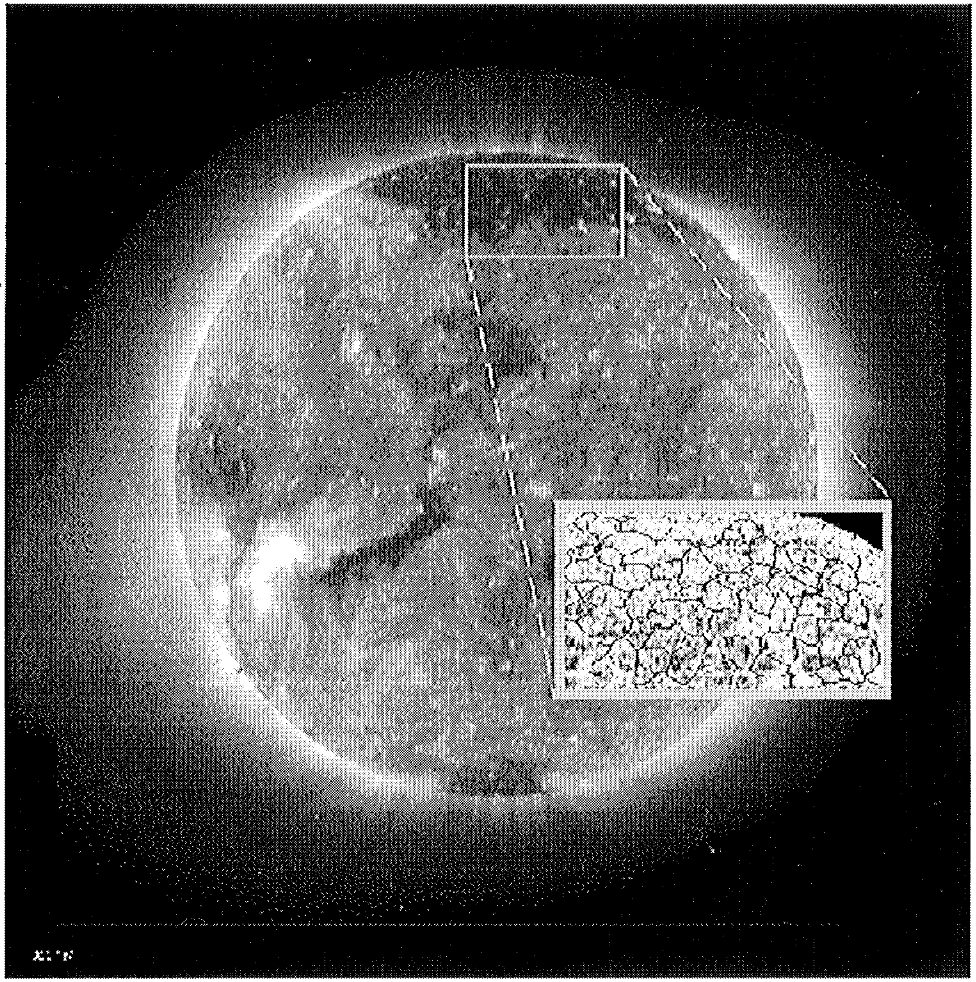
- Energy flux at 1 R_S: $F_E = 5\ 10^5$ erg cm^{-2} s^{-1}
- Speed beyond 10 R_S: $V_p = (700 - 800)$ km s^{-1}
- Proton flux at 1 AU: $n_p V_p = 2\ 10^8$ cm^{-2} s^{-1}
- Density at 1 AU: $n_p = 3$ cm^{-3}; $n_\alpha / n_p = 0.04$
- Temperatures at 1 AU:

  $T_p = 3\ 10^5$ K; $T_\alpha = 10^6$ 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



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

Insert:
SUMER
Ne VIII 770 Å
at 630 000 K

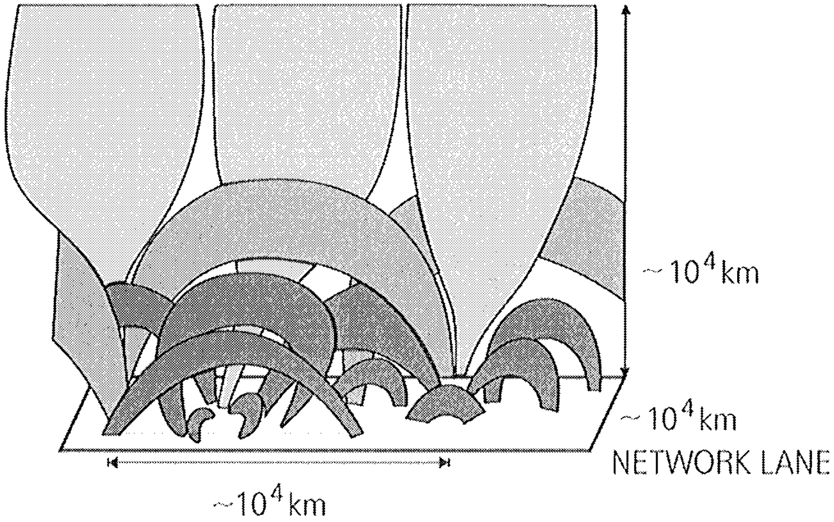
Chromosphe
ric
network
Doppler
shifts
Red: down
Blue: up

Outflow at
lanes and

Magnetic network loops and funnels

Structure of transition region

$F_B = AB$ F_M = A_V



COOLER NETWORK LOOPS ($T_{max} \leq 10^5$K)

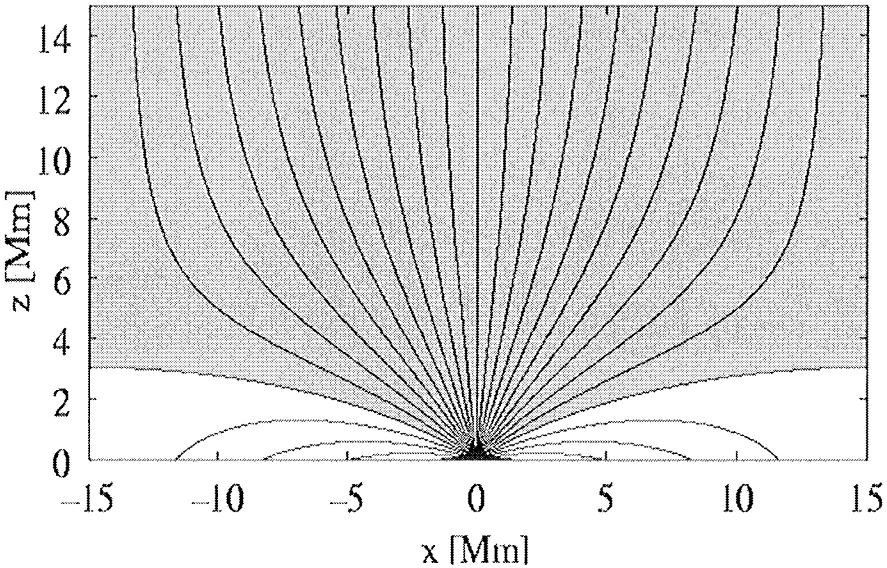
HOTTER NETWORK LOOPS (10^5K $\leq T_{max} \leq 10^6$K)

CORONAL FUNNELS

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

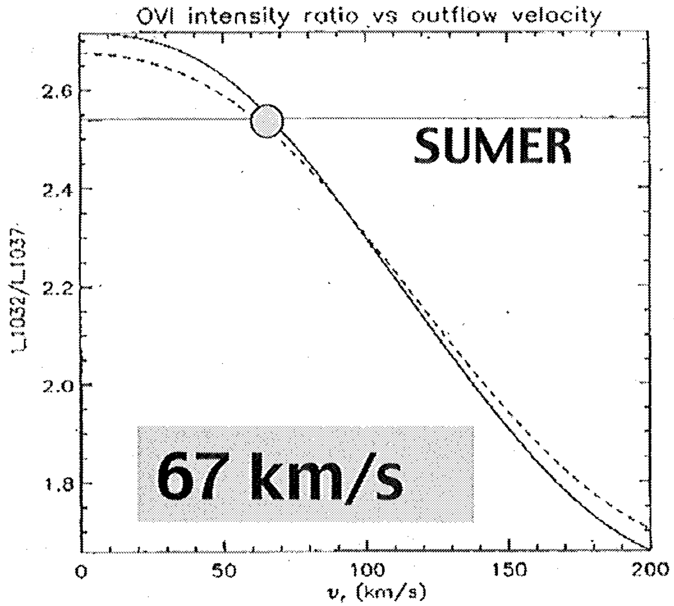
Magnetic field of coronal funnel

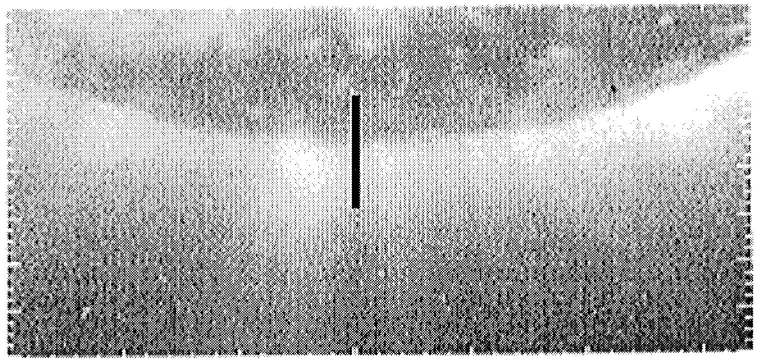
A(z) = flux tube cross section



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

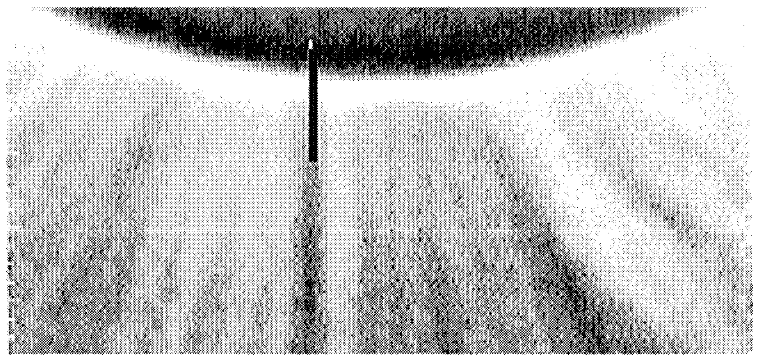
Outflow speed in interplume region at the coronal base





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

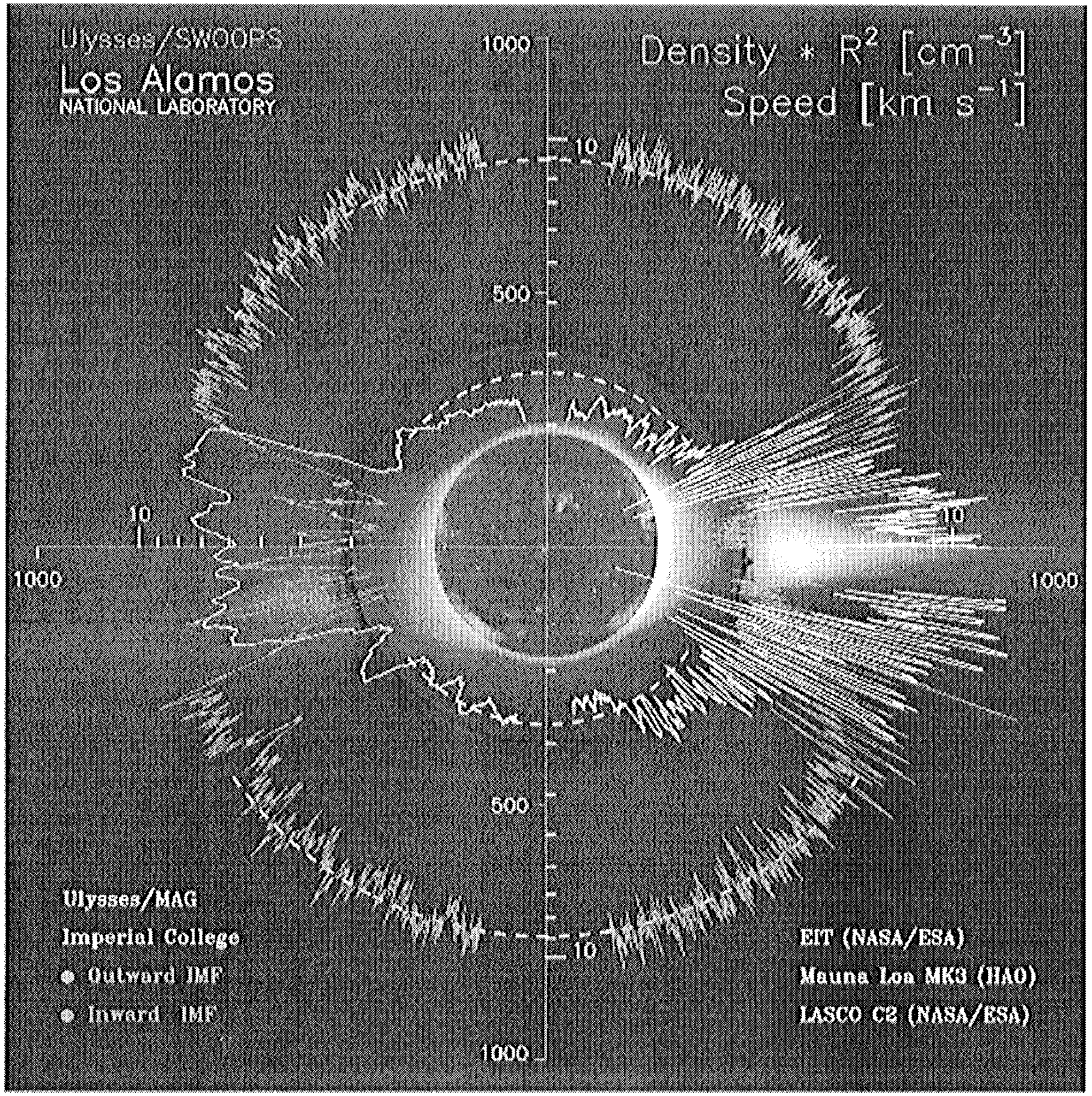
Solar wind speed and density

B outward

Ecliptic

B inward

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



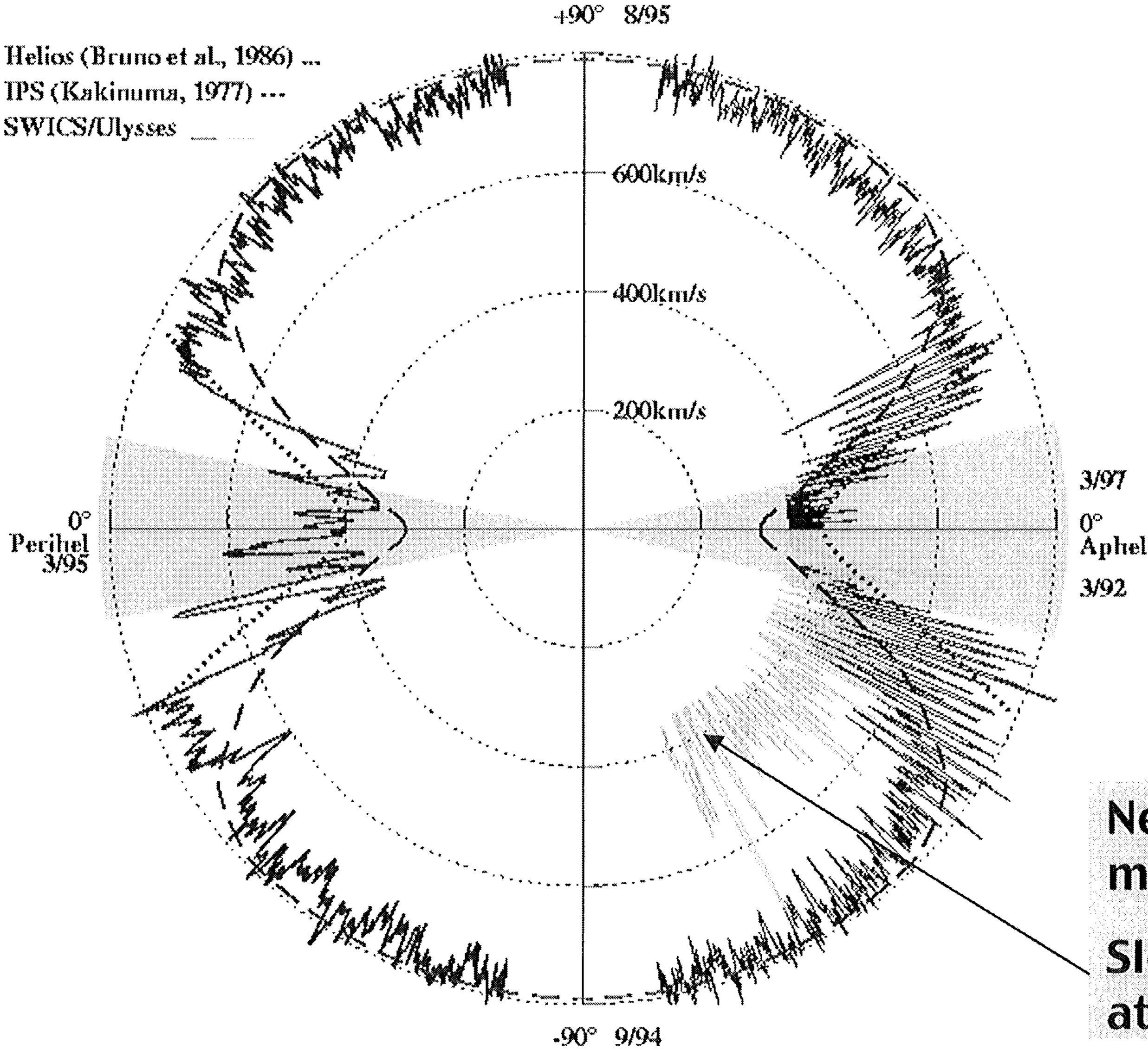
Polar diagram

V

Density

n R^2

Polar diagram of solar wind



SWICS

Ulysses

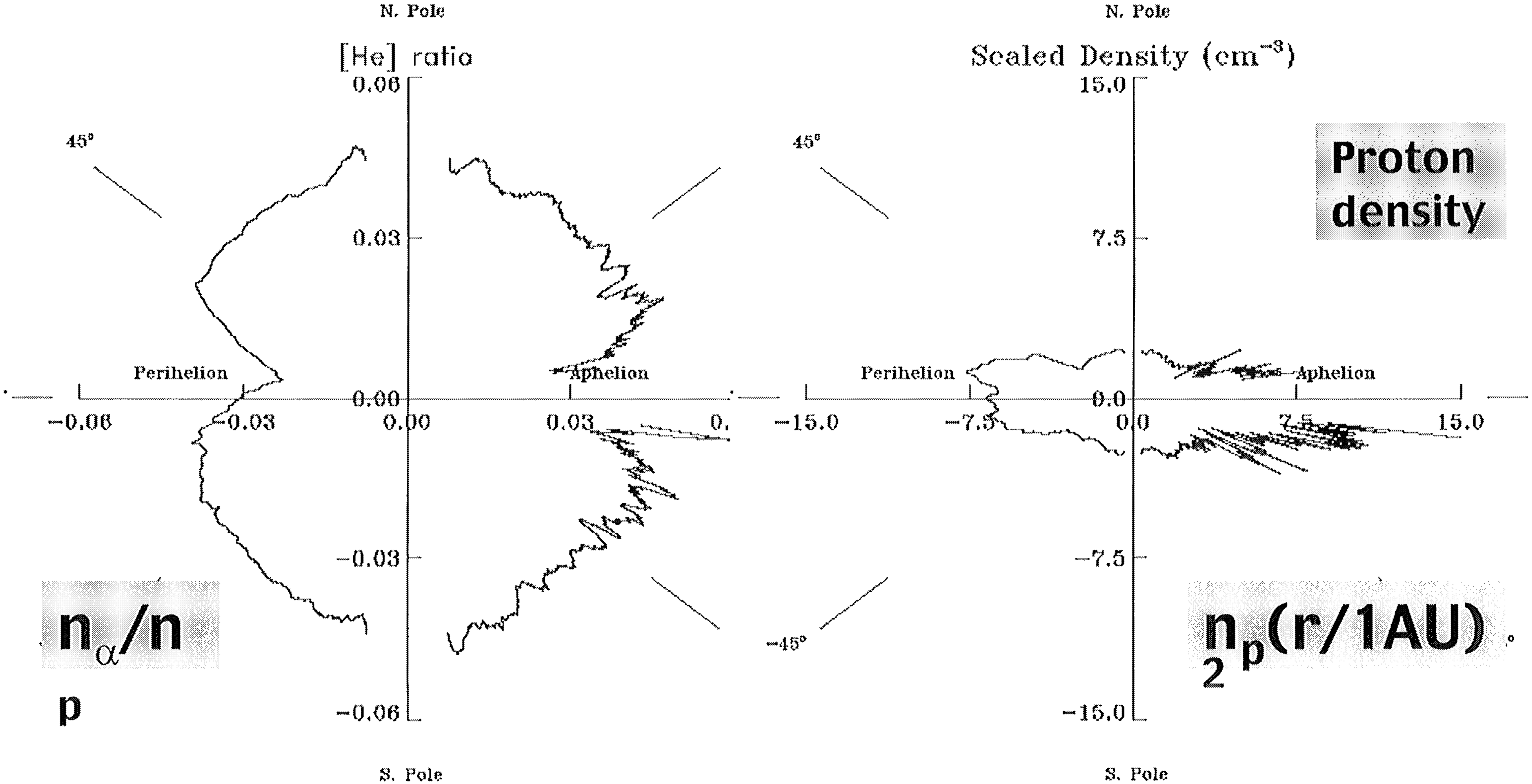
Ecliptic

Near solar maximum:

Slow wind at – 65° !

Woch, 2000

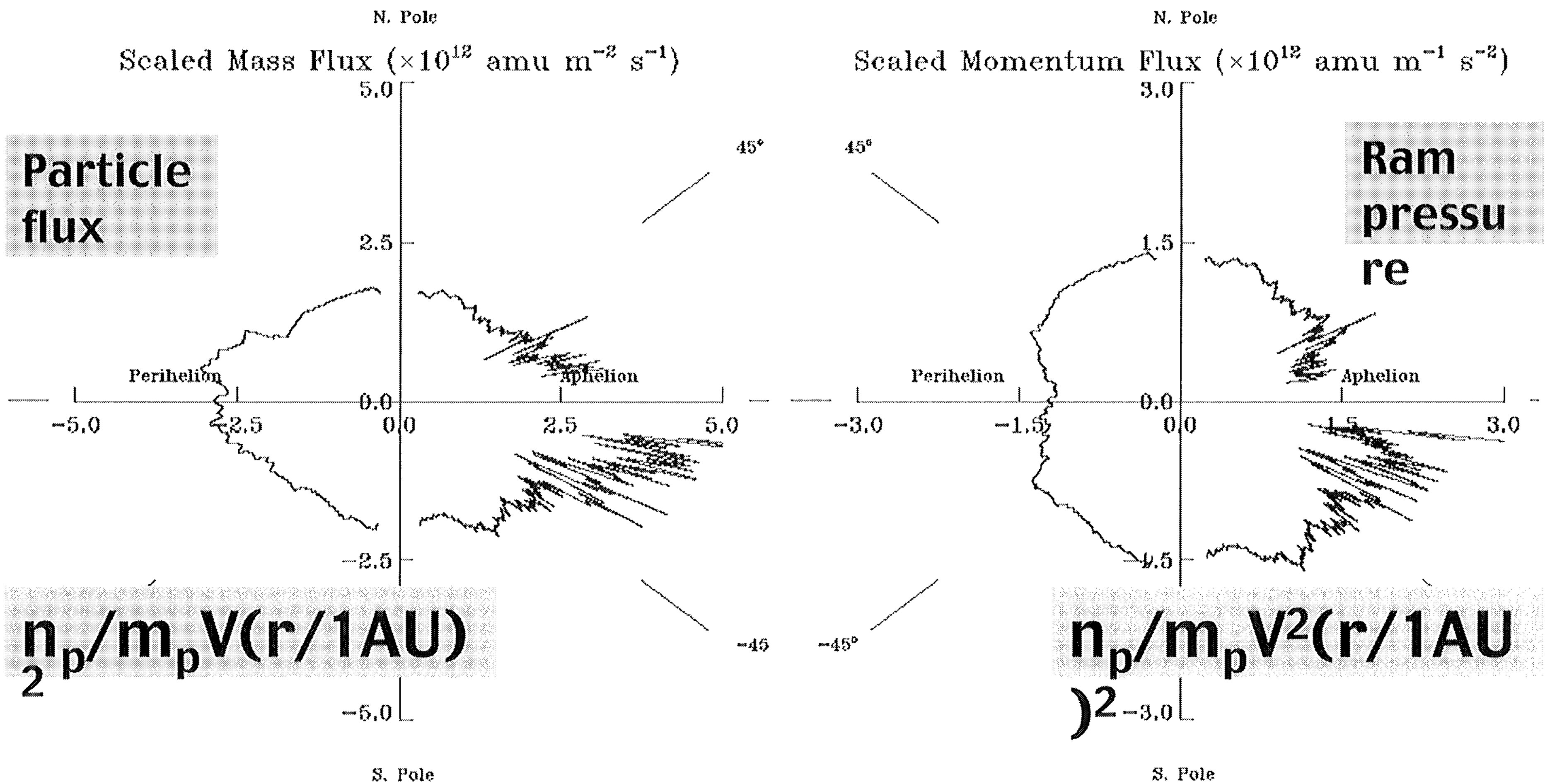
Polar plot of density and He/H ratio



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

Ulysses SWOOPS/SWICS

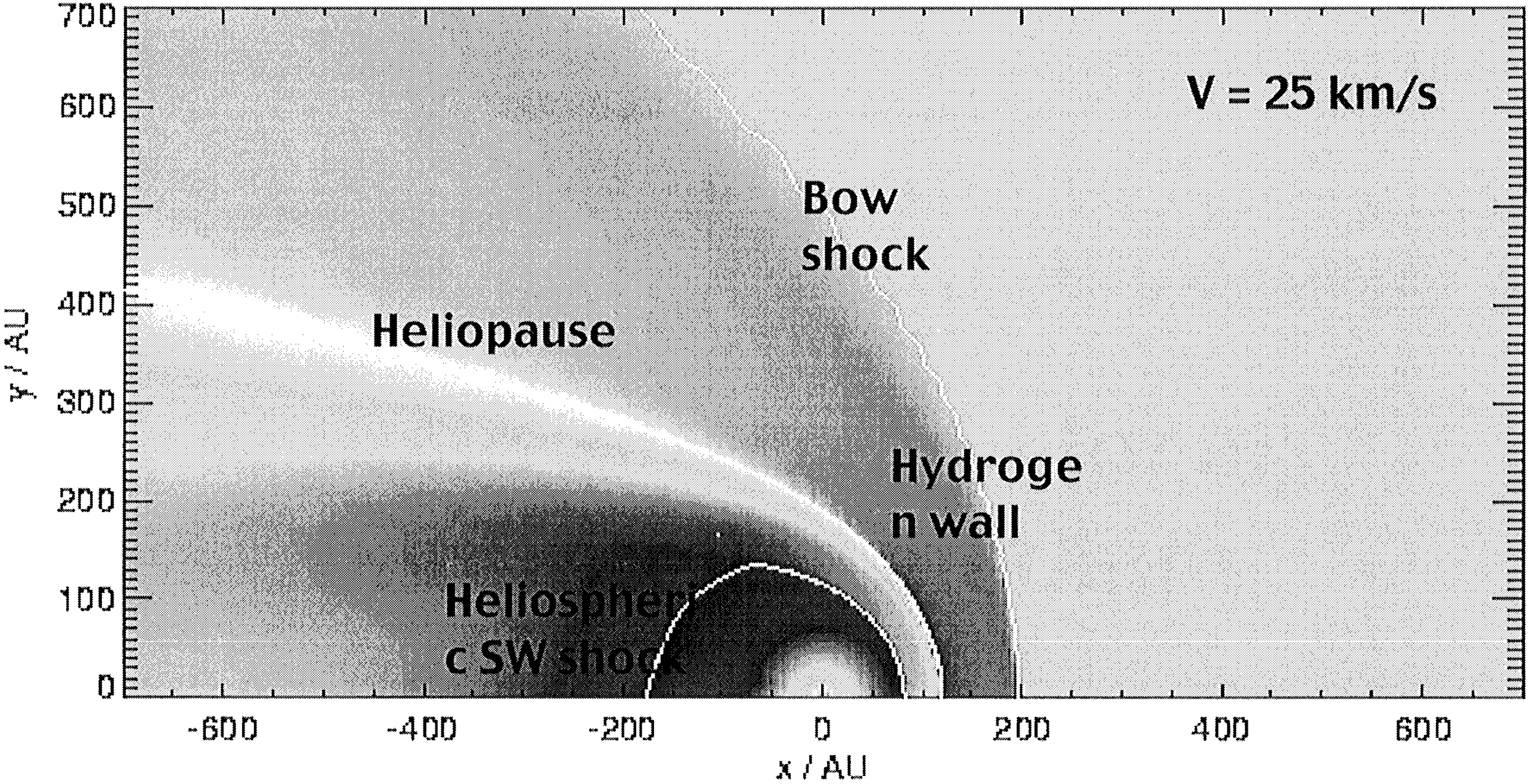
Polar plot of mass/momentum flux



McComas et al., 1998

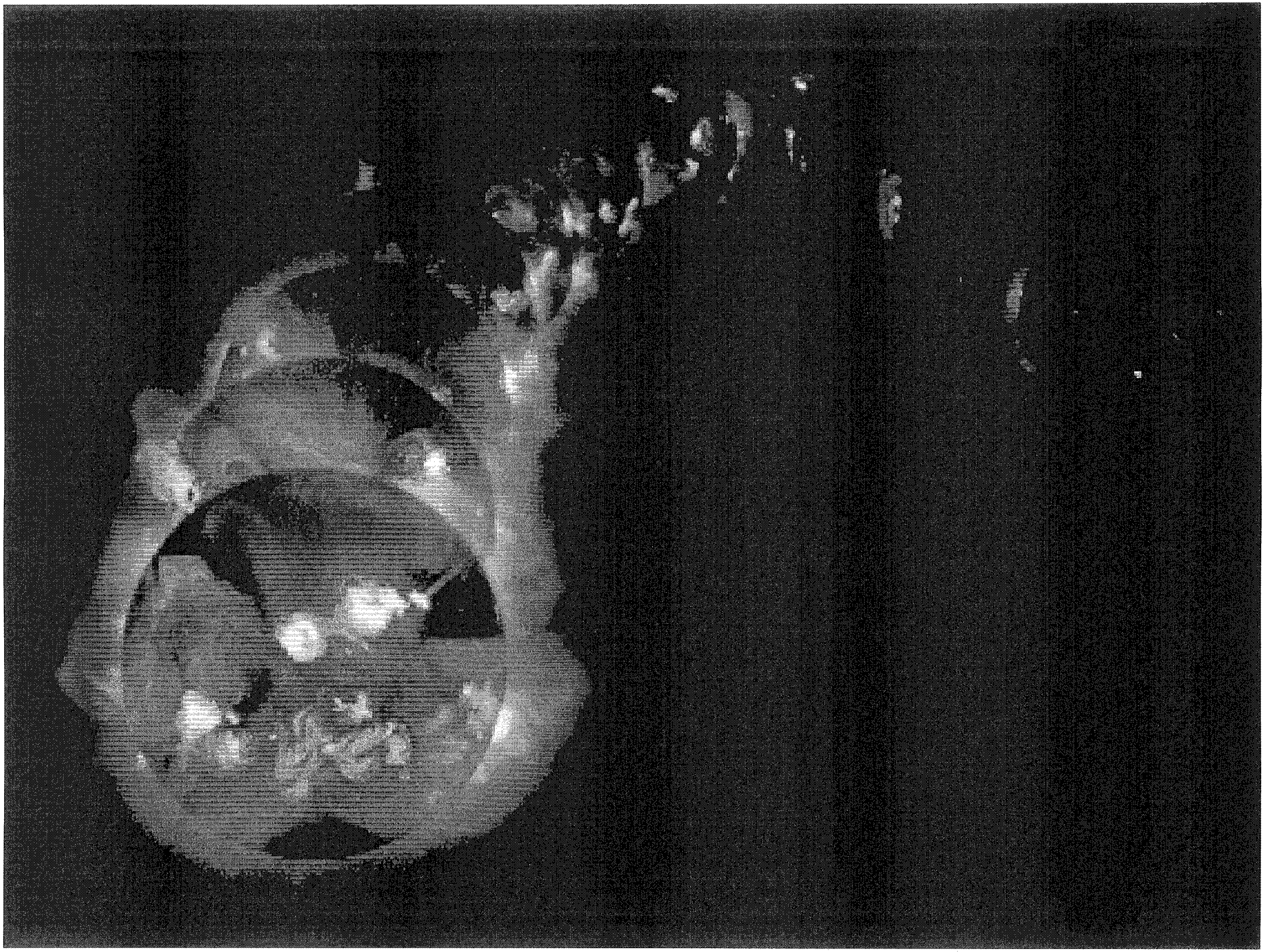
Ulysses SWOOPS/SWICS

Heliosphere and local interstellar medium

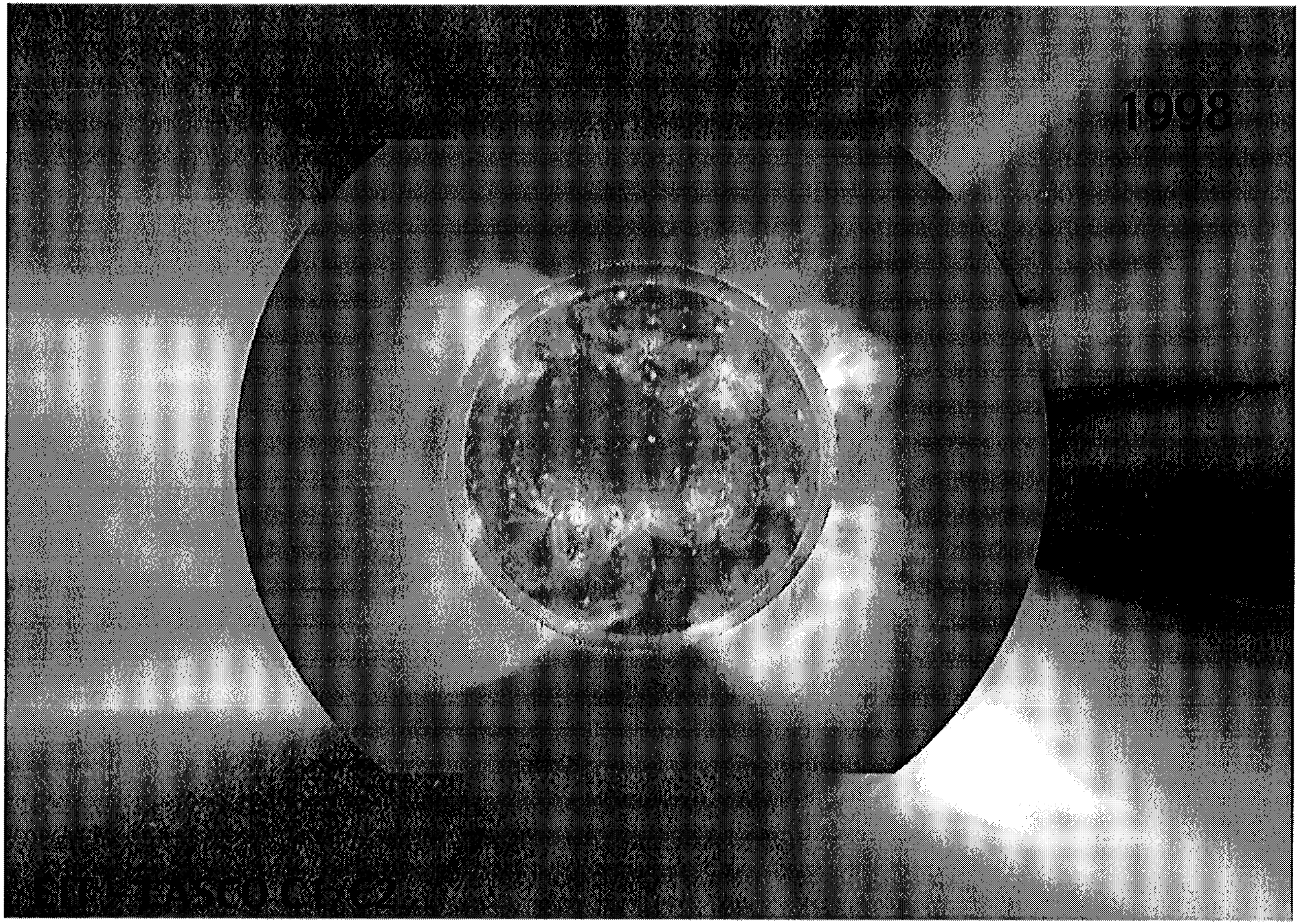


(red) $-0.3 > \log(n_e/cm^3) > -3.7$
(blue)

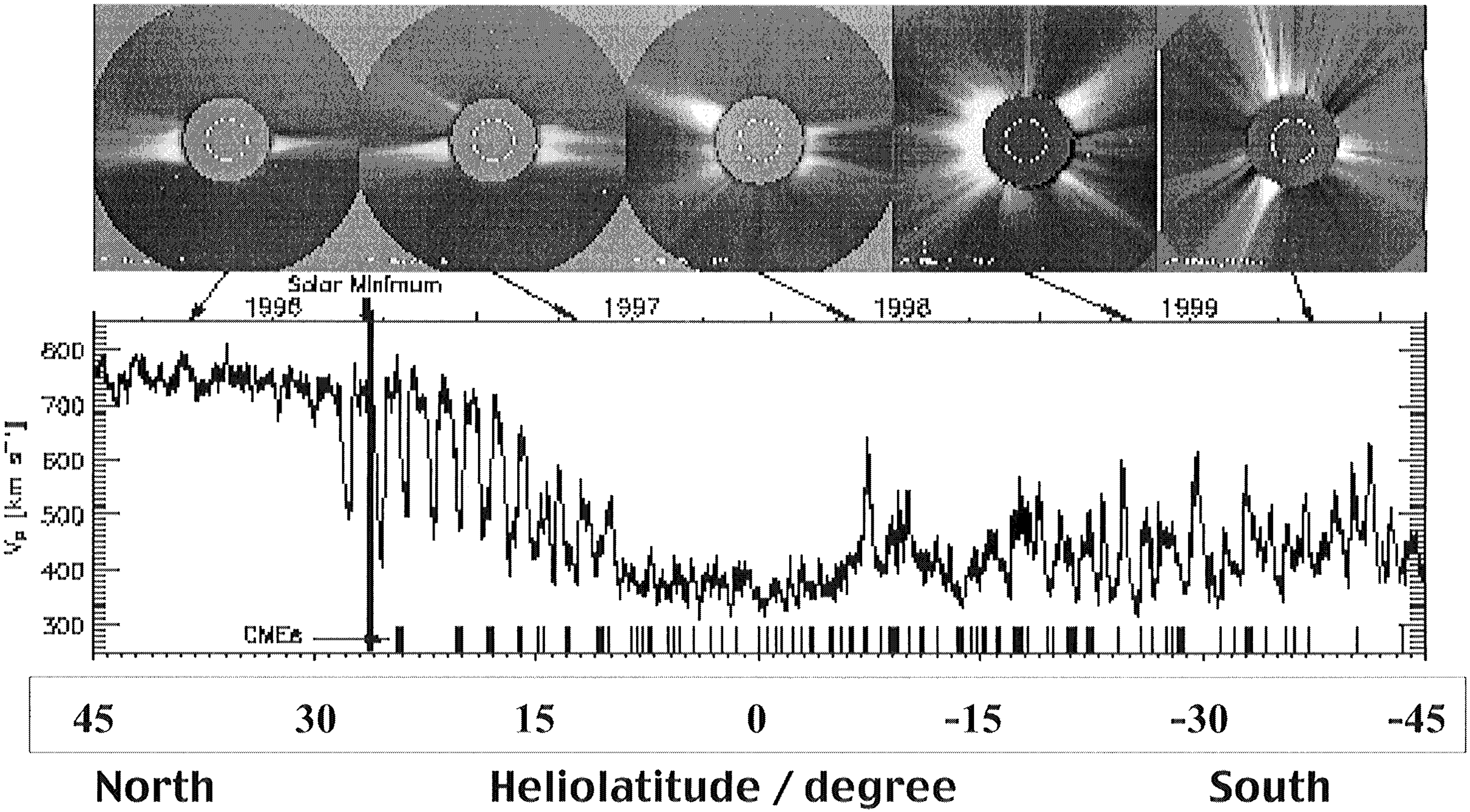
Kausch, 1998



Corona of the active sun



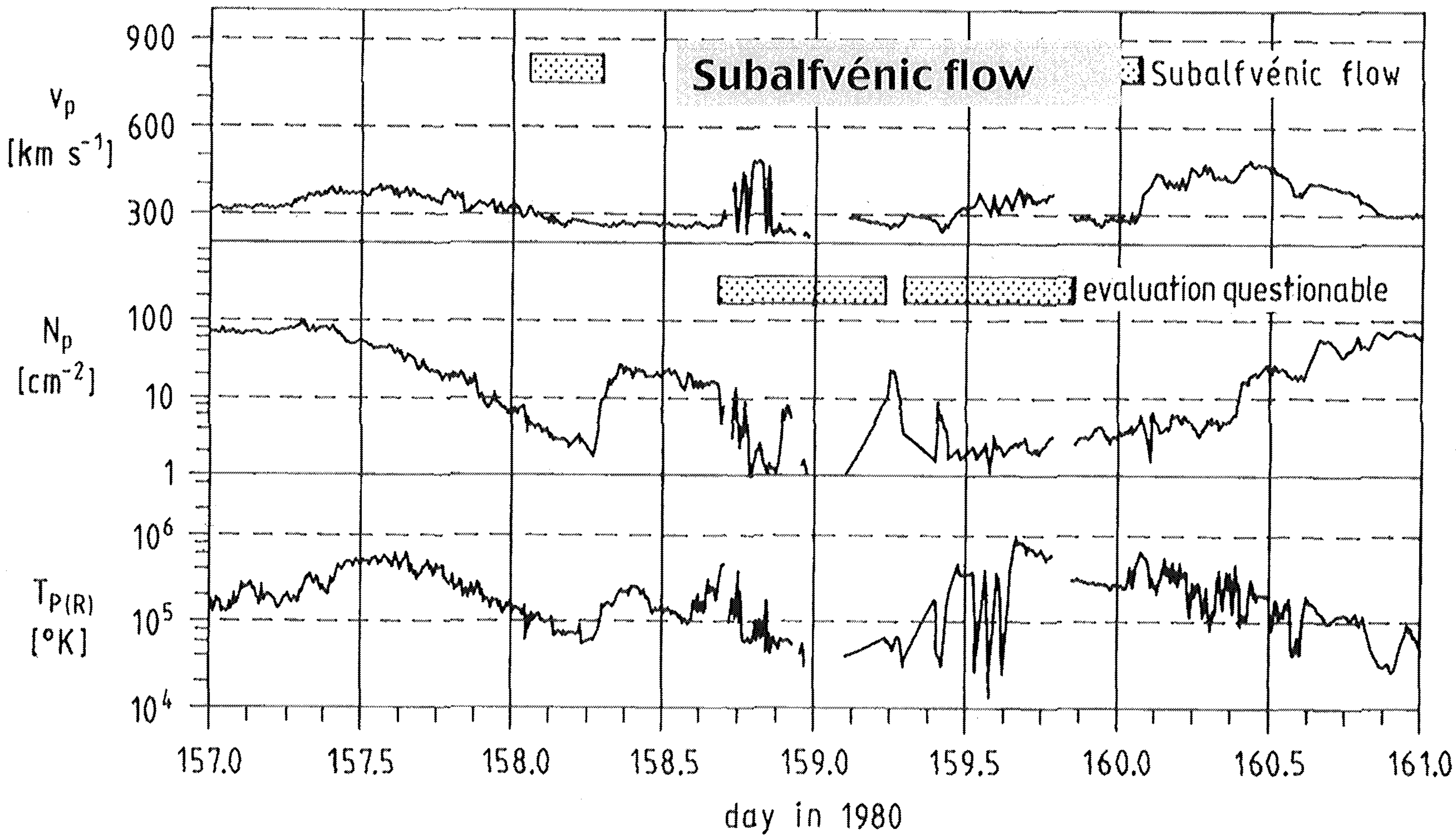
Changing corona and solar wind



McComas et al.,

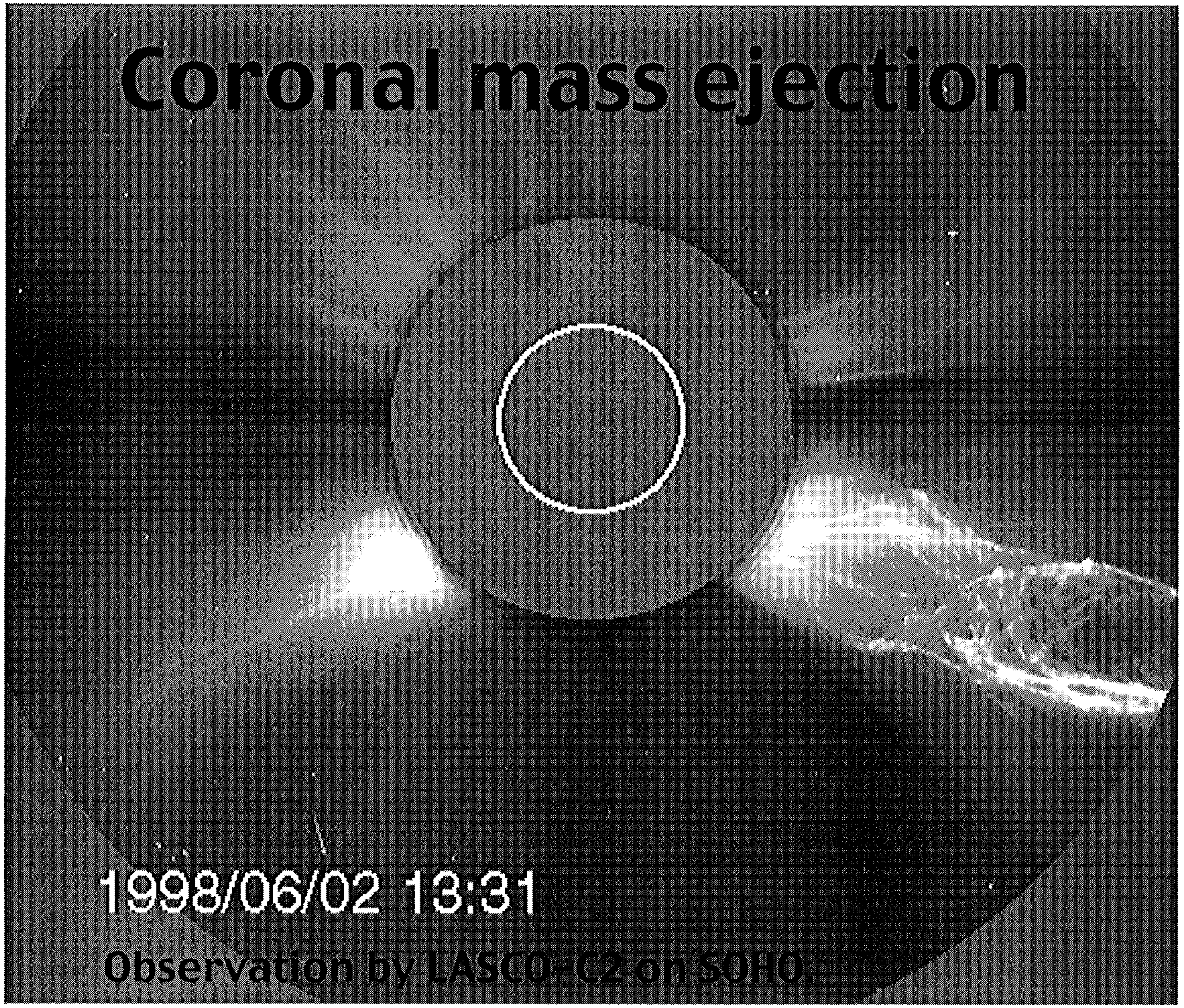
LASCO/Ulysses

Solar wind dropout



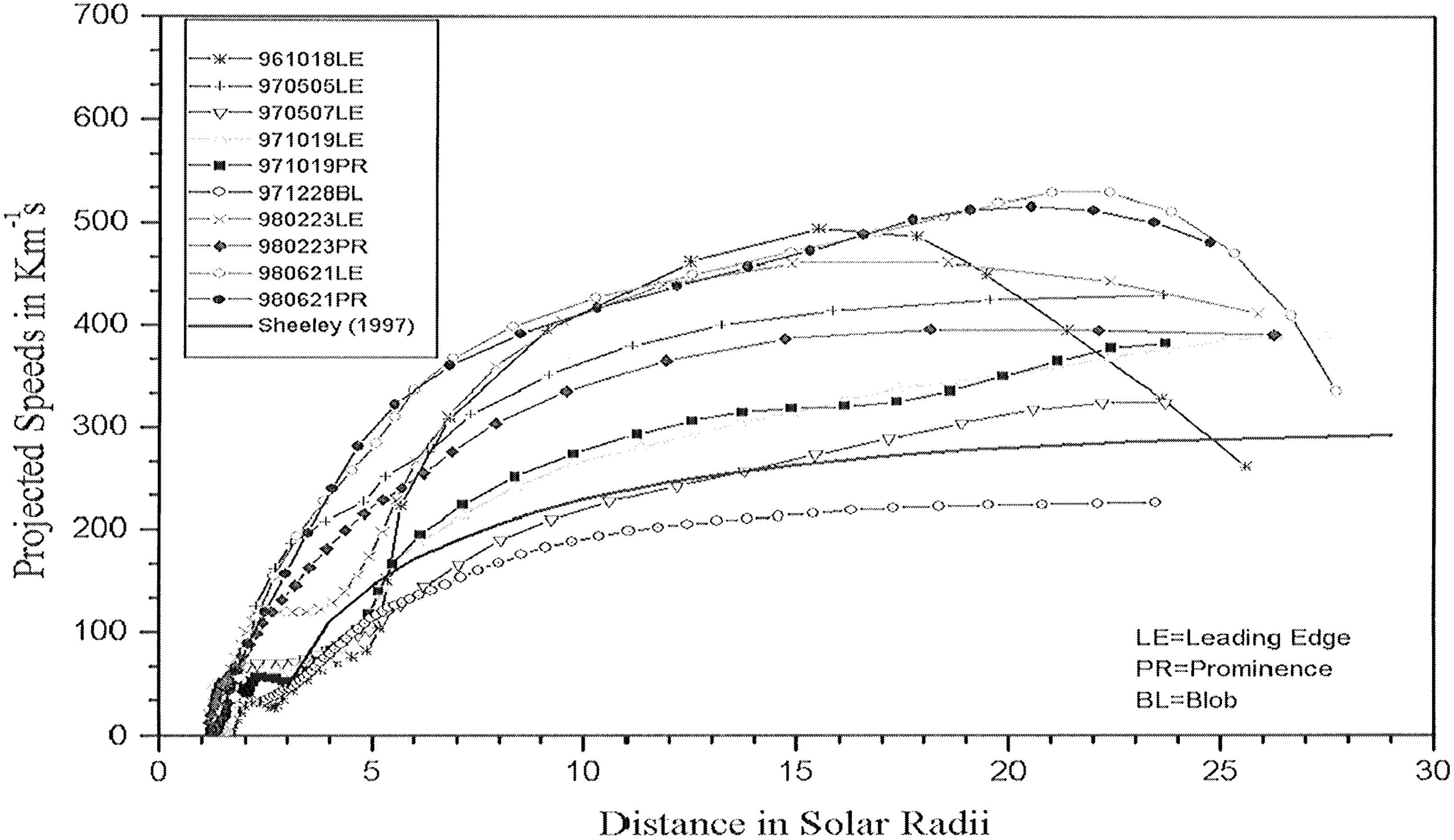
Schwenn, 1980

Helios 1 at 0.3 AU



Note the helical structure of the prominence filaments!

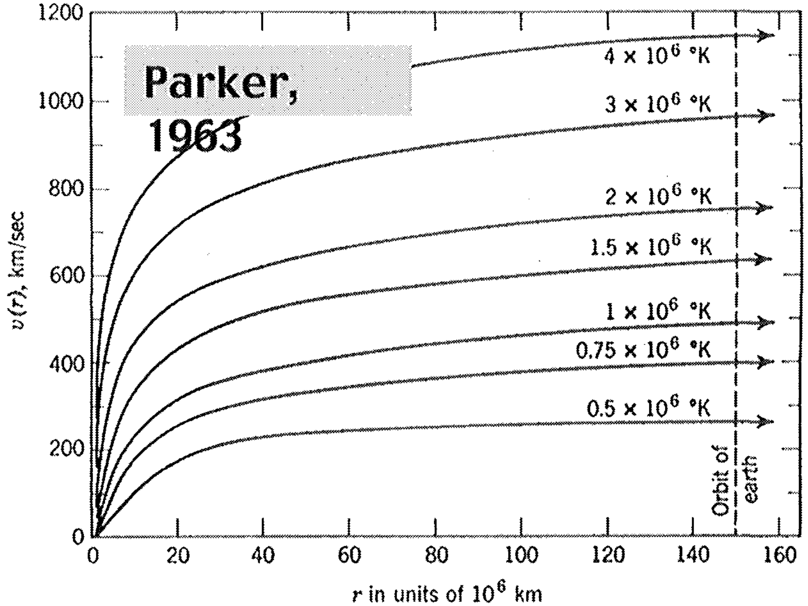
Speed profile of balloon-type CMEs



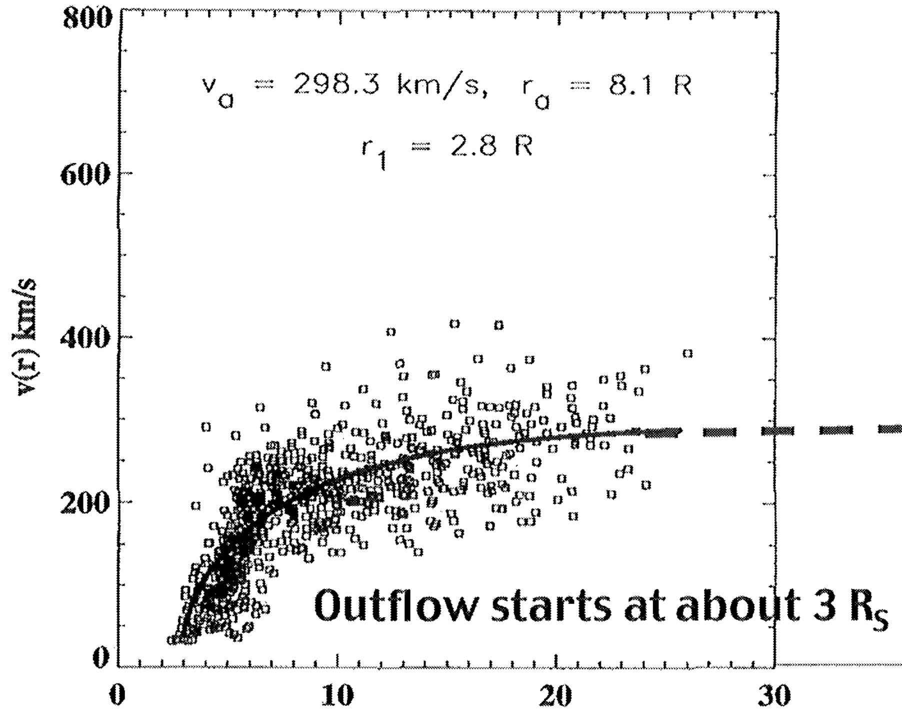
Srivastava et al., 1999

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



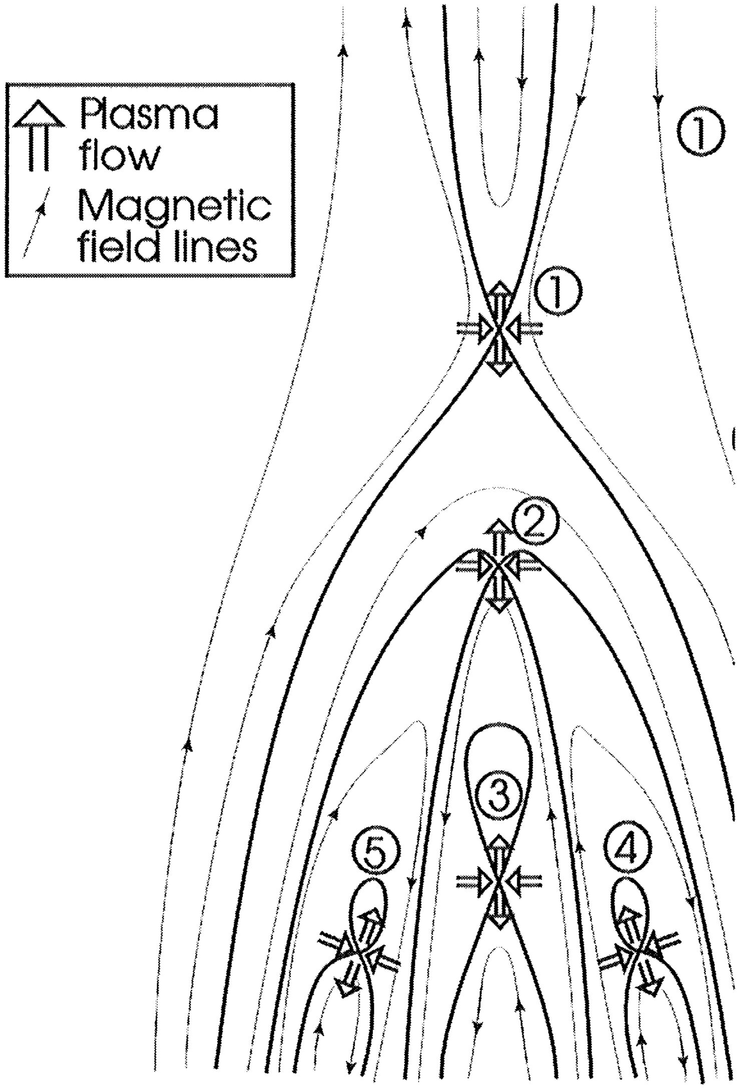
Sheeley et al., Ap.J., 484, 472, 1998

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...."

Wiegelmann et al., Solar Phys., 1999



- 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)

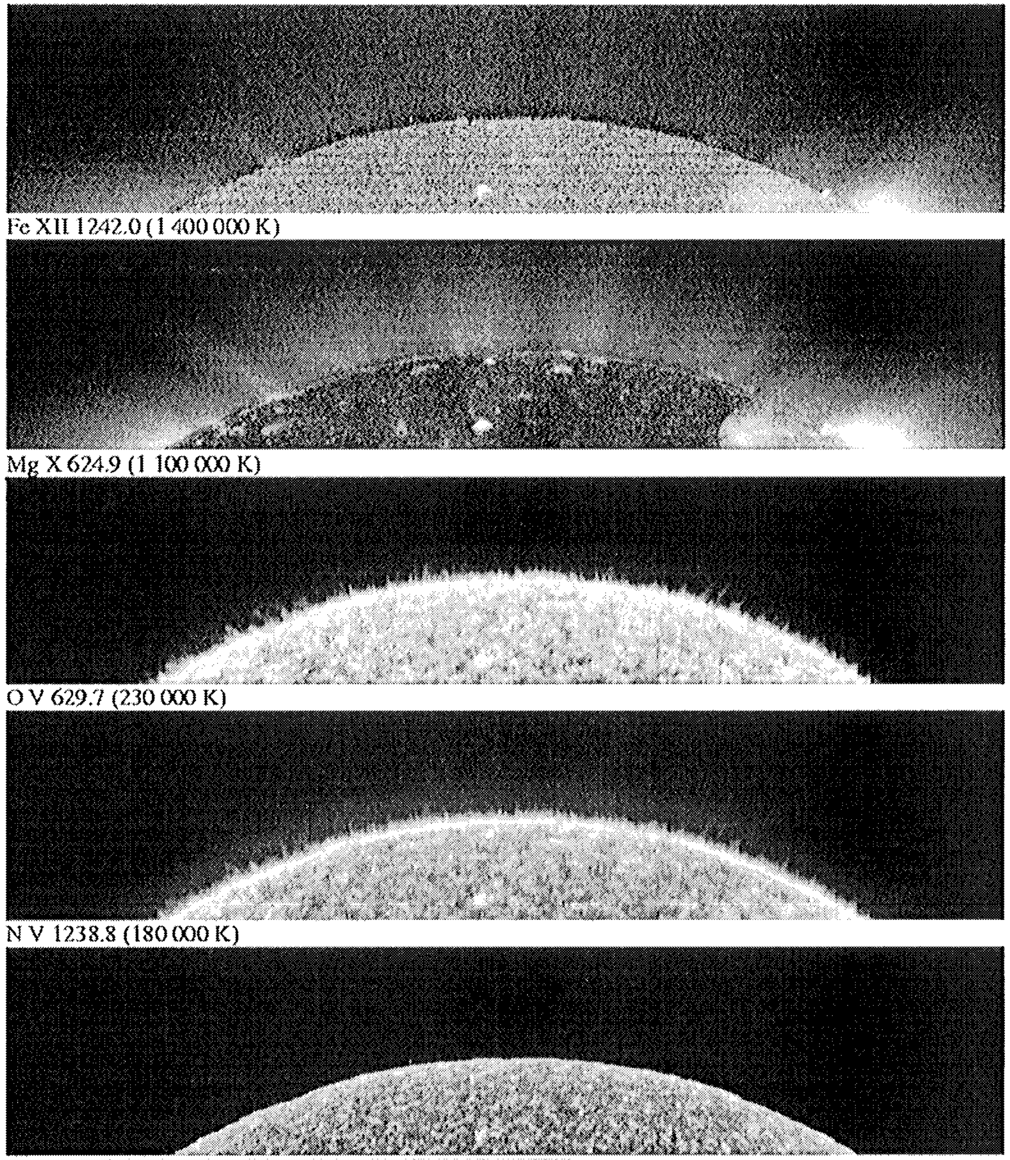
North coronal hole in various lines

1400000 K — FeXII 1242 Å

1100000 K — MgX 624.9 Å

230000 K — OV 629.7 Å

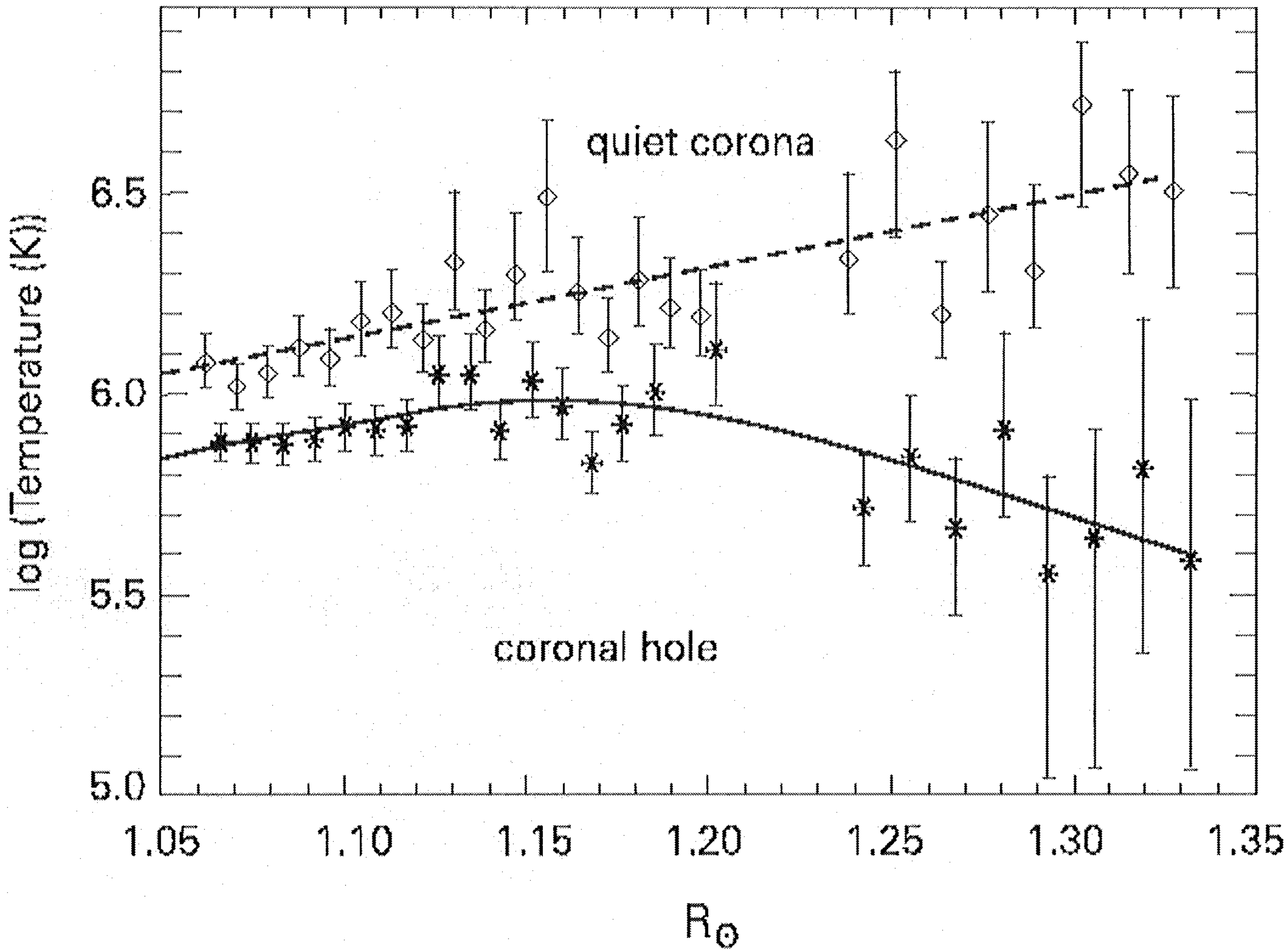
180000 K — NV 1238.8 Å



Forsyth & Marsch, Space Sci. Rev., 89, 7, 1999

SUMER/SOHO 10 August 1996

Electron temperature in the corona



Streamer belt, closed

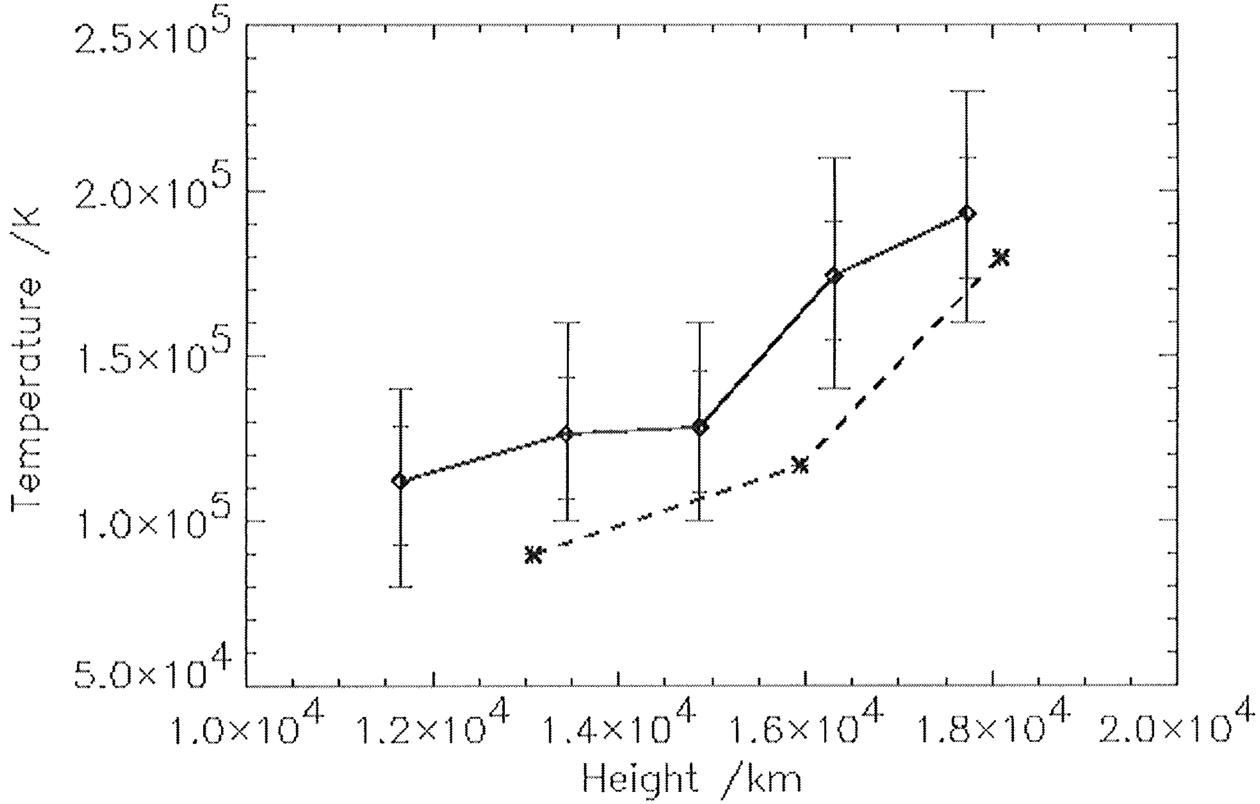
Coronal hole, open magnetically

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

Heliocentric distance

SUMER/CDS SOHO

Proton temperature at coronal base



SUMER/SOHO

Hydrogen Lyman series

Transition Region at the base of north polar CH

Marsch et al., A&A, in press, 2000

Charge-exchange equilibrium: $T_H = T_p$
Turbulence broadening: $\xi = 30\ \mathrm{km\ s^{-1}}$

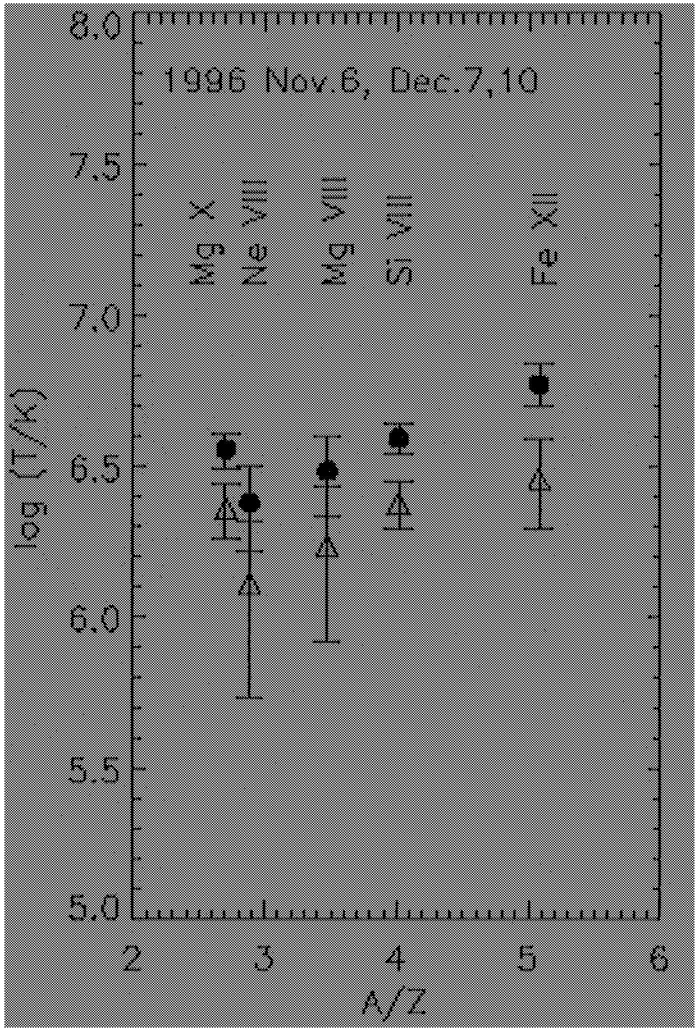
Heavy ion heating proportional to charge/mass by cyclotron resonance

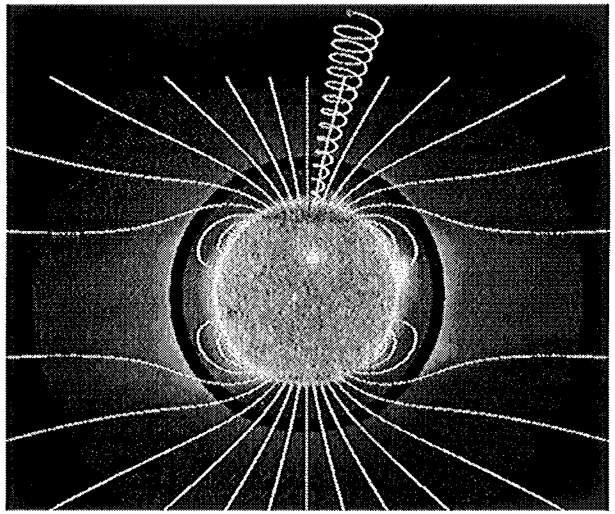
$\Omega \sim Z/A$

Heavy ion temperature

T=(2–6) MK

$r = 1.15\ R_S$



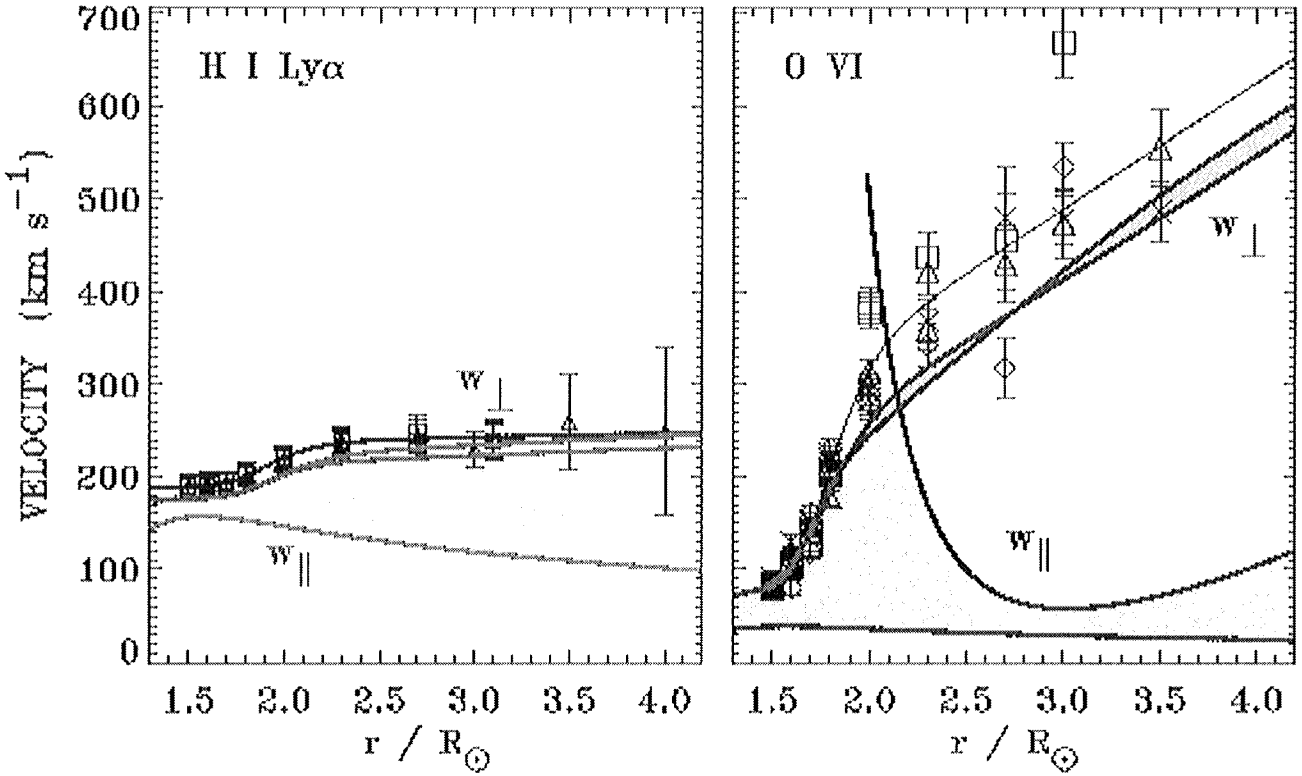


- Magnetic mirror in coronal funnel/hole
- Cyclotron resonance $\Rightarrow$ increase of μ

SUMER/SOHO

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

Oxygen and hydrogen thermal speeds in coronal holes

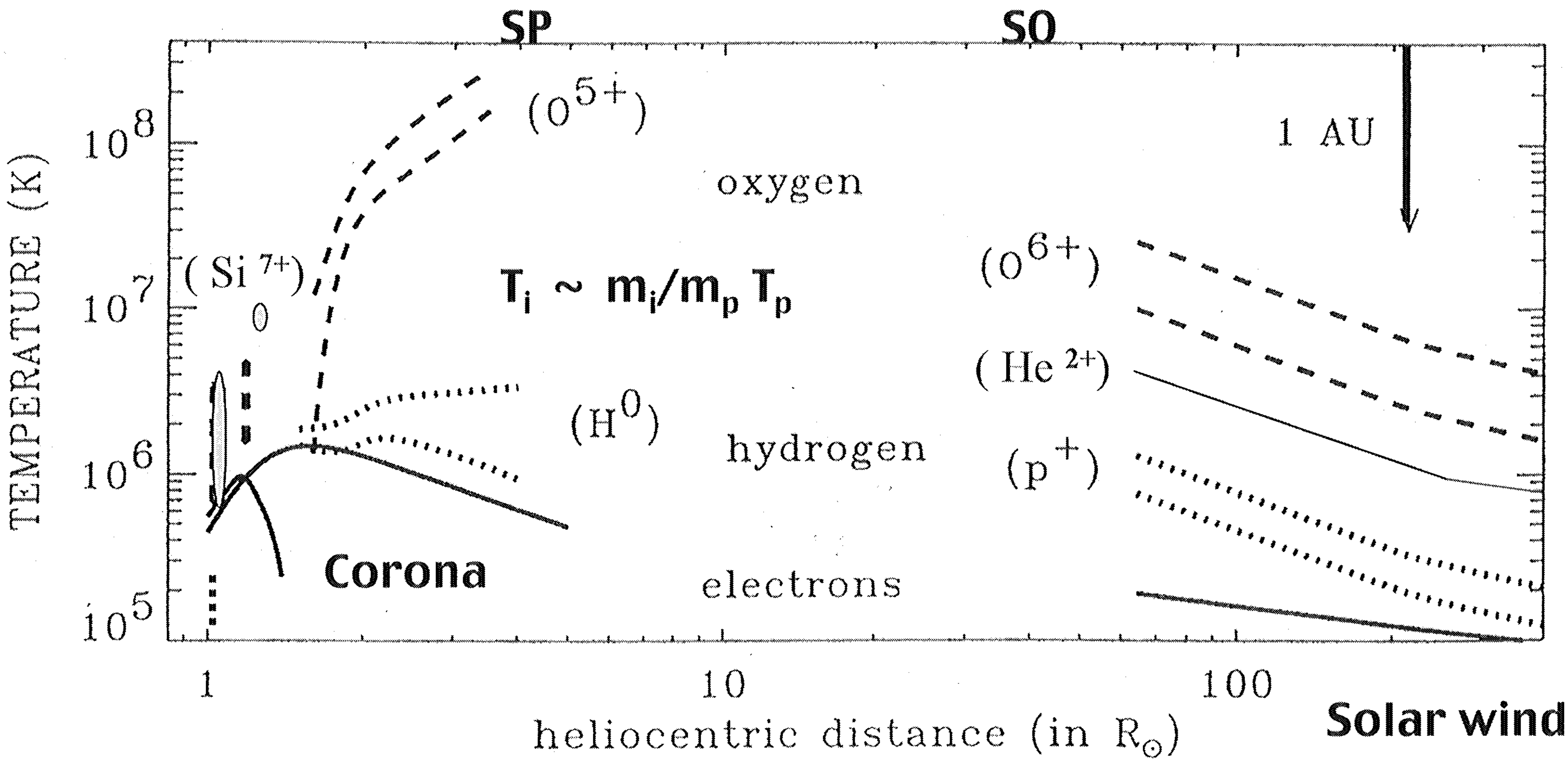


Very Strong perpendicular heating of Oxygen !

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

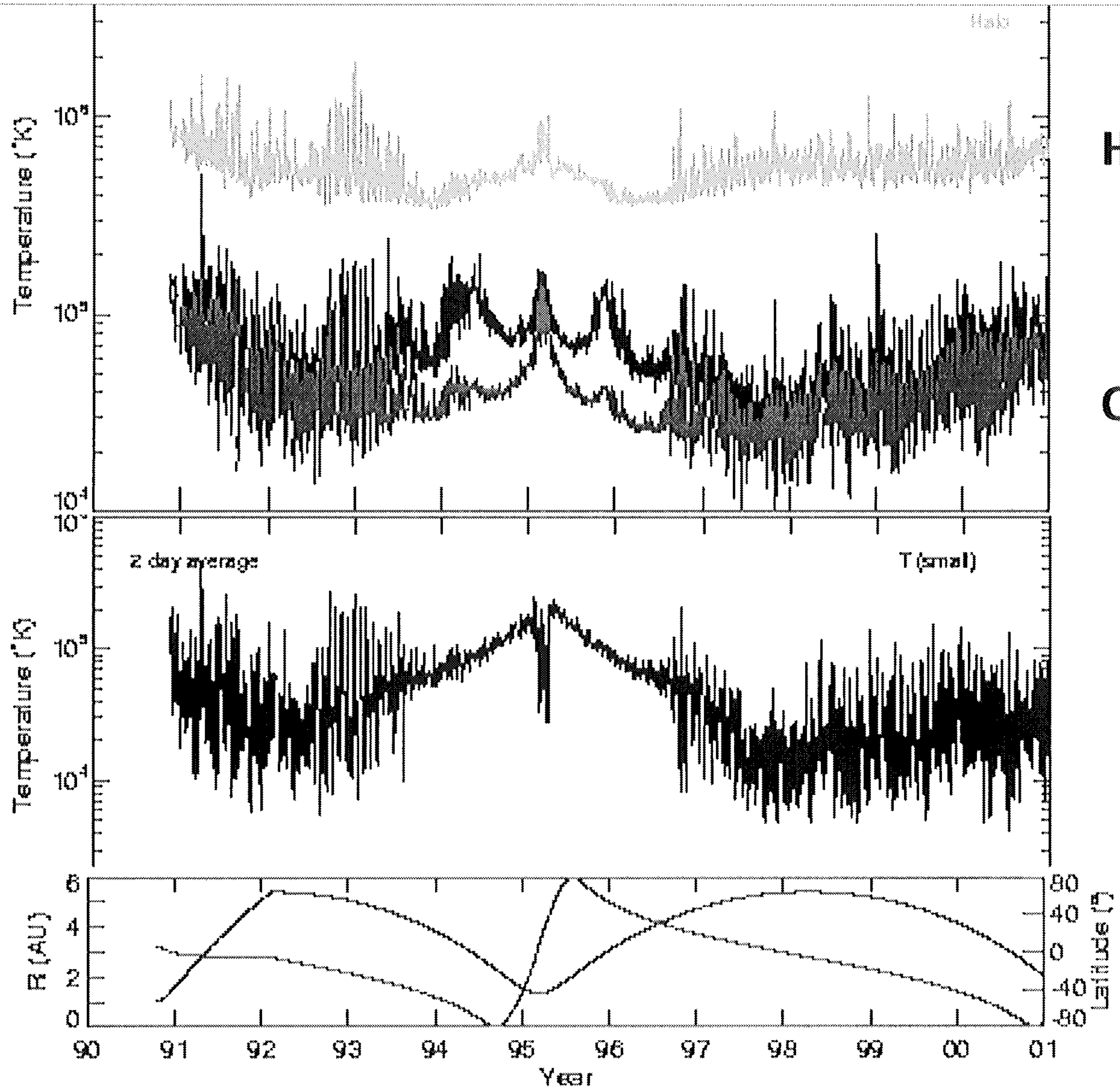
Large anisotropy: $T_{0\perp}/T_{0||} \geq 10$

Temperature profiles in the corona and fast solar wind



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

Heliospheric temperatures



Electrons

Protons

Ulysses

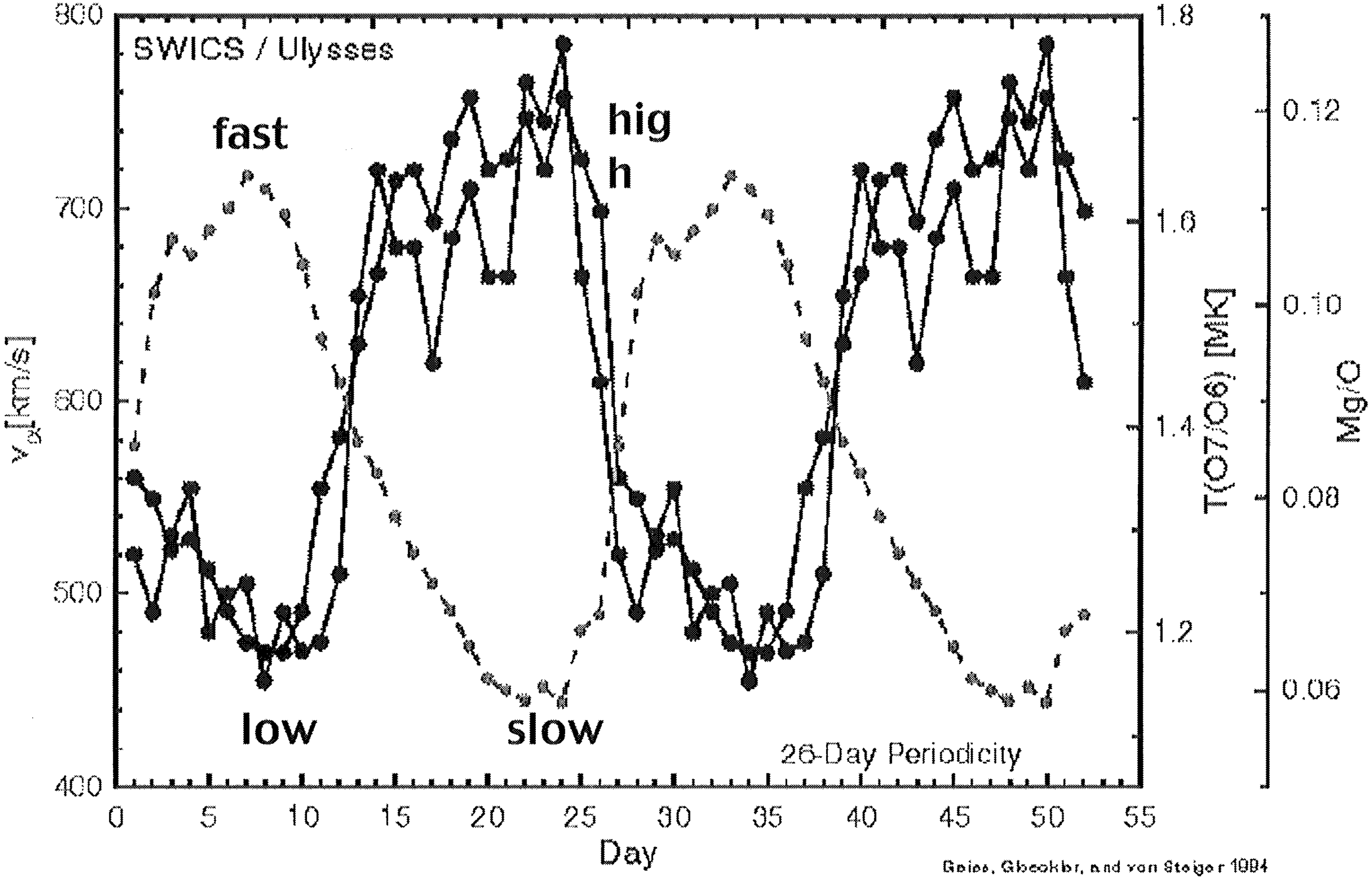
Halo (4%)

Core (96%)

$T_p \leq T_e$

McComas et al., 1998

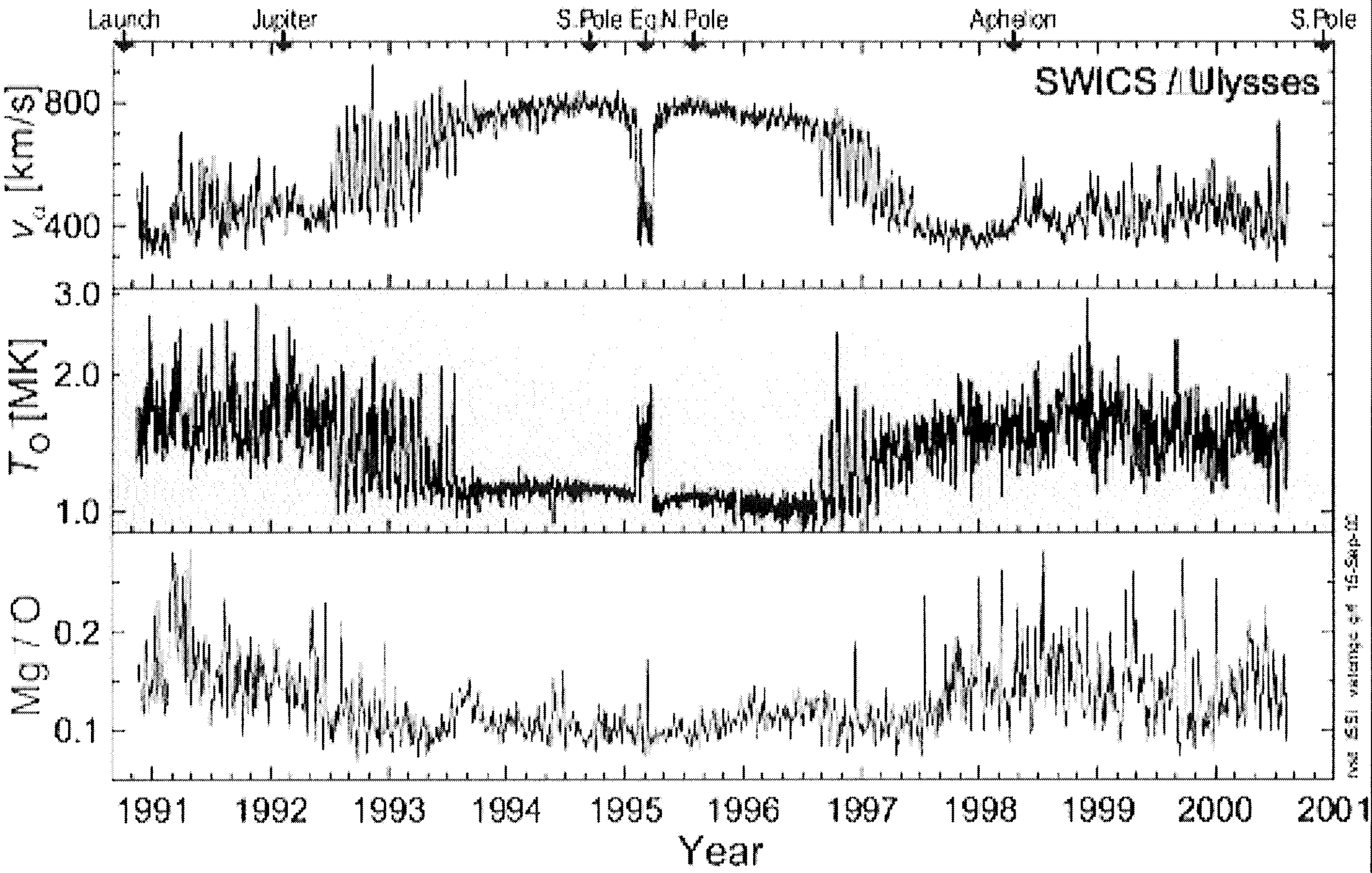
Oxygen freeze-in temperature



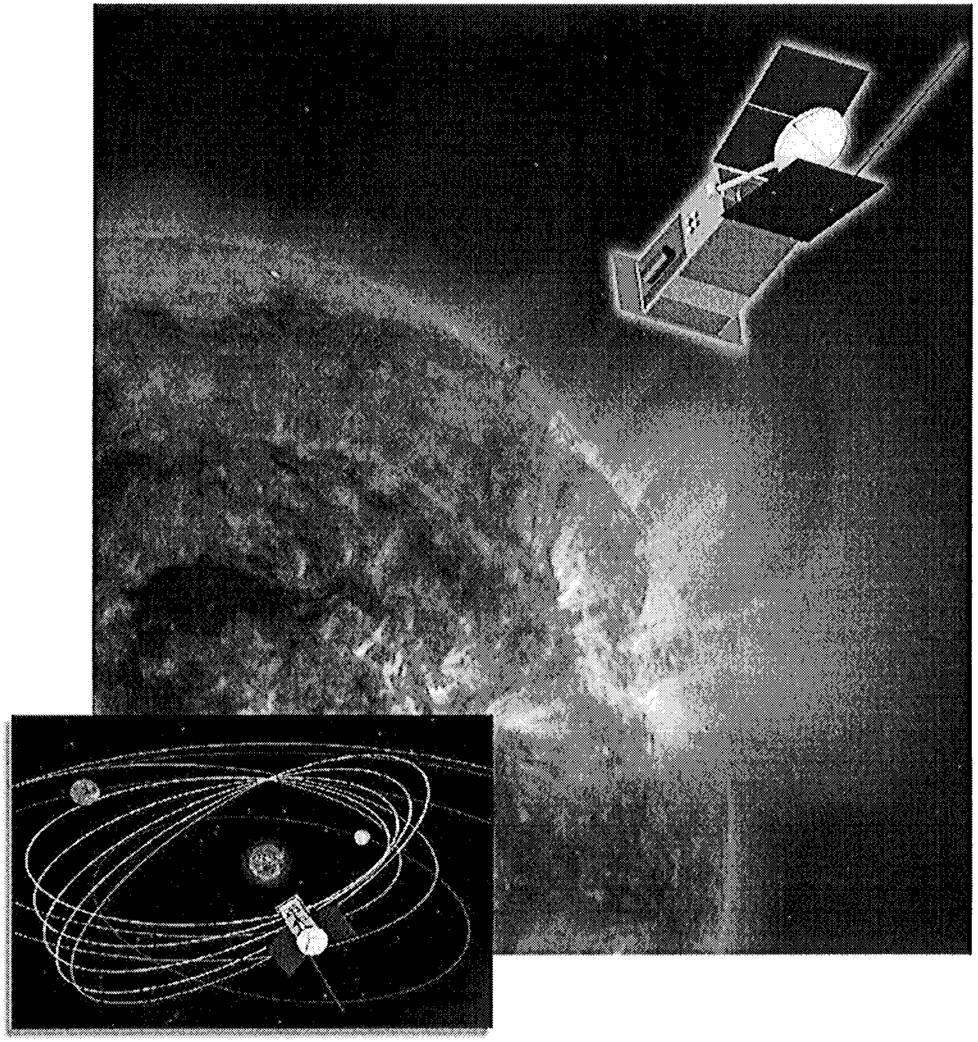
Ulysses SWICS

Geiss et al., , 1996

Correlations between wind speed and corona temperature



The future: Solar Orbiter



A high-
resolution
mission to
the Sun and
inner
heliosphere

ESA

2008 – 2013