Cours/Lecture Series

1990 – 1991 ACADEMIC TRAINING PROGRAMME

SPEAKER : G. WIBBERENZ / Kiel University
TITLE : Plasma physics in the solar system
TIME : May 13, 14, 15 from 11.00 to12.00 hrs
PLACE : Auditorium

Lecture 1 : 13 May The Sun and the interplanetary medium
Lecture 2 : 14 May Planetary magnetospheres
Lecture 3 : 15 May Energetic particles into the heliosphere

ABSTRACT

The lecture series will start with some fundamental principles of cosmic plasma physics. The main topics will deal with the sun, the interplanetary plasma, planetary magnetospheres, and energetic particles in the solar system. This includes the role of the sun in forming the heliosphere; manifestations of solar activity and the solar cycle, from large scale structures of the interplanetary medium to climatic changes; formation of planetary magnetospheres by interactions between the solar wind and planetary magnetic fields; the diversities of charged particle acceleration, in particular the role of collisionless shocks in the solar system. Some specific space projects exploring the heliosphere will be presented.

LECTURE: **Space Plasma Physics in the Solar System**

LECTURER: G. WIBBERENZ (Institut für Reine und Angewandte Kernphysik,
Universität Kiel, Otto-Hahn-Platz 1,
D-2300 Kiel)

DATE: May 13–May 15, 1991.

Abstract

The lecture series starts with some fundamental principles of cosmic plasma physics. The main topics deal with the Sun, the interplanetary plasma, planetary magnetospheres, and energetic particles in the solar system. This includes the role of the Sun in forming the heliosphere; manifestations of solar activity and the solar cycle, from large scale structures of the interplanetary medium to climatic changes; formation of planetary magnetospheres by interactions between the solar wind and planetary magnetic fields; the diversities of charged particle acceleration, in particular the role of collisionless shocks in the solar system. Some specific space projects exploring the heliosphere will be presented, in particular contributions of the University of Kiel to the International Sun Earth Explorer (ISEE) and the space probes HELIOS and ULYSSES.

SPACE PHYSICS IN THE SOLAR SYSTEM

O V E R V I E W

1. Cosmic Electrodynamics
   - some fundamental principles
2. The Sun
   - an active star
3. The heliosphere
   - domain of the solar wind
4. Magnetospheres
   - interaction between magnetic dipoles and streaming plasma
5. Energetic particles in the solar system
   - interactions with electric and magnetic fields

COSMIC ELECTRODYNAMICS

Some particular aspects:

- No permanent magnetic fields and no stationary electrostatic fields, fields are generated by moving fluids of high conductivity.
- Huge volumina take part in the interactions which is one reason for the high effective conductivity.
- In general, there are no fixed boundaries (corresponding to walls in laboratory plasmas). Boundaries are formed by the interactions processes itself, and their location may vary on different time scales.

IDEAL MHD:

- High conductivity
- no space charges

REAL MHD:

- effects of finite resistivity
- "diffusion" of magnetic field lines
- reconnection

Electromagnetic Forces

$$\vec{K} = e\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

on point charge e with velocity $\vec{v}$

$$\vec{f} = \rho_e \vec{E} + \vec{j} \times \vec{B}$$

on charge density ρ_e, current $\vec{j}$.

Euler's equation (no viscosity) for continuum (fluid)

$$\rho \frac{d\vec{u}}{dt} = -\text{grad}\, p + \vec{j} \times \vec{B} + \vec{g}$$

Without proof:

$$f_i = (\vec{j} \times \vec{B})_i = \sum_{i=1}^{3} \frac{1}{\mu_0} \frac{\partial}{\partial x_i} (B_i B_j - \frac{1}{2} \delta_{ik} B^2)$$

Maxwell's stress tensor for $\vec{B} = (0, 0, B)$:

$$\vec{f} = \nabla \vec{\vec{T}} \qquad \text{with} \qquad \vec{\vec{T}} = \frac{1}{2\mu_0} \begin{pmatrix} -B^2 & 0 & 0 \\ 0 & -B^2 & 0 \\ 0 & 0 & +B^2 \end{pmatrix}$$

Maxwell's equations ($\mu = 1$, $\epsilon = 1$: no permeability, no dielectric properties, no space charges)

$$\begin{aligned} \mathrm{rot}\vec{E} &= -\partial\vec{B}/\partial t \\ \mathrm{rot}\vec{B} &= \mu_0\vec{j} \\ \mathrm{div}\vec{E} &= 0 \\ \mathrm{div}\vec{B} &= 0 \end{aligned} \quad \longleftarrow \left\{ \begin{aligned} \vec{B} &= \mu_0\vec{H} \\ \vec{D} &= \epsilon_0\vec{E} \\ \rho_e &= 0 \end{aligned} \right.$$

Ohm's law in moving fluid for plasma motion $\vec{u}$: (can be derived from Lorentz-invariance):

$$\vec{j} = \sigma(\vec{E} + \vec{u} \times \vec{B})$$

Replace

$$\begin{aligned} \vec{E} &= \frac{\vec{j}}{\sigma} - \vec{u} \times \vec{B} \\ \vec{j} &= \frac{1}{\mu_0}\mathrm{rot}\vec{B} \end{aligned}$$

leads to MHD-equations

MHD-equations:
(relation between $\vec{u}$ and $\vec{B}$!)

$$\rho \frac{d\vec{u}}{dt} = -\text{grad}\, p + \vec{j} \times \vec{B}$$

Magnetic forces influence motion of plasma.

$$\frac{\partial B}{\partial t} = \text{rot}\left(\vec{u} \times \vec{B}\right) + D_m \Delta \vec{B}$$

"frozen-in" term diffusive term

Motion $\vec{u}$ of plasma determines $\vec{B}$.
(Starting point for dynamo theory!)

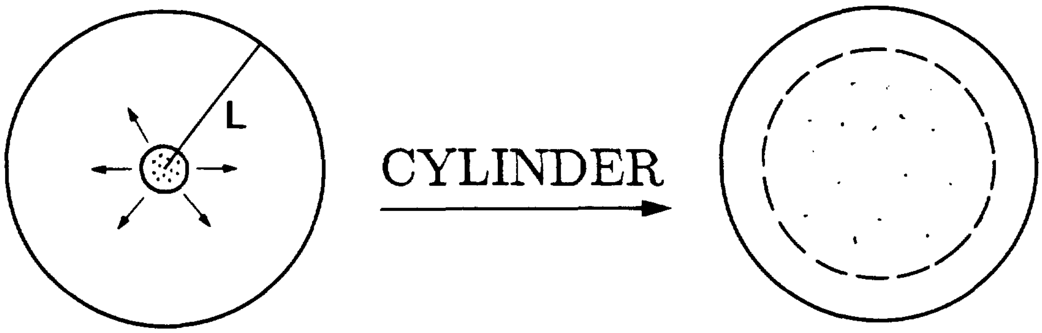
Diffusive term with $D_m = \frac{1}{\sigma \mu_0}$
leads to time constant for fieldline diffusion

$$t_{diff} \propto L^2 \mu_o \sigma.$$

<u>"DIFFUSION" OF MAGNETIC FIELD LINES</u>

Let $\vec{u} = 0$

$$\frac{\partial \vec{B}}{\partial t} = D_m \Delta \vec{B} \qquad \underline{\text{diffusion equation}}$$



$$\underline{t_{diff}} \approx \frac{L^2}{D_m} = L^2 \mu_0 \sigma$$

1. Cu, $L = 10$ cm: $t_{diff} = 0.7$ sec
2. SUNSPOT, $L = 30\,000$ km: $t_{diff} = 4$ years
3. INTERPLANETARY PLASMA, $L = 10^5$ km: $t_{diff} \approx 150\,000$ years

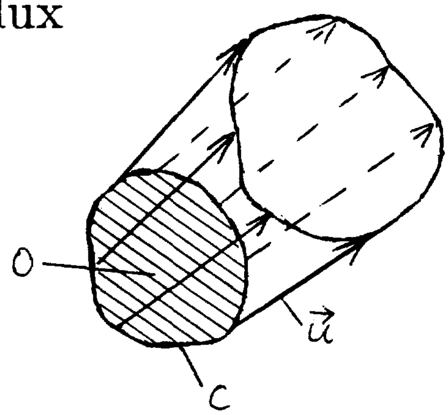
$\longrightarrow$ <u>"FROZEN-IN" CONDITION MAY BE WELL FULFILLED IN COSMIC PLASMA.</u>

The case of ideal MHD: $\sigma = \infty$

$$\frac{\partial B}{\partial t} = \text{rot}\left(\vec{u} \times \vec{B}\right)$$

Consider plasma motion of closed contour C

$$\phi = \int_O \vec{B}\, d\vec{o} \qquad \text{magnetic flux}$$



Without proof:

$$\frac{d\phi}{dt} = 0$$

Theorem of "frozen–in" magnetic field.

Plasma carries magnetic field (and vice versa). Intimate relation between plasma and magnetic field.

Numerous applications

1. Simple sunspot model
2. Solar prominences (filaments)
3. Formation of magnetopause
4. Spiral shape of interplanetary magnetic field
5. Alfvén waves

Special cases

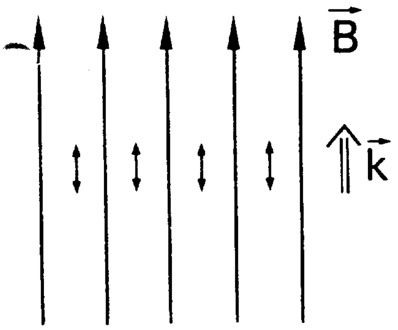
A $E_M \gg E_{Pl}$: MF keeps plasma from flowing perpendicular to field. Example: Coronal arches.

B $E_{Pl} \gg E_M$: Plasma carries MF. Example: Solar wind and interplanetary magnetic field.

MHD-WAVES

general: $c_w = \sqrt{\epsilon/\rho}$

ϵ = "elasticity"
ρ = mass density



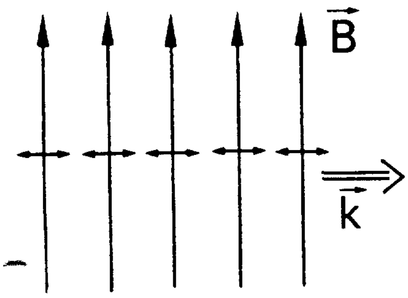
SIMPLE ACOUSTIC WAVES

$\epsilon = \gamma p$

$c_s = \sqrt{\gamma p/\rho}$

solar wind

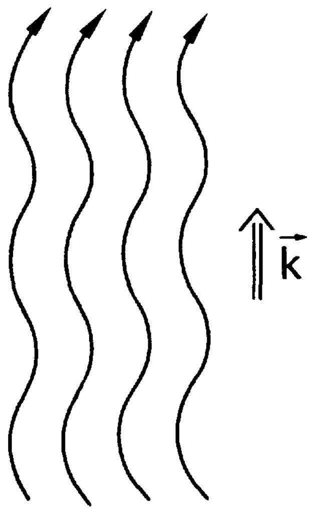
$c_s \approx 30\ \mathrm{km\,s^{-1}}$



MAGNETO-ACOUSTIC WAVE

$\epsilon = \gamma p + B^2/2\mu_0$

$c_{MA}^2 = c_s^2 + c_{ALF}^2$



ALFVÉN WAVES

(elastic waves along rope

$c_{ALF} = \sqrt{B^2/\mu_0\rho}$

solar wind

$c_{ALF} \approx 45\ \mathrm{km\,s^{-1}}$

Reconnection

How can we remove the pearls from the string?

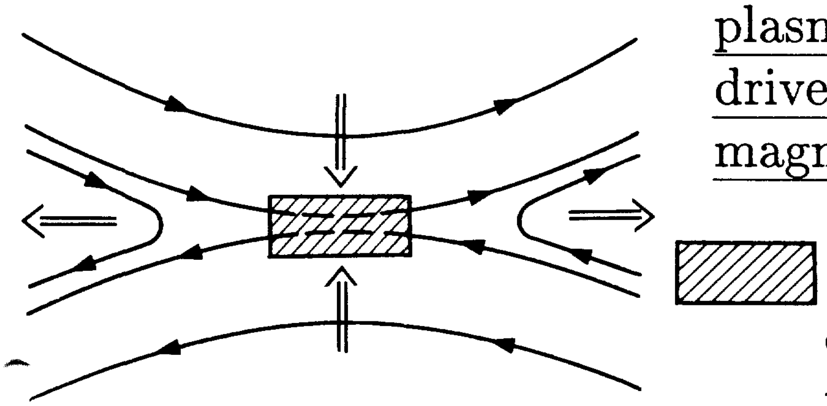
- Thread it from the end (inject plasma from the ionosphere into the magnetosphere or from the photosphere of the Sun into the corona along open magnetic field lines)
- Cut field lines and glue them together again = reconnection.

HOW and WHERE?
Finite resistivity required (non-ideal MHD).
Important over small spatial scales. Remember:

$$t_{diff} \propto L^2 \mu_o \sigma$$

RECONNECTION

plasma IN



plasma OUTflow driven by magnetic stresses

"frozen-in" condition violated,

region with $\vec{R} \neq 0$ IN

$$\vec{E} + \vec{u} \times \vec{B} = \vec{R}$$

$\vec{R} = 0:\ \sigma = \infty$

$\vec{R} \neq 0:$ finite resistivity on small scales

REGION OF PLASMA HEATING

⟶ anomalous resistivity

⟶ increase of reconnection rate

LARGE ELECTRIC FIELDS

⟶ particle acceleration

Domain of simulations!

IMPORTANT CONSEQUENCES OF RECONNECTION

1. ENERGY CONVERSION
   (a) plasma heating
   (b) $\vec{E}$-field: particle acceleration

FEEDBACK

2. RECONNECTION OF MAGNETIC FIELD LINES
   (not all solutions stationary!)

3. TRANSPORT OF PLASMA

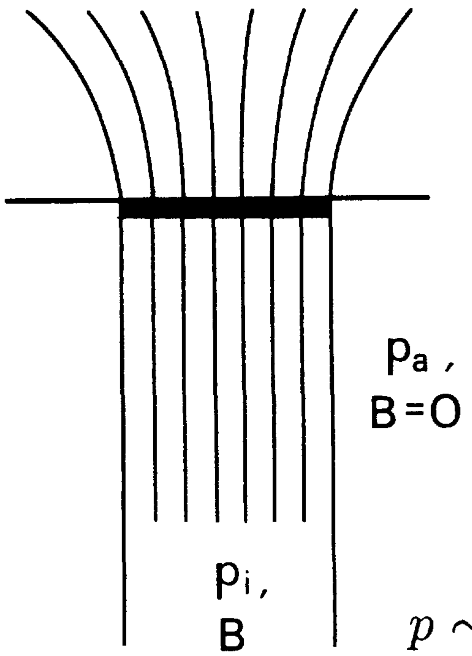
4. CHANGE OF CONDUCTIVITY

THE SUN AND THE INTERPLANETARY MEDIUM

Some guidelines:

- The temperature profile of the Sun and the atmospheric layers: photosphere, chromosphere, corona.
- The solar cycle and the general magnetic field of the Sun.
- The structure of the solar corona (unipolar, bipolar, complex).
- Individual features (sunspots, filaments, arches, ...).
- The solar wind.
- The relation between coronal and interplanetary structures.
- The extent of the heliosphere and the transition to the interstellar medium.

SIMPLE SUNSPOT MODEL



Equilibrium

vertical: $\frac{\partial p}{\partial z} = g_0 \rho_0$

horizontal: $p_i + \frac{B^2}{2} = p_a$

$$\downarrow$$

$$\frac{\partial p_i}{\partial z} = \frac{\partial p_a}{\partial z} \Rightarrow \rho_i = \rho_a$$

$$p \sim \rho T \begin{cases} p_i < p_a \\ \Downarrow \\ \boxed{T_i < T_a} \end{cases}$$

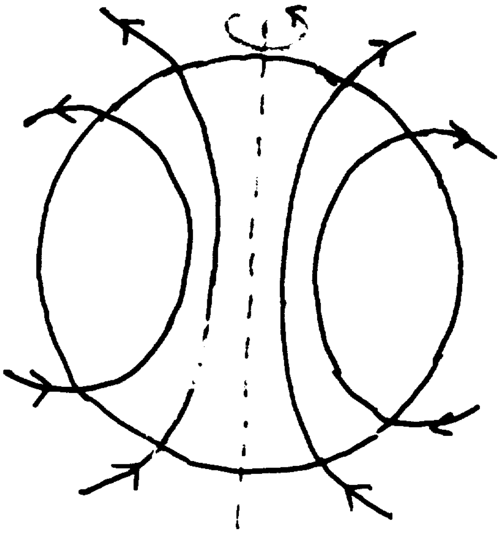
Existance of magnetic field leads to COOLING.

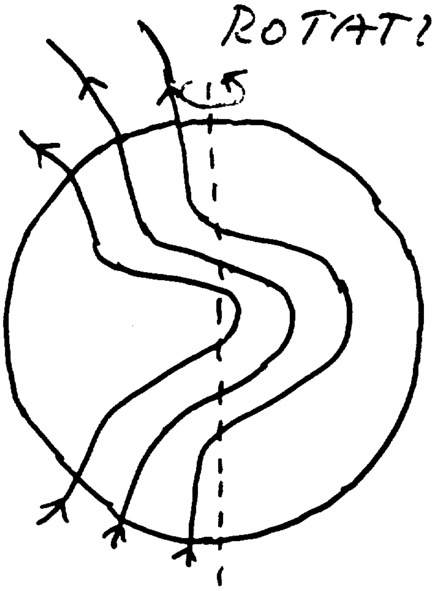
$$\boxed{B \approx 4000 \text{ Gauss}} \qquad \boxed{\Delta T \approx 1600^\circ}$$

$$\Downarrow$$

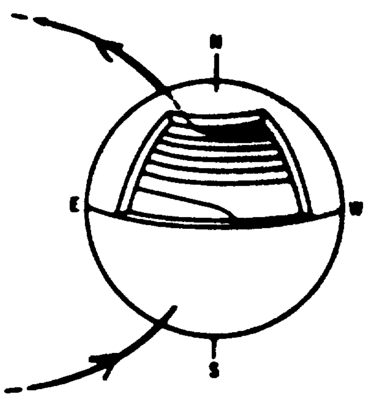
$$\frac{I_{spot}}{I_{phot}} \approx \begin{cases} 0.13 \ (3\,000\text{Å}) \\ 0.46 \ (10\,000\text{Å}) \end{cases}$$

DIPOLE FIELD + DIFFERENTIAL ROTATION

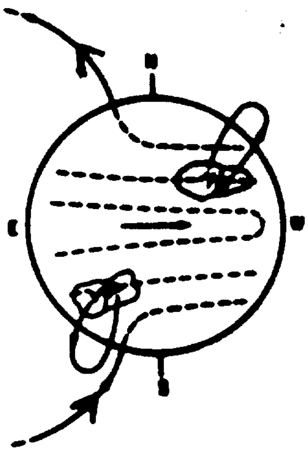




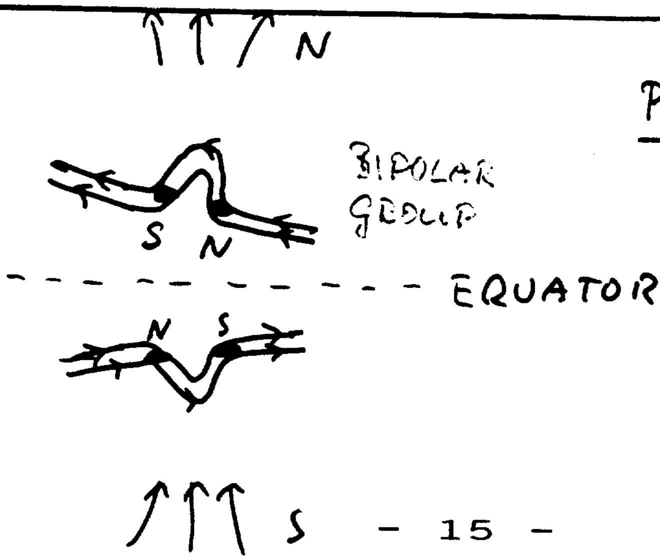
BABCOCK'S MODEL



MULTIPLE WRAPPING OF SINGLE FIELDLINE



MAGNETIC FLUX COMES TO SURFACE



POLARITY RULES

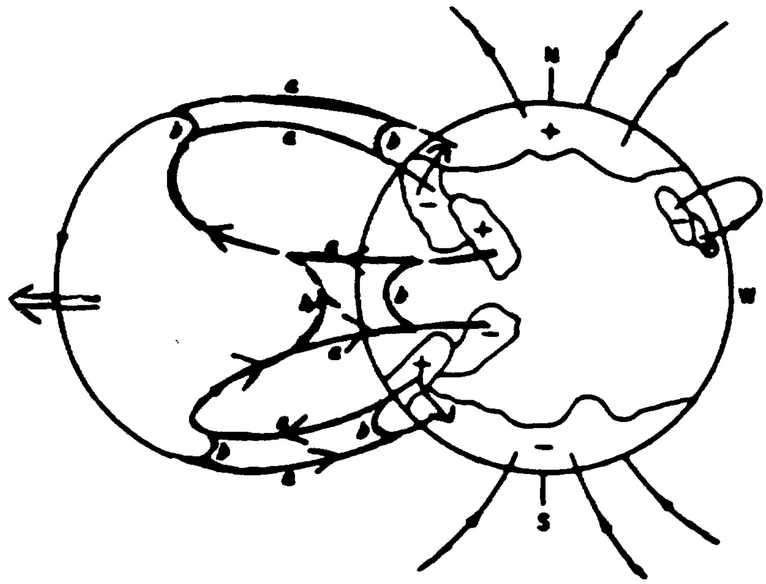
(REVERSAL DURING SUBSEQUENT CYCLE)

ENERGY CONVERSION DURING THE SOLAR CYCLE

$$E_{kin} \longrightarrow E_{mag} \longrightarrow E_{th} + E_{part}$$

(differential rotation) (reconnection) + reconfiguration + weakening of field

Magnetic flux leaves



RECONNECTION leads to the most energetic processes of solar activity:

FLARES +

CMEs (Coronal Mass Ejections)

MISSING SUNSPOTS AND THE LITTLE ICE AGE

SUNSPOTS MAUNDER MINIMUM ↓

↓

SOLAR ACTIVITY ↓

↓

SOLAR WIND, FLARES, SHOCKS ↓

↓

MODULATION OF GALACTIC COSMIC RAYS (↑)

↓

C^{14}-PRODUCTION ↑

↓

ΔC^{14} DURING ASSIMILATION ↑
CARBON 14-RECORD:

NUMBER OF AURORAE (INDIRECT EVIDENCE) ⟵

INDEPENDENT TREE RING DATING ⟶

CLIMATE RECORDS

↓

LITTLE ICE AGE

? ⇗ 0.4 % ?

⇙

LOW MAGNETIC ACTIVITY OF THE SUN EVERY FEW HUNDRED YEARS (≈420)

1980-86: 0.1 %

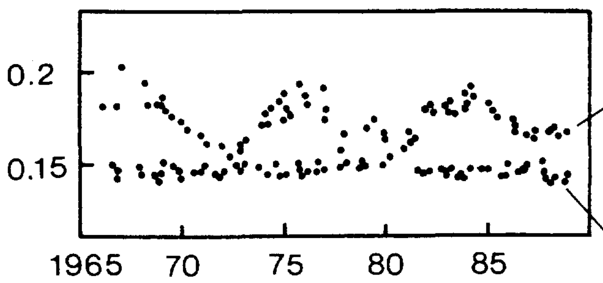
SUNSPOT NUMBER ⟺ SOLAR CONSTANT

STUDIES OF SUN-LIKE STARS!

STUDY OF 74 SOLAR TYPE STARS

(same age and mass $\Longrightarrow$ same magnetic fields!)

13 stars studied monthly since 1966.
Brightness in Ca H+K lines
= measure for temperature
= measure for magnetic activity.



STAR HD 81809
(normal cycle)

STAR HD 9562
(long term lull in activity, “Maunder minimum” state)

Roughly 1/3 of solar type stars are “magnetically flat”. (··········) :
Conclusion: Sun may spend considerable amount of time in magnetic minima.

$\Delta S_{\odot} = 0.4\%? \Longrightarrow$
sufficient for $\approx 1°$ CLIMATIC EFFECT

(Baliunas and Jastrow, Nature 6 Dec 1990; Giampapa, same place)

SOLAR WIND

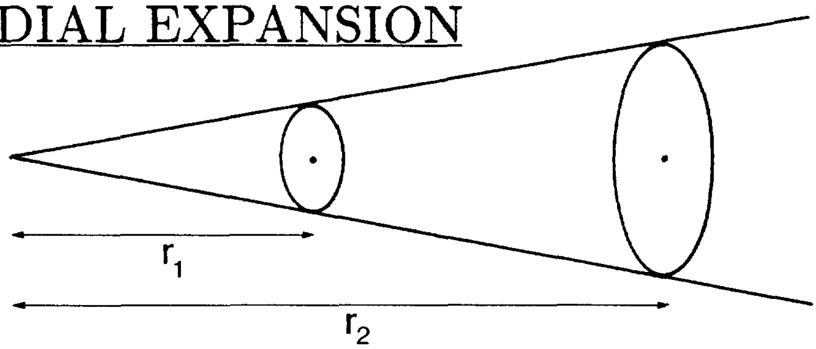
Hydrostatic equilibrium ?

1950	Biermann: cometary tails
1957	Parker model: steady expansion
1962	Neugebauer and Snyder: Mariner 2

Results of continuous measurements:

1. RADIAL STREAMING without interruption
2. $\bar{V}_w \approx 400$ km/s, $V_w = 300 \ldots 700$ km/s
3. $\bar{n} \approx 3 - 5$ protons/cm^3, $n = 0.1 - 80$ cm^{-3}
4. $T_p \approx 3 \cdot 10^4 \ldots 4 \cdot 10^5$ K $\quad (T_c \approx (1-2) \cdot 10^6$ K$)$
5. Strong TEMPORAL VARIATIONS, "recurrent" fast streams
6. Plasma carries MAGNETIC FIELD of solar origin

RADIAL EXPANSION



Frozen-in magnetic field:

$$\Phi = \pi B_1 r_1^2 = \pi B_2 r_2^2 = const.$$

$$\underline{\underline{B(r) = r^{-2}}}$$

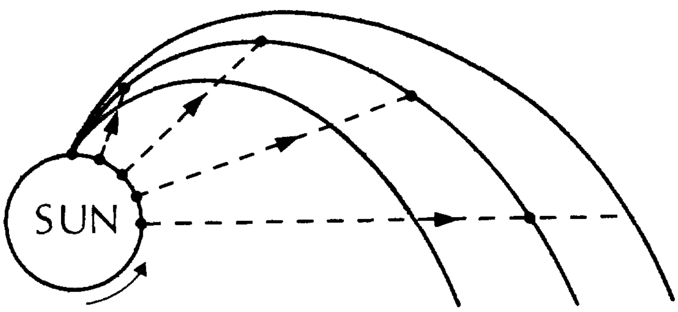
Earth's orbit = 213 $r_\odot$

$$B_{r=r_E} = \left(\frac{1}{213}\right)^2 \cdot B_{r=r_\odot}$$

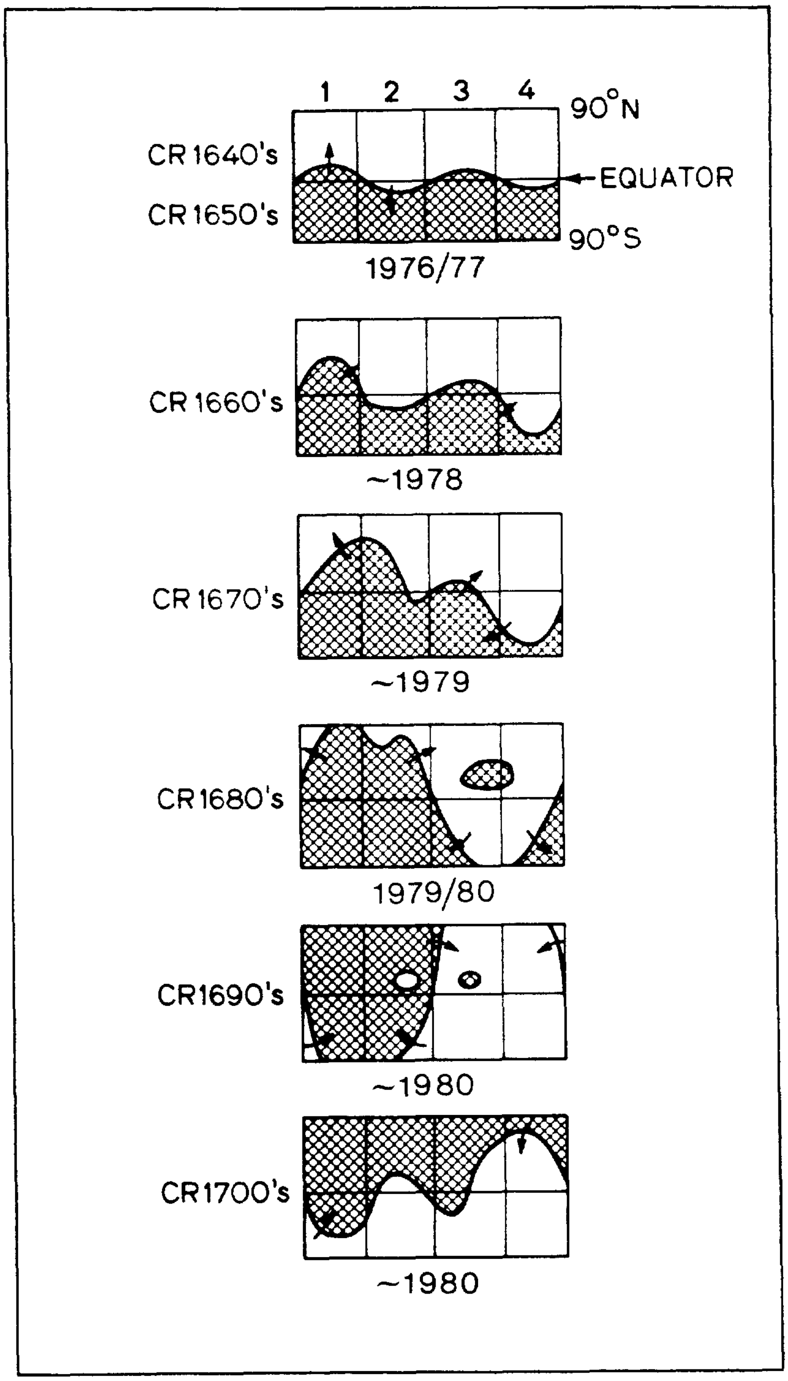
$$\downarrow \qquad\qquad \downarrow$$

$$\approx 5 \cdot 10^{-5}\text{Gauss} \qquad\qquad 2\ \text{Gauss}$$

$$= 5\gamma = \underline{\underline{5\text{nT}}}$$



Archimedian spiral



Change of magnetic polarities in the solar corona from solar minimum onwards

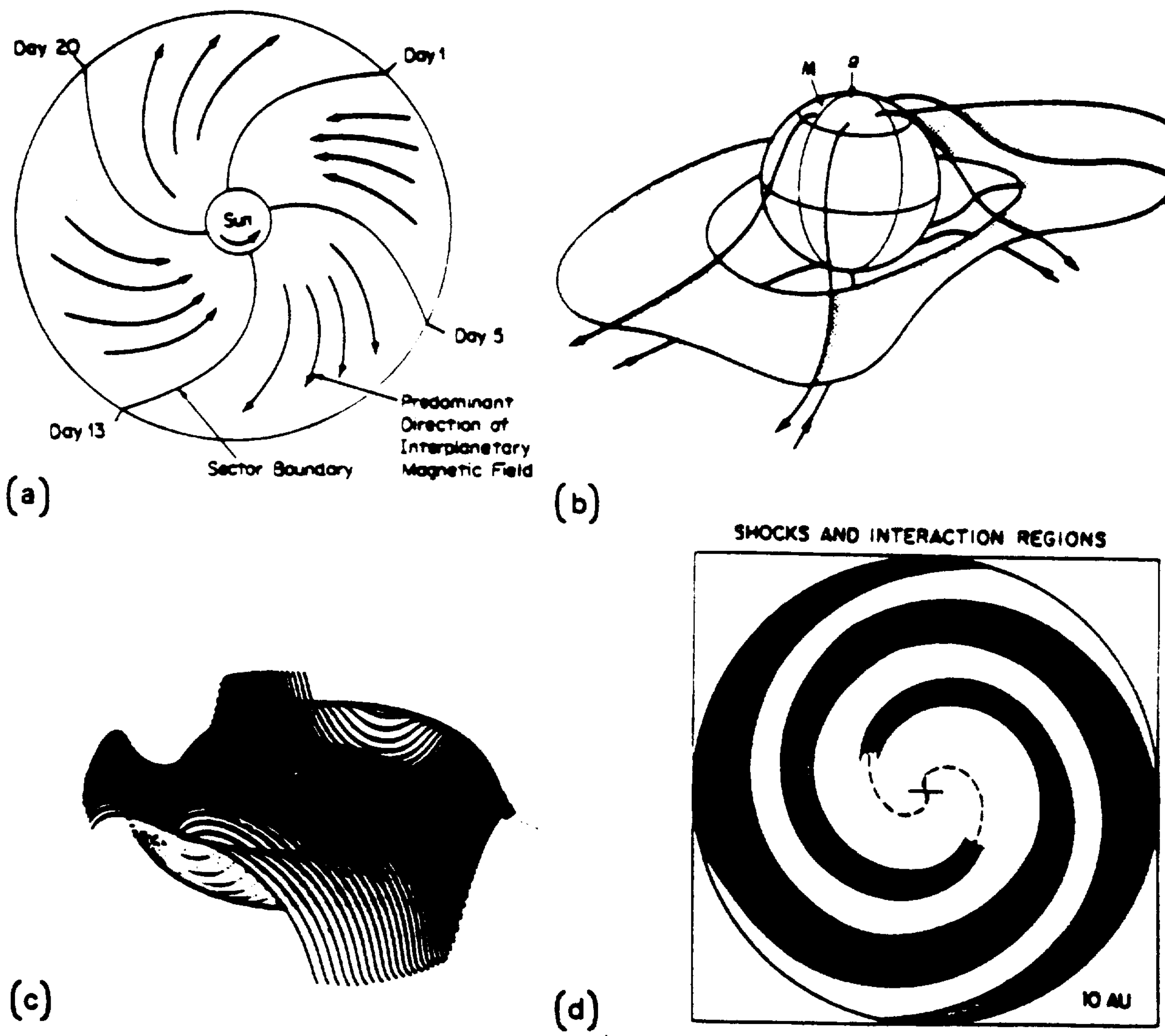
Interplanetary magnetic field structures generated by the Sun

(a) Spiral and sector structure

(b) Neutral sheet between regions of opposite polarity

(c) Warped current sheet out to large distances

(d) Corotating interaction regions

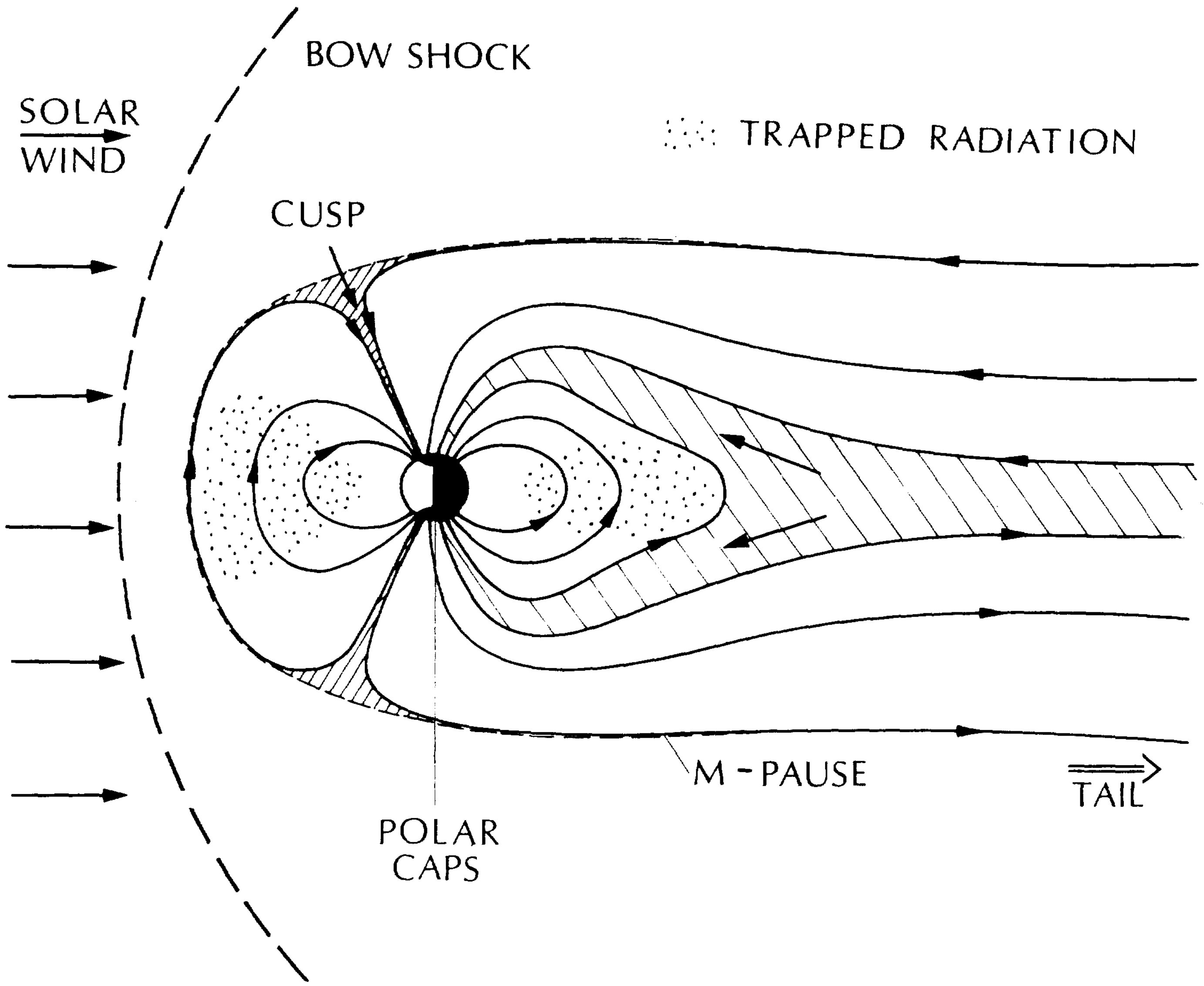


SOLAR WIND: SOME OPEN PROBLEMS

1. Realistic model for high speed streams from coronal holes (supply of sufficient energy).

2. Related to general question of the heating of the corona.

3. Origin of slow solar wind: transition from closed loops to open field lines!



AURORAL OVAL :

REGION BETWEEN OPEN
AND CLOSED FIELD LINES
(PARTICLE ENTRY!)

Topological structure of the Earth's magnetosphere

PARTICLES AND FIELDS

PLASMA — MAGNETIC FIELDS — ENERGETIC PARTICLES

(thermal) — — (suprathermal)

In wide regions of the heliosphere:

$$\epsilon_{PL} \gg \epsilon_{MF} \gg \epsilon_{PART}$$

ϵ = energy density

electric fields $\vec{E} \approx 0$

$$\Rightarrow \quad p = \frac{1}{c}\sqrt{W_{tot}^2 - m_0^2 c^4} = const$$

PROPAGATION

SMOOTH FIELDS: adiabatic (focusing, reflection, drift)

TURBULENT FIELDS: pitch angle scattering

Particles are used as probes for the large- and small-scale structures of the magnetic field.
(Well developed theory, results in closed form available.)

ACTIVE PLASMA:

- Space charges (double layers) and magnetic field aligned electric fields.
- The thermal plasma has a tail of suprathermal particles. A variety of effetcs leads to particle acceleration.
- Wave-particle interactions, generation of turbulence and plasma waves.

ELECTRIC FIELDS IN "ACTIVE" PLASMA

(Notably near boundaries and in complex magnetic fields)

$\Longrightarrow$ PARTICLE ACCELERATION ($\vec{E} \neq 0$)

How do we get electric fields?

1. Space charges ($\vec{E} \parallel \vec{B}$)
   + electrostatic waves
   (= turbulence with $\delta\vec{E} \parallel \vec{B}$, "stochastic" HF!)

2. $\partial\vec{B}/\partial t \neq 0$

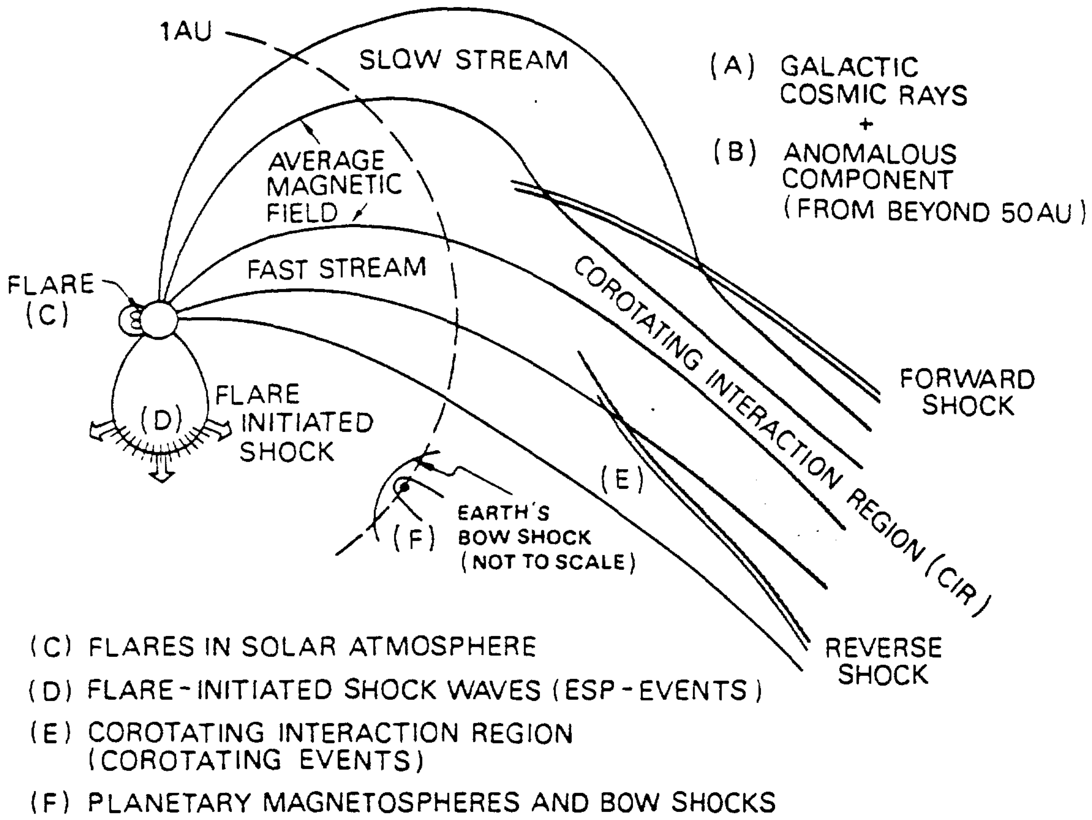
   $d\Phi/dt \sim \oint \vec{E}\, d\vec{s}$

   a) temporal changes (Betatron)
   b) moving magnetic fields (Fermi-effect)
   c) reconnection

ACCELERATION PROCESSES IN THE SOLAR SYSTEM

PHYSICAL MODEL	PROCESS	LOCATION	REMARKS
ED	Betatron	planetary magnetospheres (Earth, Jupiter, Saturn)	slow process
MHD	Fermi-effect (linear)	first order: approaching shocks? super-events? second order: interplanet. shocks	fast process hypothetical slow process
	shock drift	interplanetary shocks	fast, limited energy gain
MHD	slow reconnection $\vec{E} \perp \vec{B}$	solar corona? low energy solar cosmic rays?	hypothetical
	fast reconnection (release of magnetic energy)	solar flares (first phase); magnetospheric tail bursts $\longrightarrow$	origin of magnetic substorms
ACTIVE PLASMAS	double layers ($\vec{E} \parallel \vec{B}$)	auroral particles	peak at fixed energy
	stochastic acceleration (2nd order Fermi-effect)	solar flares (second phase?); interplanetary acceleration?	fast for sufficient turbulence
	non-linear Fermi-effect at shocks (self-generated MHD-turbulence)	Earth's bow shock interplanetary shocks solar flares? termination shock (anomalous comp.)?	($\leq$ 50 KeV) ($\leq$ 500 KeV) ($\leq$ 10 GeV?)

? = hypothetical



Energetic particle components in the solar system

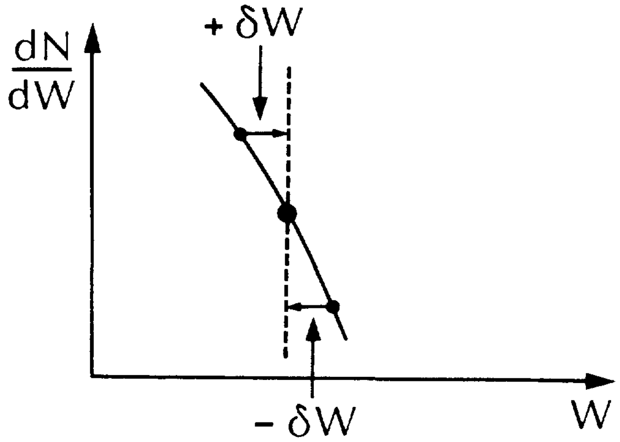
PROBLEM: no systematic forces

arbitrary phase relations between particles and waves lead to losses and gains!

Nature's solution:

a) stochastic processes (+ no particle collisions!) lead to power laws

b) time

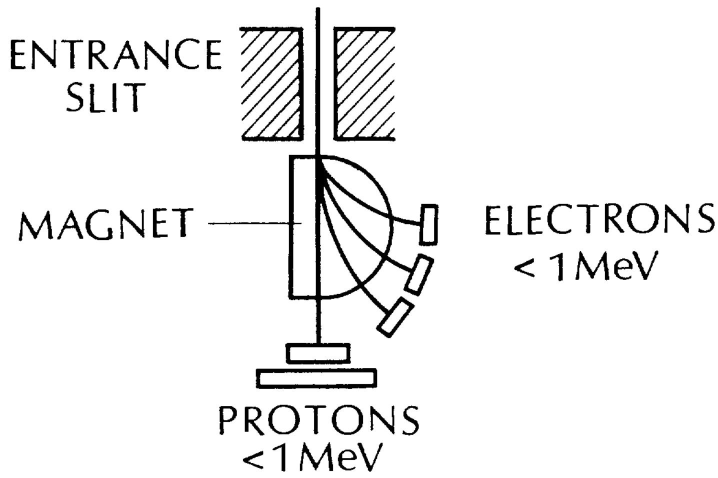


DIFFUSIVE SHOCK ACCELERATION:

$$t_{accel} \approx \frac{6D}{|V_{sh}|^2} \approx \frac{v_{part}}{|V_{sh}|} \cdot \frac{\lambda}{|V_{sh}|}$$

BOW SHOCK:	~ 10 minutes	(~ 10^5 eV)
IPL SHOCK:	~ hours	(~ 10^6 eV)
FLARES:	~ seconds	(~ 10^9 eV)
GALACTIC COSMIC RAYS:	~ 10^6 years?	(~ 10^{15} eV)

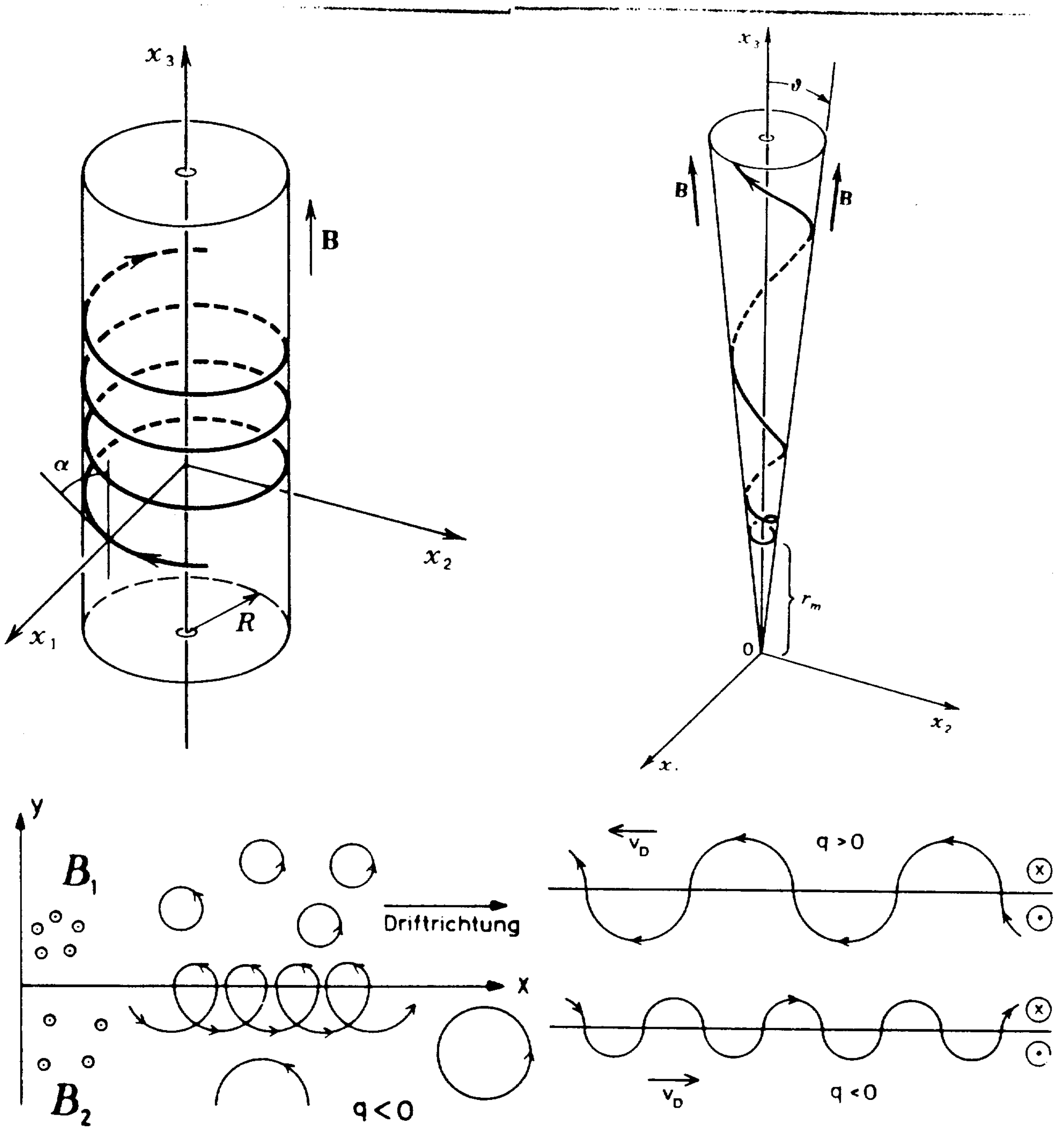
ISEE-2 INSTRUMENT (Lindau/Kiel)
low energy electrons and protons



BOW SHOCK ACCELERATION

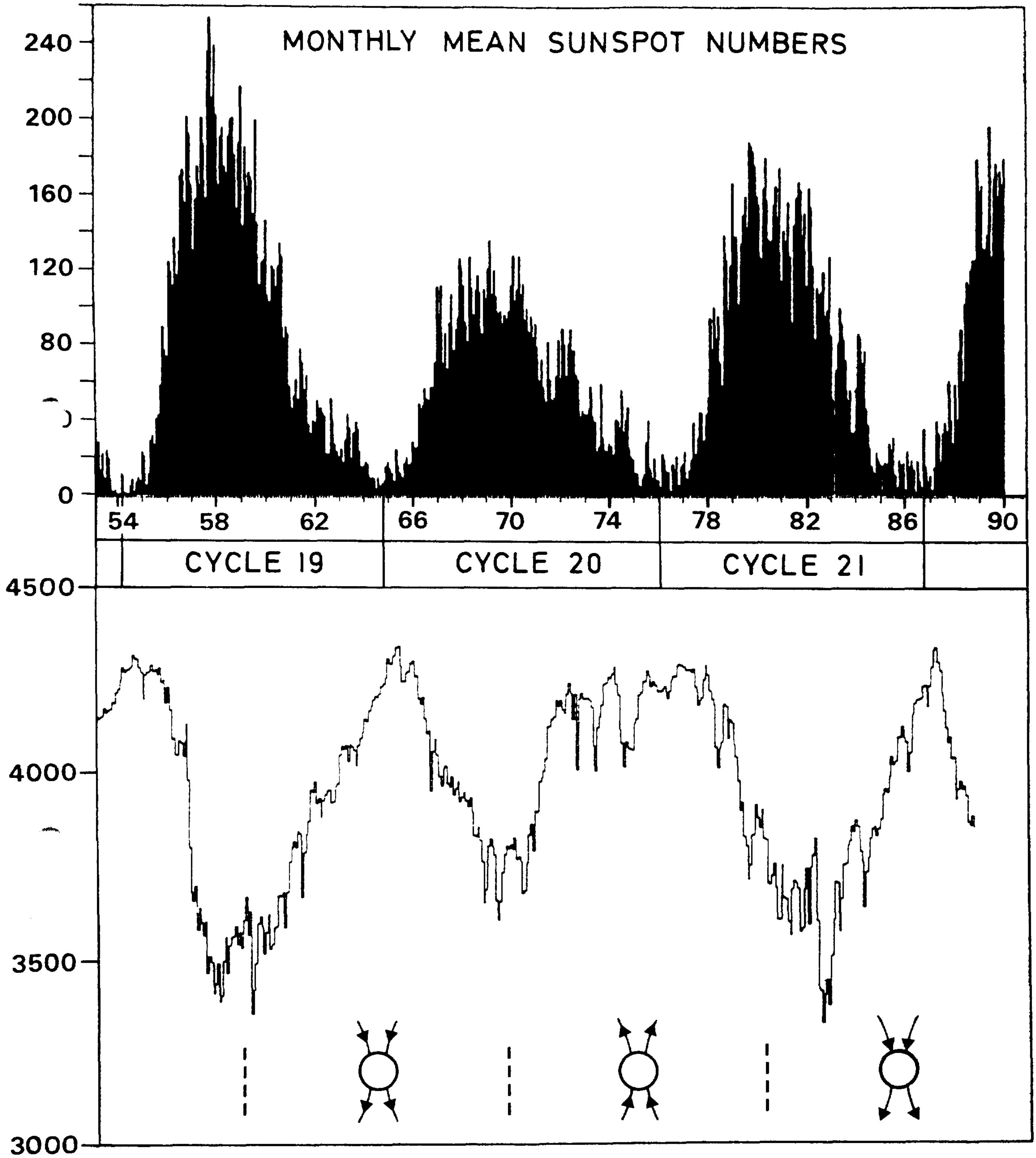
1. solar wind protons reflected
2. two-stream instability
3. proton-cyclotron waves
4. scattering of additional protons, Fermi-effect gets efficient (λ small!)
5. waves and particles grow together (positive feed-back)

Time constant after switch-on to radial field direction: $\sim$ 10 min
$(\delta B/B \approx 7\%,\ \delta\epsilon_{part} \approx \delta(B^2/2\mu_0))$



Charged particle propagation in smooth magnetic fields: gyration, focusing/mirroring, and drift

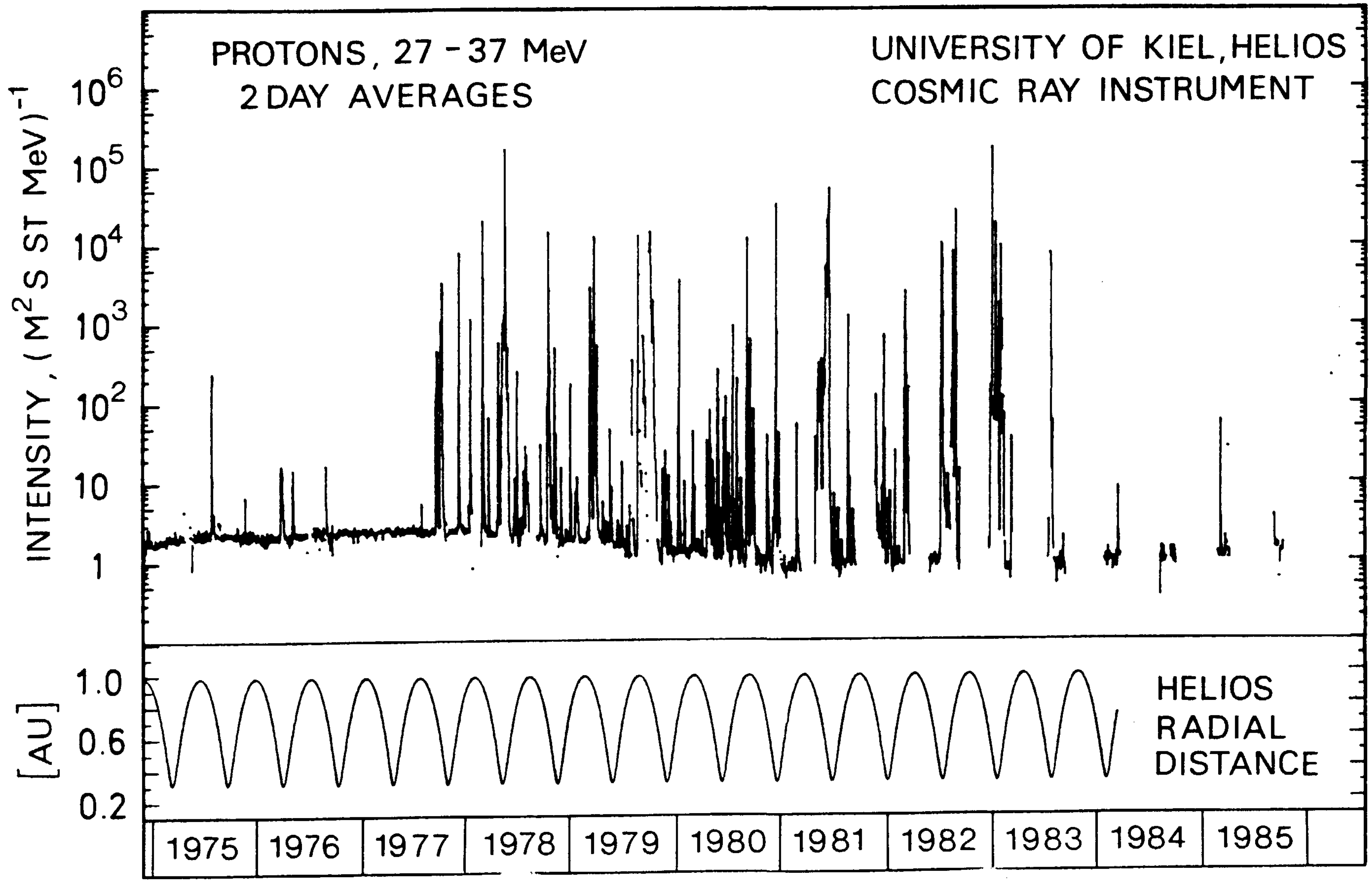
Variation of sunspot number (above) and cosmic ray intensity with the solar cycle (below)



CLIMAX AVERAGE COSMIC RAY INTENSITY
1953 to 1988

Variation of cosmic ray intensity during one solar cycle:

Superposition of individual solar cosmic ray events
on smoothly varying galatic cosmic radiation



References:

(The following list of references is far from representative. It will allow interested readers to enter into some of the fundamental principles and some recent developments.)

1. H. Alfvén, C.G. Fälthammar, **Cosmical Electrodynamic**, Clarendon Press, Oxford 1963.
2. T.J. M. Boyd and J.J. Sanderson, **Plasma Dynamics**, Nelson and Sons Ltd., London 1969.
3. H. Alfvén, **Cosmic Plasma**, D. Reidel, Dordrecht 1981.
4. E.N. Parker, C.F. Kennel, and L.J. Lanzerotti (Eds.), **Solar System Plasma Physics**, Vol. I-III, North-Holland Publ. Company, Amsterdam 1979.
5. M. Stix, **The Sun**, Springer-Verlag, Berlin 1989.
6. E. Tandberg-Hanssen and A.G. Emslie, **The Physics of Solar Flares**, Cambridge University Press, 1988.
7. A.J. Hundhausen, **Coronal Expansion and Solar Wind**, Springer-Verlag, Berlin 1972.
8. R. Schwenn and E. Marsch (Eds.), **Physics of the Inner Heliosphere**, Vol. 1 and 2, Springer-Verlag, Vol. 1 (1990), Vol. 2 (in press).
9. J.G. Roederer, **Dynamics of Geomagnetically Trapped Radiation**, Springer-Verlag, Berlin 1970.
10. J.A. Ratcliffe, **An Introduction into the Ionosphere and Magnetosphere**, Cambridge University Press, London 1972.
11. B.T. Tsurutani and R.G. Stone (Eds.), **Collisionless Shocks in the Heliosphere: Reviews of Current Research**, Geophysical Monograph 35, American Geophysical Union, Washington, D.C., 1985.
12. L. Koch-Miramond and M.A. Lee, **Particle Acceleration Processes, Shock Waves, Nucleosynthesis and Cosmic Rays**, Adv. Space Res. Vol. 4, Numbers 2-3, 1984.

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