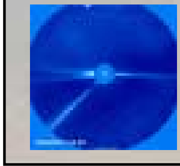
Physics of the heliosphere; an introduction

Lectures at the
International Max-Planck-Research School
Oktober 2002
by Rainer Schwenn, MPAe Lindau



7. Cosmic rays in the heliosphere; the edge of the solar system
- Solar cosmic rays
- Galactic cosmic rays
- The anomalous component
- Where the heliophere ends

„Cosmic radiation“, i.e. high energy particles

There are two basic kinds according to their origin:

Galactic Cosmic Rays (GCR) are

1. energetic particles accelerated outside our solar system, i.e. in our galaxy or outside, with energies up to 10^{21} eV.
2. The „Anomalous Component of Galactic Cosmic Rays“ (ACR).

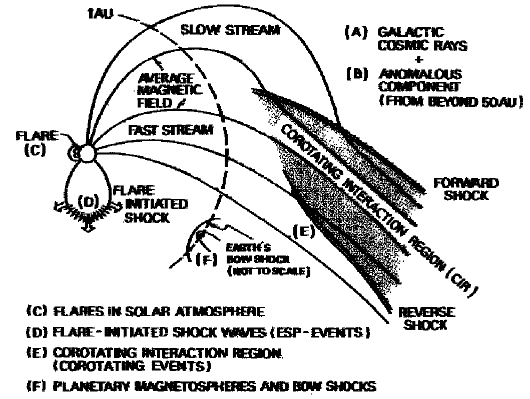
Solar Cosmic Rays (SCR) occur

1. in connection with flares, with some 100 MeV, rarely up to GeV,
2. at shock fronts, with some 100 keV,
   - CME driven,
   - at planetary bow shocks,
   - at shocks at Corotating Interaction Regions (CIRs)

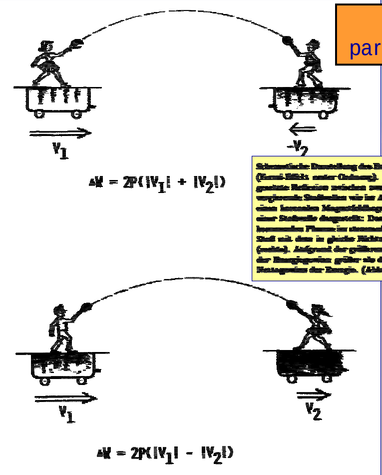
Fundamental acceleration mechanisms:

Linear acceleration in electric fields,
Synchrotron acceleration in magnetic fields,
Acceleration at shock waves (Fermi 1, Fermi 2)

„Cosmic radiation“, i.e. high energy particles



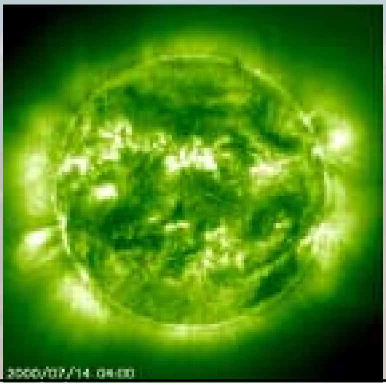
How to accelerate particles at shock waves



[illegible]

Problem for the Fermi 1/2 processes to work efficiently:
A „seed population“ of particles with medium energies is required!

The “Bastille event”, with all blows and whistles: July 14, 2000.



The biggest flare of the present solar cycle so far, observed by **EIT** on July 14, 2000.

The “Bastille event”, with all blows and whistles: July 14, 2000

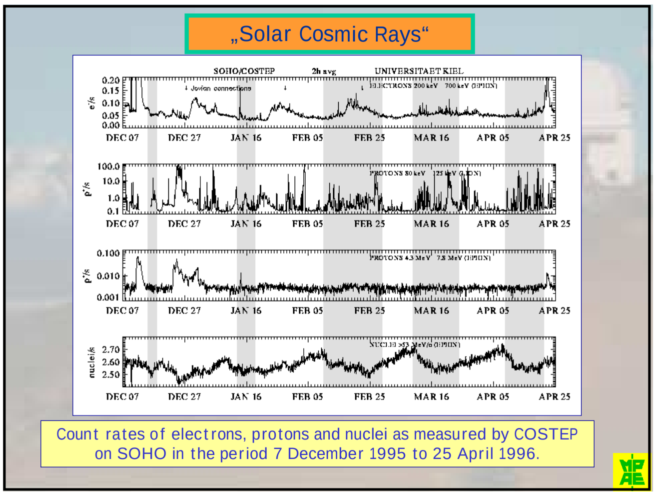
An optical telescope as a Cosmic Ray detector...!

The huge solar mass ejection on July 14, 2000, observed by **LASCO-C3**.

The “snow shower” is due to particles, accelerated to extremely high speeds during the ejection. They penetrate the instrument walls and let the CCD scintillate.

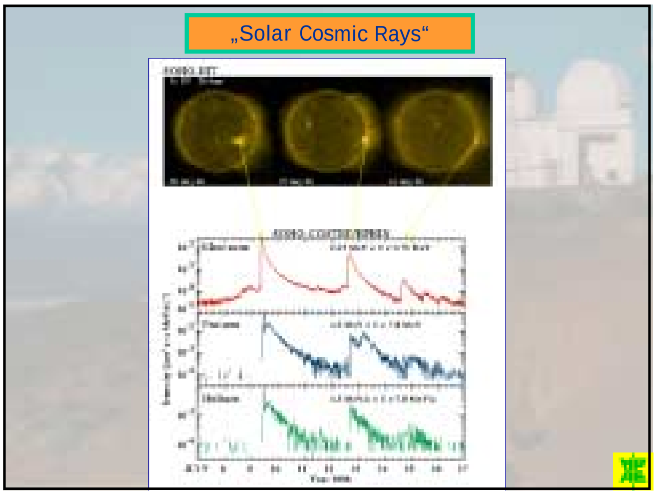
Serious danger for astronauts during EVAs!

The "Bastille 2000 event" and its effects

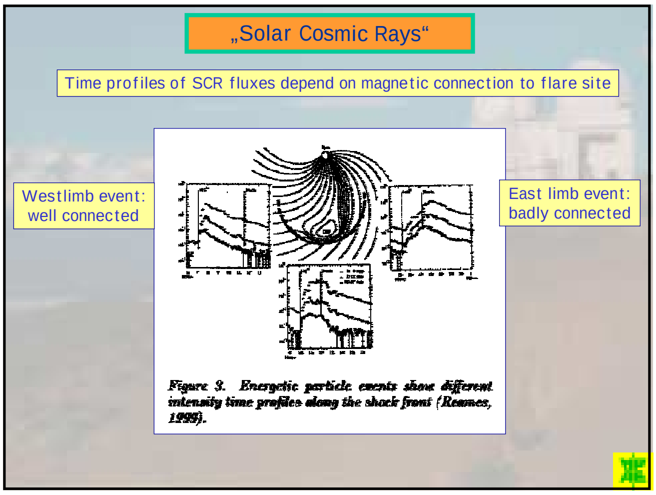


„Solar Cosmic Rays“

Count rates of electrons, protons and nuclei as measured by COSTEP on SOHO in the period 7 December 1995 to 25 April 1996.



„Solar Cosmic Rays“



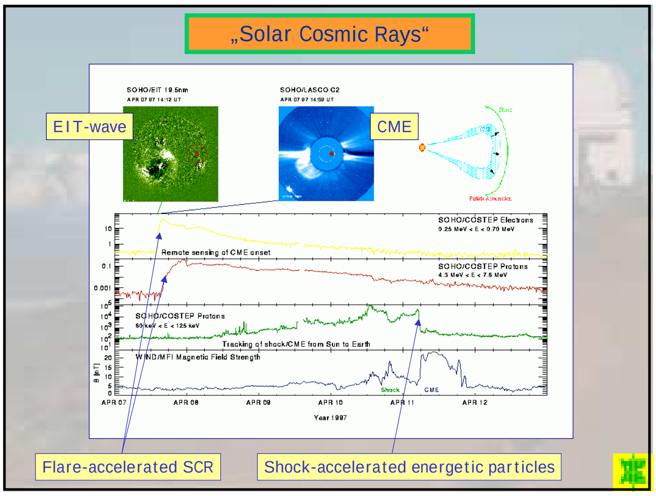
„Solar Cosmic Rays“

Time profiles of SCR fluxes depend on magnetic connection to flare site

Westlimb event: well connected

East limb event: badly connected

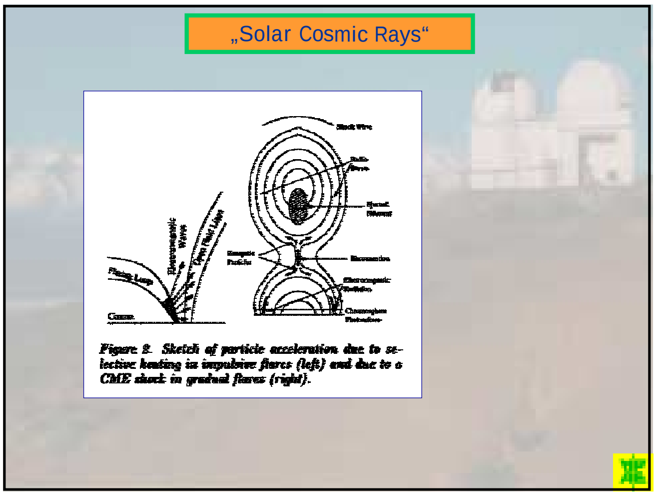
Figure 3. Energetic particle events show different intensity time profiles along the shock front (Reames, 1999).



„Solar Cosmic Rays“

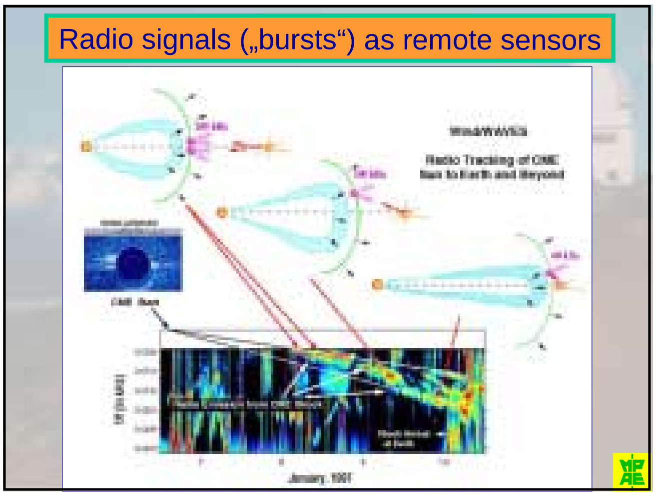
Flare-accelerated SCR

Shock-accelerated energetic particles

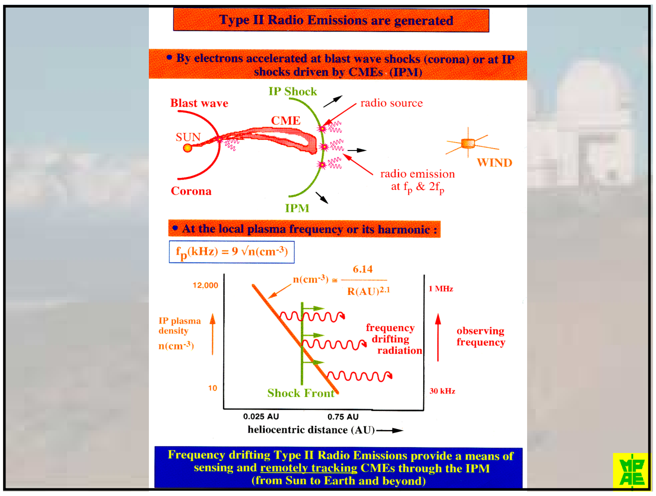


„Solar Cosmic Rays“

Figure 2. Sketch of particle acceleration due to selective heating in impulsive flares (left) and due to a CME shock in gradual flares (right).



Radio signals („bursts“) as remote sensors



Type II Radio Emissions are generated

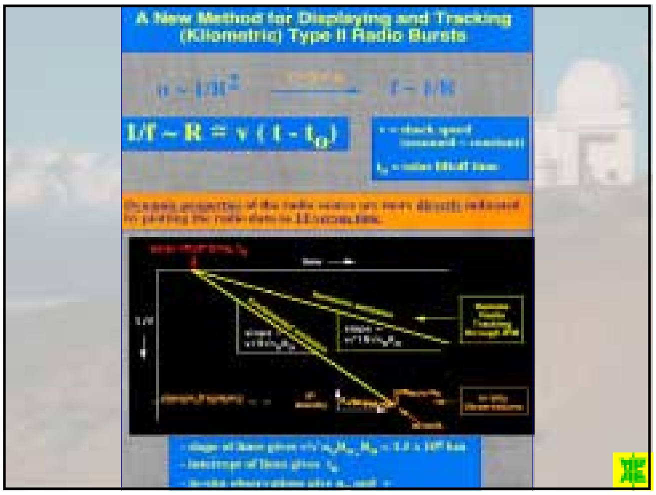
- By electrons accelerated at blast wave shocks (corona) or at IP shocks driven by CMEs (IPM)

- At the local plasma frequency or its harmonic :

$f_p(\mathrm{kHz}) = 9\sqrt{n(\mathrm{cm}^{-3})}$

$n(\mathrm{cm}^{-3}) \cong \frac{6.14}{R(\mathrm{AU})^{2.1}}$

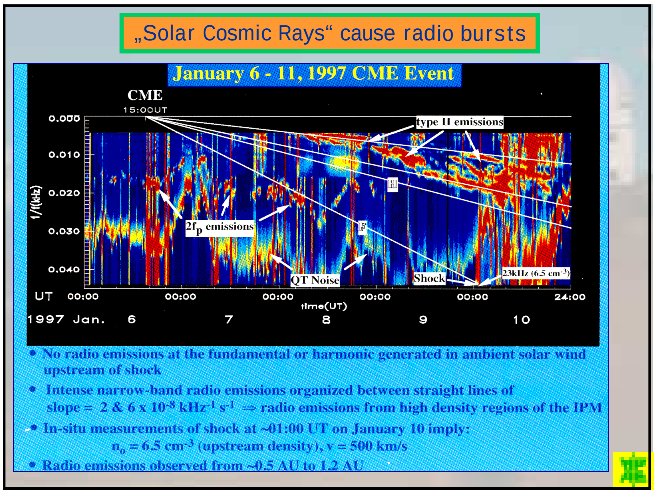
Frequency drifting Type II Radio Emissions provide a means of sensing and remotely tracking CMEs through the IPM (from Sun to Earth and beyond)



A New Method for Displaying and Tracking (Kilometric) Type II Radio Bursts

$n \sim 1/R^2 \longrightarrow f \sim 1/R$

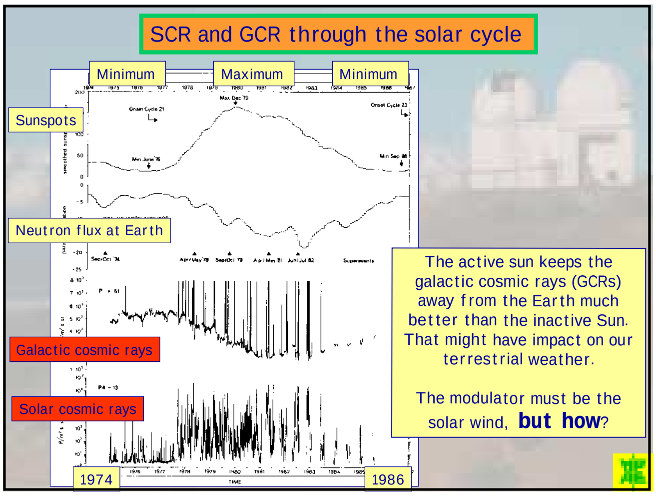
$1/f \sim R = v\,(t - t_0)$



„Solar Cosmic Rays“ cause radio bursts

January 6 - 11, 1997 CME Event

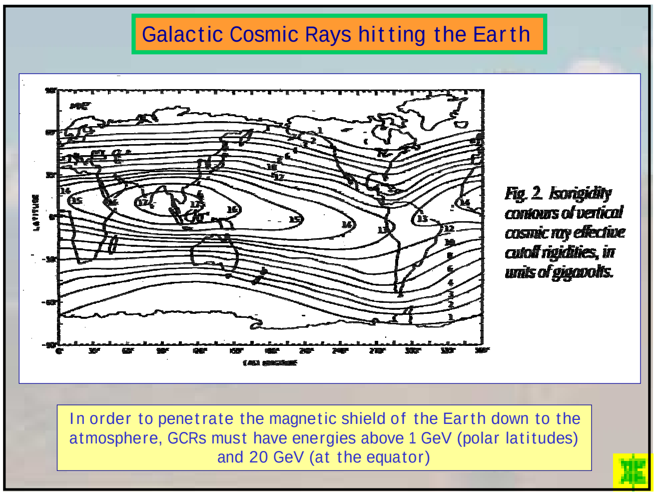
- No radio emissions at the fundamental or harmonic generated in ambient solar wind upstream of shock
- Intense narrow-band radio emissions organized between straight lines of slope = 2 & 6 x 10^{-8} kHz^{-1} s^{-1} ⇒ radio emissions from high density regions of the IPM
- In-situ measurements of shock at ~01:00 UT on January 10 imply:
  $n_o = 6.5$ cm^{-3} (upstream density), v = 500 km/s
- Radio emissions observed from ~0.5 AU to 1.2 AU



SCR and GCR through the solar cycle

The active sun keeps the galactic cosmic rays (GCRs) away from the Earth much better than the inactive Sun. That might have impact on our terrestrial weather.

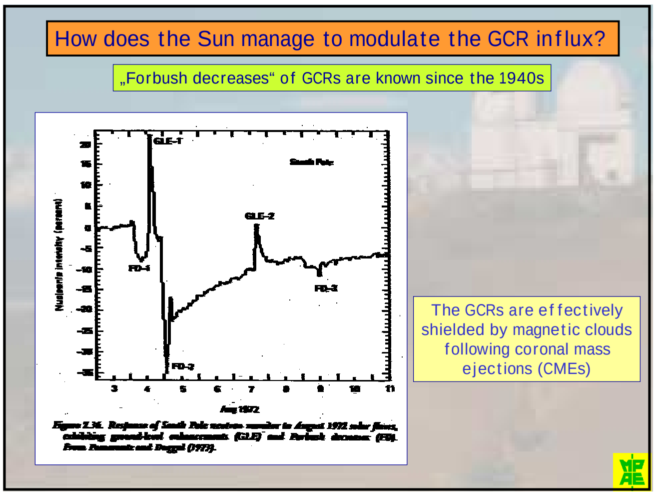
The modulator must be the solar wind, **but how**?



Galactic Cosmic Rays hitting the Earth

Fig. 2. Isorigidity contours of vertical cosmic ray effective cutoff rigidities, in units of gigavolts.

In order to penetrate the magnetic shield of the Earth down to the atmosphere, GCRs must have energies above 1 GeV (polar latitudes) and 20 GeV (at the equator)

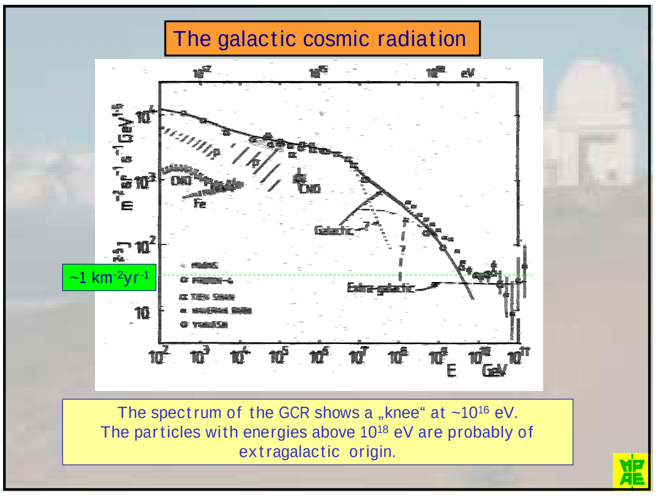


How does the Sun manage to modulate the GCR influx?

„Forbush decreases“ of GCRs are known since the 1940s

Figure 7.36. Response of South Pole neutron monitor to August 1972 solar flares, exhibiting ground-level enhancements (GLE) and Forbush decreases (FD). From Pomerantz and Duggal (1973).

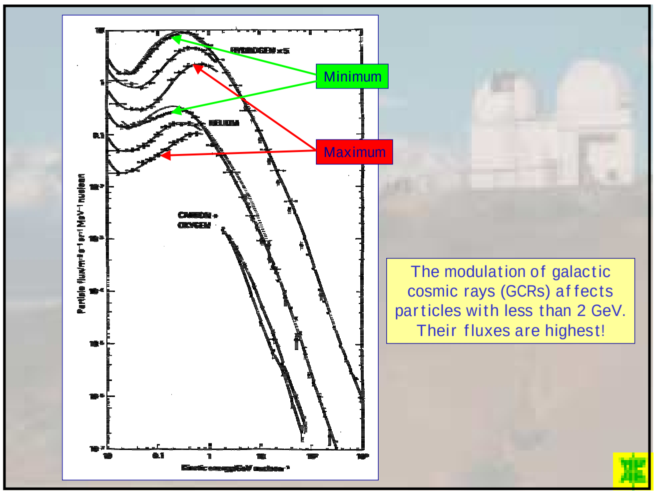
The GCRs are effectively shielded by magnetic clouds following coronal mass ejections (CMEs)



The galactic cosmic radiation

~1 km^{-2}yr^{-1}

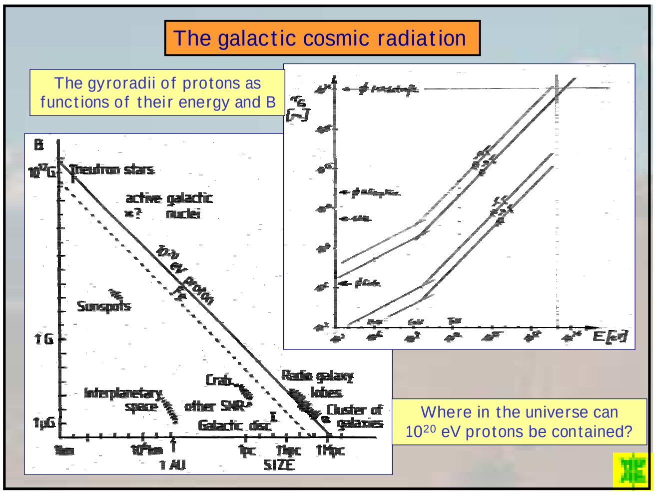
The spectrum of the GCR shows a „knee“ at ~10^{16} eV.
The particles with energies above 10^{18} eV are probably of extragalactic origin.



Minimum

Maximum

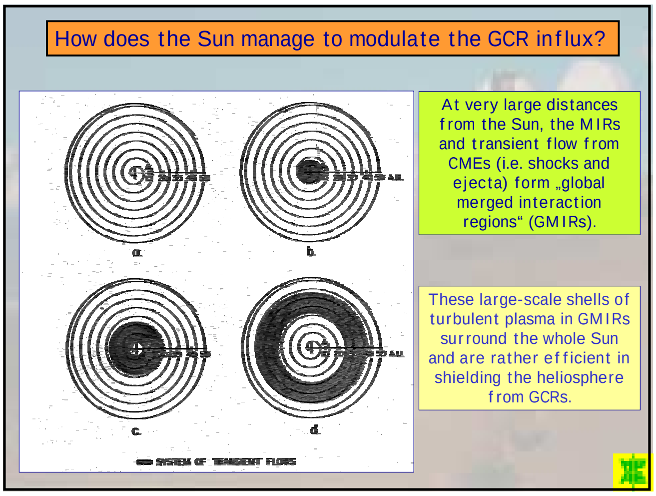
The modulation of galactic cosmic rays (GCRs) affects particles with less than 2 GeV. Their fluxes are highest!



The galactic cosmic radiation

The gyroradii of protons as functions of their energy and B

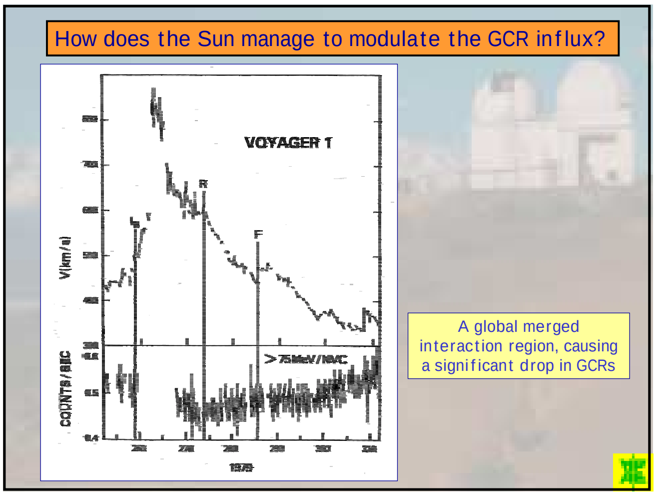
Where in the universe can 10^{20} eV protons be contained?



How does the Sun manage to modulate the GCR influx?

At very large distances from the Sun, the MIRs and transient flow from CMEs (i.e. shocks and ejecta) form „global merged interaction regions“ (GMIRs).

These large-scale shells of turbulent plasma in GMIRs surround the whole Sun and are rather efficient in shielding the heliosphere from GCRs.



How does the Sun manage to modulate the GCR influx?

A global merged interaction region, causing a significant drop in GCRs

How does the Sun manage to modulate the GCR influx?

At large distances from the Sun, the CIRs from several solar rotations merge to form „merged interaction regions“ (MIRs)

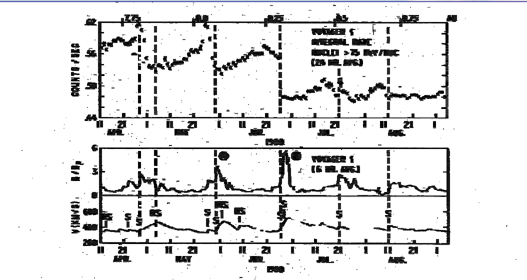
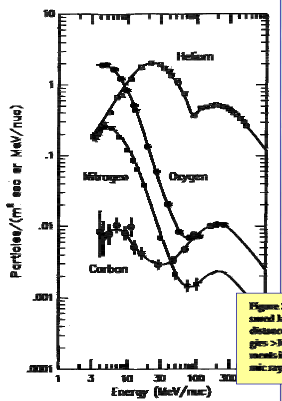


Fig. 10. Voyager 1 observations of cosmic ray intensity versus time (top) and the magnetic field strength and bulk speed (bottom) for April to September 1980. "S" denotes the position of a forward shock, and "RS" denotes the position of a reverse shock.

A sequence of merged interaction regions, causing a stepwise decrease in GCR flux.

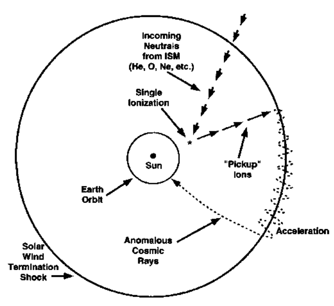
The „Anomalous“ Cosmic Radiation (ACR)



The „anomalous“ component of the cosmic radiation (ACR). It ocurs only for a few atomic species, e.g., He, N, O, C.

Figure 2. Intensity of cosmic ray He, C, N, and O nuclei as a function of their measured kinetic energy. These data were measured by instruments on Voyager 2 at a distance of ~23 AU from the Sun during the 1987 solar minimum. At kinetic energies >100 MeV/nuc, the particles are of galactic cosmic ray origin. The enhancements in the spectra of He, N, and O below ~50 MeV/nuc are due to anomalous cosmic rays. A somewhat smaller ACR contribution is also observed for C.

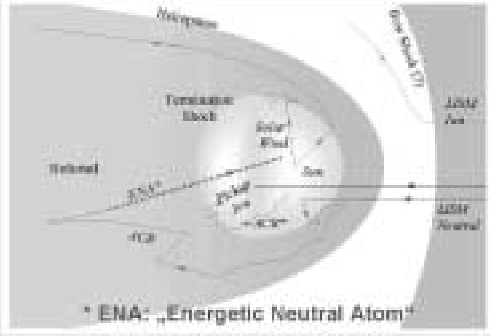
The „Anomalous“ Cosmic Radiation (ACR)



The origin of the„anomalous“ component of the cosmic radiation (ACR):

1. Interstellar neutral particles penetrate the inner heliosphere.
2. They become singly ionized by solar UV radiation.
3. The ions are picked up by the solar wind and swept to the outer heliosphere.
4. At the termination shock they are accelerated to some 10 MeV/nucleon.
5. They may enter the inner heliosphere again and appear as ACRs.

The „Anomalous“ Cosmic Radiation (ACR)



Further: some ACR particles are turned into „energetic neutral atoms“ (ENA) by charge exchange with neutral atoms of the LISM.

Where the heliosphere ends

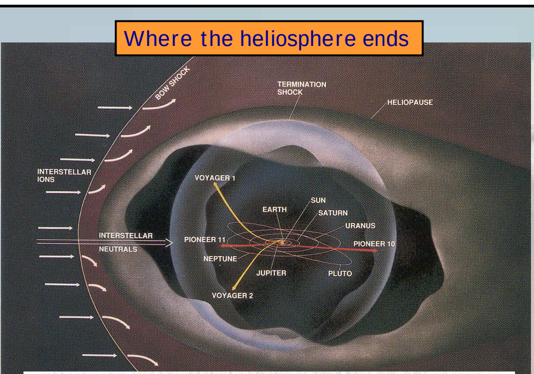
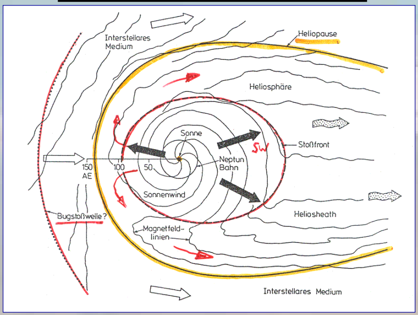


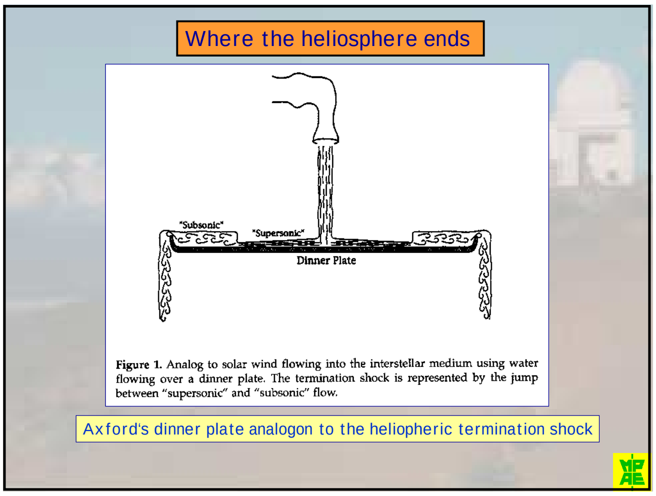
Figure 3. Schematic illustration of the large-scale structure of the heliosphere. Surrounding the solar wind termination shock is the heliopause, which forms the interface between solar and interstellar plasma, and a possible "bow shock" that may be located beyond the heliopause. The present positions of the Pioneer and Voyager spacecraft are indicated. The termination shock is assumed to be 67 AU from the Sun, as derived from an analysis of 1987 anomalous cosmic ray data from Pioneer 10 and Voyager 2.

Where the heliosphere ends



Local interstellar medium (LISM):
B_i: 0.3 to 0.5 nT
T_i: 10^4 K
V_i: 27 km s^{-1}
N_i: 0.1 cm^{-3}

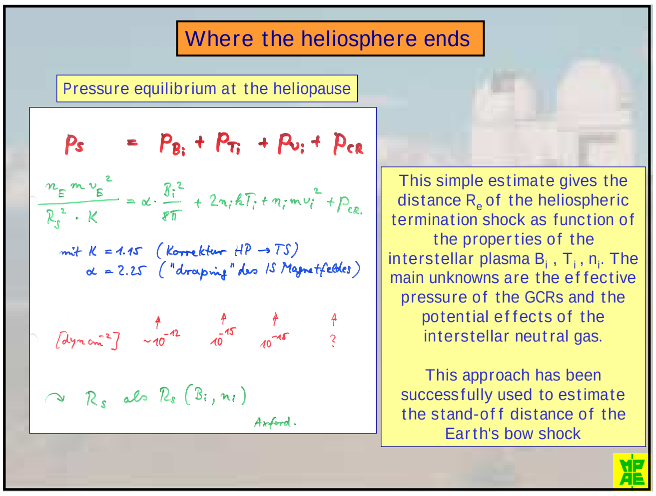
Solar wind (at 1 AU)
B_{sw}: 2 nT
T_{sw}: 10^5 K
V_{sw}: 400 km s^{-2}
N_{sw}: 5 cm^{-3}



Where the heliosphere ends

Figure 1. Analog to solar wind flowing into the interstellar medium using water flowing over a dinner plate. The termination shock is represented by the jump between "supersonic" and "subsonic" flow.

Axford's dinner plate analogon to the heliopheric termination shock



Where the heliosphere ends

Pressure equilibrium at the heliopause

$$P_S = P_{B_i} + P_{T_i} + P_{v_i} + P_{CR}$$

$$\frac{n_E m v_E^2}{R_S^2 \cdot K} = \alpha \cdot \frac{B_i^2}{8\pi} + 2 n_i k T_i + n_i m v_i^2 + P_{CR}$$

mit $K = 1.15$ (Korrektur HP → TS)
$\alpha = 2.25$ ("draping" des IS Magnetfeldes)

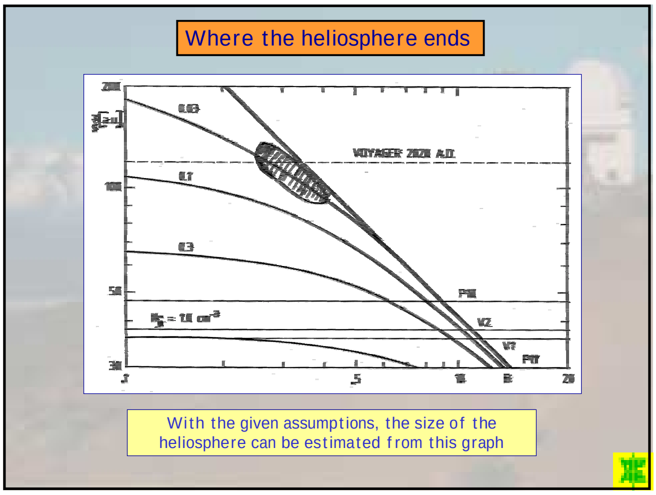
$[\mathrm{dyn\,cm^{-2}}]$ $\uparrow \sim 10^{-12}$ $\uparrow 10^{-15}$ $\uparrow 10^{-15}$ $\uparrow$?

$\curvearrowright$ R_S als $R_S(B_i, n_i)$

Axford.

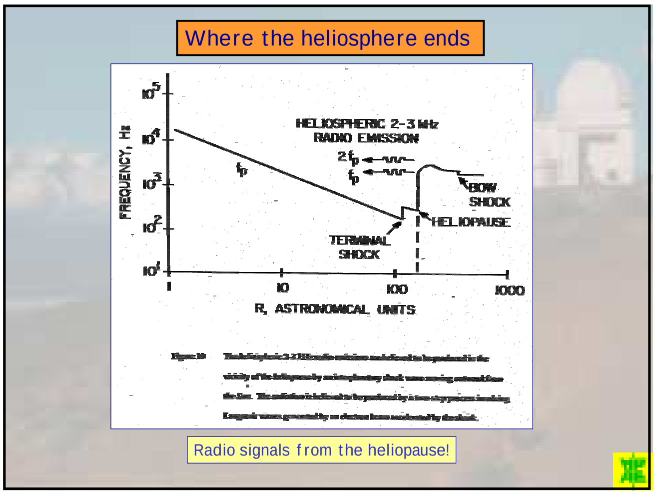
This simple estimate gives the distance R_e of the heliospheric termination shock as function of the properties of the interstellar plasma B_i , T_i , n_i. The main unknowns are the effective pressure of the GCRs and the potential effects of the interstellar neutral gas.

This approach has been successfully used to estimate the stand-off distance of the Earth's bow shock



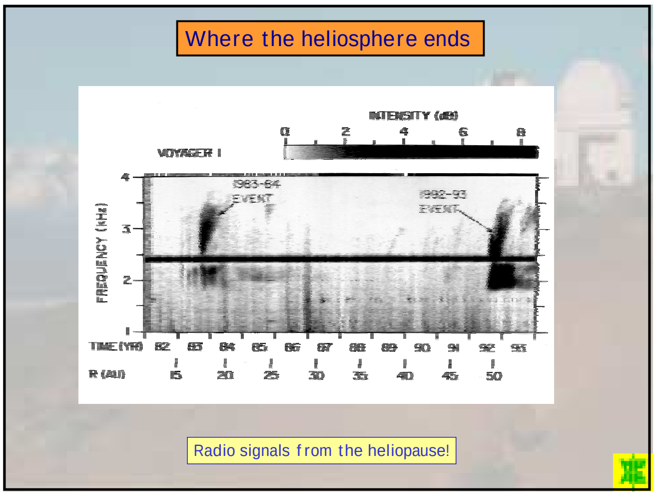
Where the heliosphere ends

With the given assumptions, the size of the heliosphere can be estimated from this graph



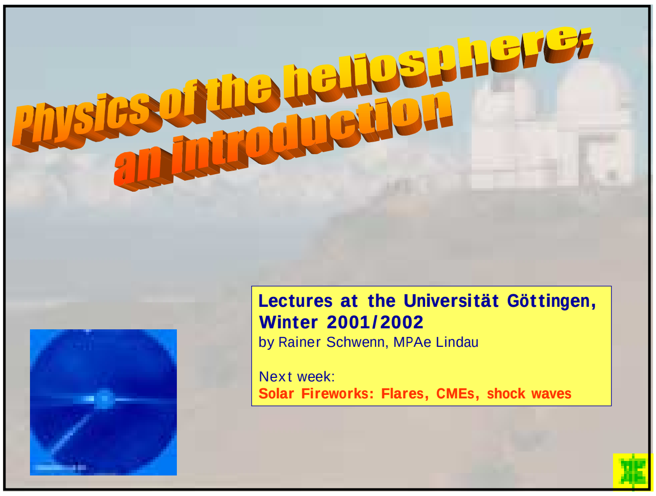
Where the heliosphere ends

Radio signals from the heliopause!



Where the heliosphere ends

Radio signals from the heliopause!



Physics of the heliosphere: an introduction

Lectures at the Universität Göttingen, Winter 2001/2002
by Rainer Schwenn, MPAe Lindau

Next week:
Solar Fireworks: Flares, CMEs, shock waves