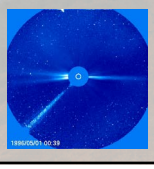
Physics of the heliosphere: an introduction

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



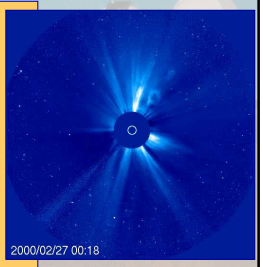
6. Variations on all time scales
- The ballerina dances through the solar cycle
- The modulation of Galactic Cosmic Rays: How?
- Irradiance variations
- Biological record for past solar activity!
- Butterflies on the Sun?
- The Sun affects climate on Earth
- What causes global warming: The Sun or mankind?

There are two more types of solar wind!

3. Low speed wind of "maximum" type

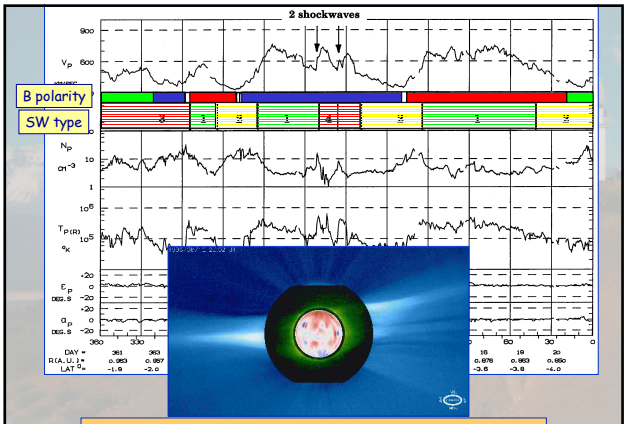
Similar characteristics as (2), except for

Helium content	4%, highly variable
Source	above active regions, at activity maximum,
Signatures	very variable, shock waves often imbedded,



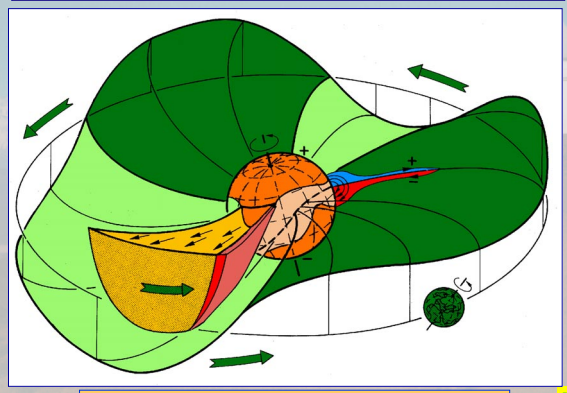
4. Ejecta following interplanetary shocks

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



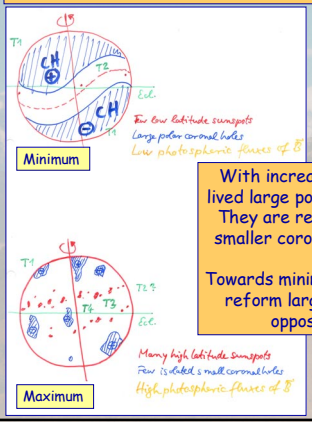
In this solar rotation in early 1975 (1996) we found all four types of solar wind!

The ballerina Sun right before activity minimum



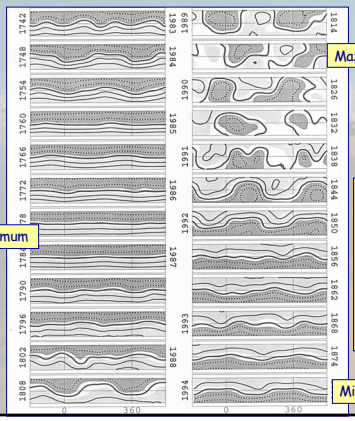
The Sun as a "ballerina", according to *Alfvén, 1977.*

Coronal hole evolution through the solar cycle



With increasing solar activity, the long-lived large polar cap coronal holes dissolve. They are replaced by several short-lived smaller coronal holes distributed all over the Sun.
Towards minimum, the small holes merge to reform large polar holes, but now with opposite magnetic polarity.

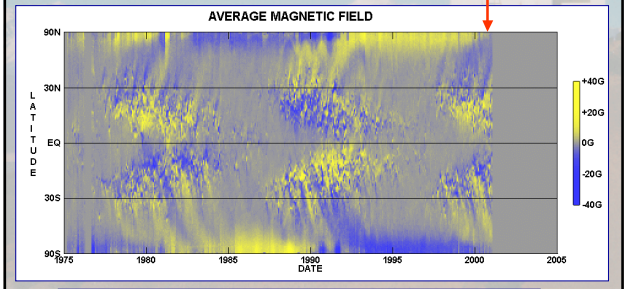
The ballerina dancing through the solar cycle



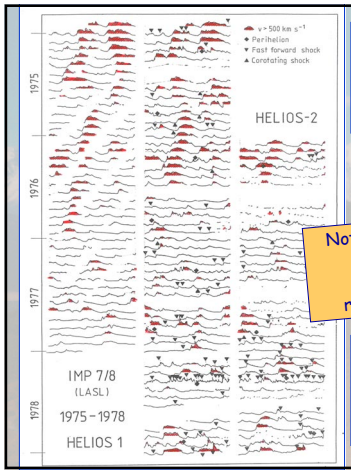
At activity maximum, the ballerina skirt flips over, and the magnetic polarity is then reversed at next minimum. The magnetic cycle of the sun (the "Hale-cycle") takes 22 years!

Butterfly diagram for magnetic flux

polar field reversal



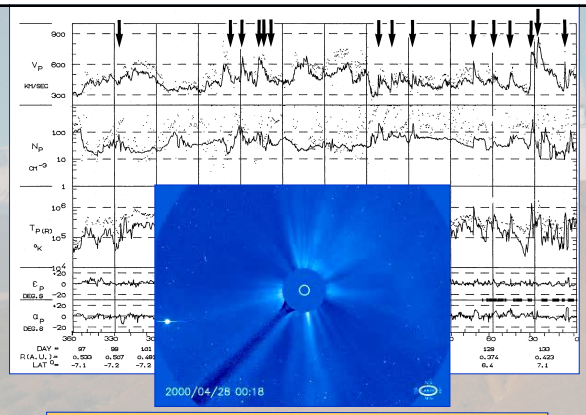
The magnetic cycle of the Sun , the „Hale-Cycle", takes 22 years



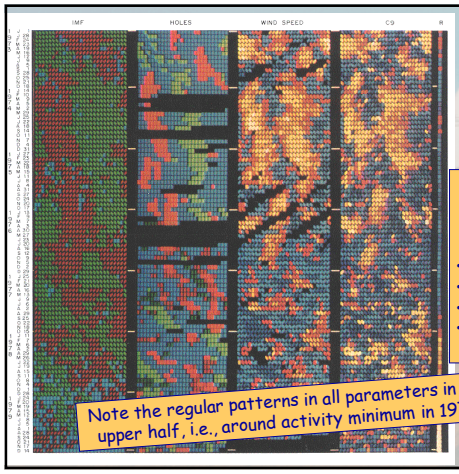
The solar wind stream structure, observed by the Helios and IMP spacecraft from activity minimum in 1975/76 onward.

Note: the cause of the recurring high speed streams is the **quiet Sun,** right before activity minimum

With increasing solar activity (in 1978), many transient events destroyed any regular solar wind structure



With increasing solar activity (in 1978, 2000), many transient events destroyed any regular solar wind structure

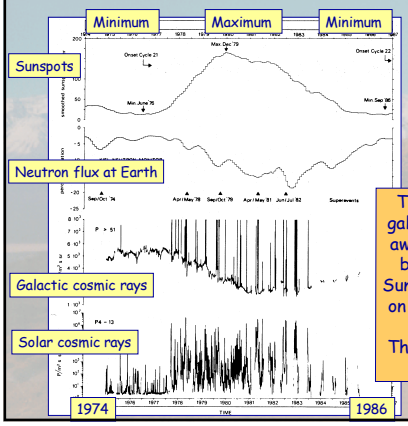


7 years of data, arranged by solar rotations:

- IP Magnetic field,
- Coronal holes,
- Solar wind speed,
- Geomagnetic index

Note the regular patterns in all parameters in the upper half, i.e., around activity minimum in 1975.

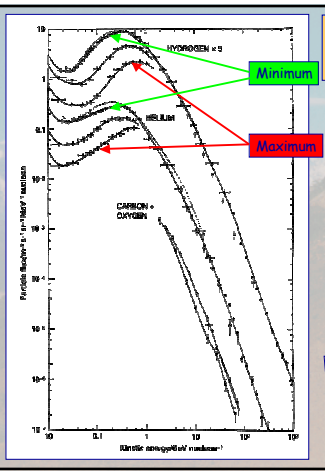
„Galactic Cosmic Radiation" through the solar cycle



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?**

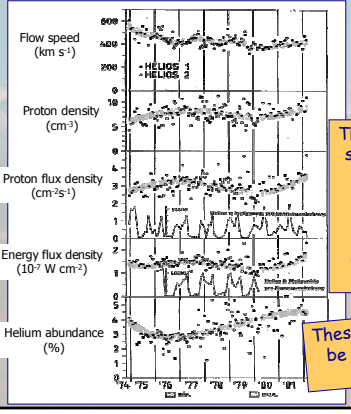
The modulation of GCR spectra



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

The question is: how does the solar wind accomplish such strong GCR modulation ?

The solar wind through the solar cycle

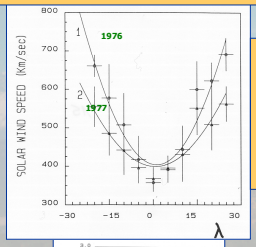


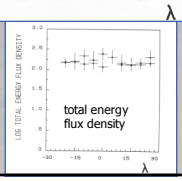
The solar cycle variation of solar wind parameters, as observed by the Helios solar probes.

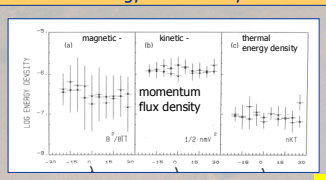
Each point denotes an average over a full solar rotation.

These variations appear not to be sufficient for producing GCR modulation !

Solar wind properties as functions of heliomagnetic latitude, observed by **Helios1/2** and **IMP**



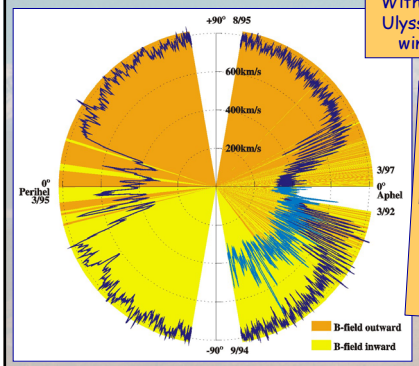




Note in particular:

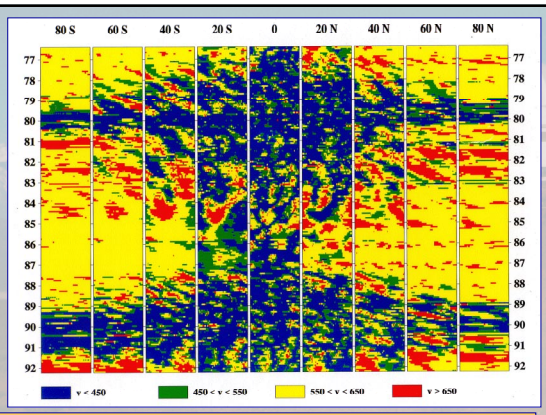
- the slow wind "belt" is only 30 deg wide,
- it is asymmetric w.r.t. the ecliptic,
- it widens with increasing activity,
- the momentum flux density is invariant,
- the total energy flux density is invariant

How does the Sun manage to modulate the GCR influx?



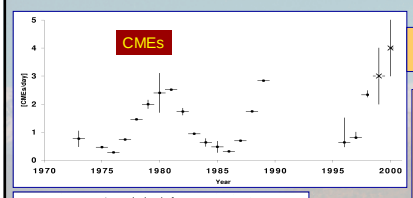
With increasing activity: Ulysses found slow solar wind at all latitudes!

In the ecliptic plane, the solar wind modulation is small, but at high latitudes it is substantial!
Note that the influx of GCRs from polar latitudes is much easier because of the more radial field lines (Not true any more!)

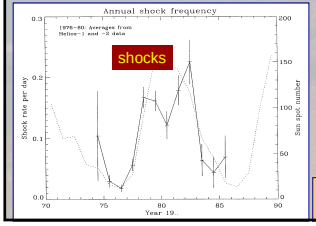


The model by Wang & Sheeley, to explain solar wind speeds in terms of their „field expansion factor" measured near the photosphere

CMEs and shocks during 2 solar cycles



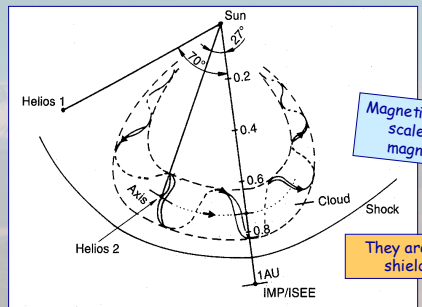
The daily rate of all CMEs



- Between minimum and maximum, the rates of both: shocks and CMEs vary by a factor of 10.
- The ratio between CME and shock rates is 10.
- There is a clear maximum of CME occurrence at maximum acticivty.
- The shock rate shows a double peak: maximum occurrence before and after the maximum.

The daily rate of shocks seen by an *in-situ* observer

Ejected plasma clouds in space



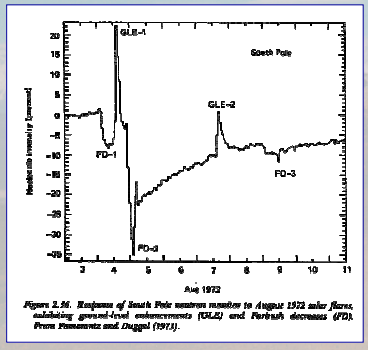
Magnetic clouds imply large-scale rotations of the magnetic field vector

They are rather effective in shielding off the GCRs!

Sketch showing the possible large-scale geometry of the MC observed by Helios 2 and IMP/ISEE in April 1979 (see Fig. 10) based on results of the MVA of the magnetic field data. Helios 1 did observe the shock, but not the MC. *Arrows* denote the orientation of the magnetic field lines at the cloud's outer boundaries and on its axis

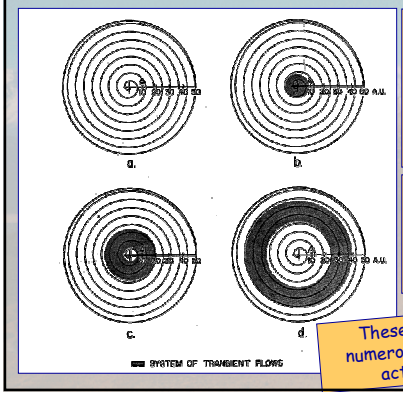
How does the Sun manage to modulate the GCR influx?

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



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

How does the Sun manage to modulate the GCR influx?

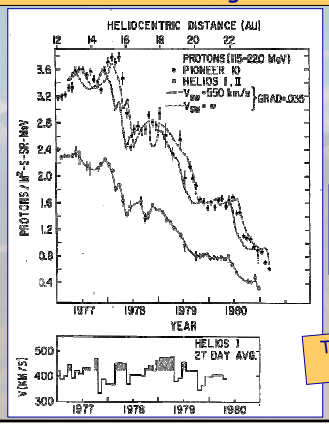


At very large distances from the Sun, the „merged Interaction Regions" (MIRs) and transient flows from CMEs (i.e. shocks and ejecta) form „global merged interaction regions" (GMIRs).

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

These shells are more numerous and efficient at activity maximum

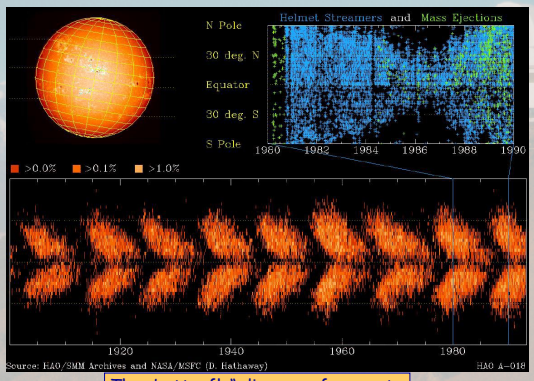
How does the Sun manage to modulate the GCR influx?



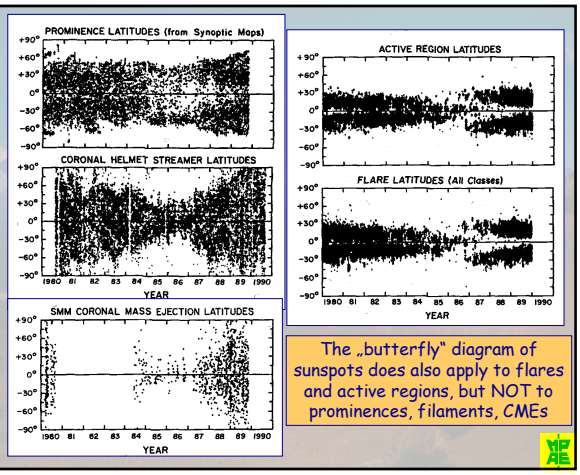
A sequence of global merged interaction regions caused a stepwise decrease in GCR flux.

That might explain the solar cycle modulation of GCRs.

Solar cycles and Earth's climate variations

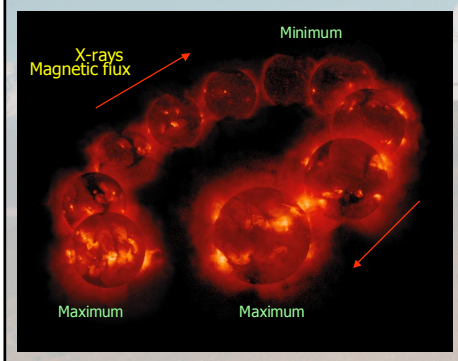


The „butterfly" diagram of sunspots



The „butterfly" diagram of sunspots does also apply to flares and active regions, but NOT to prominences, filaments, CMEs

The solar activity cycle, seen in X-rays



The short-wave radiation varies strongly through the activity cycle: from a factor 2 in the UV (<100 nm) up to a factor 100 in X-rays.

Solar spectral irradiance in the UV range

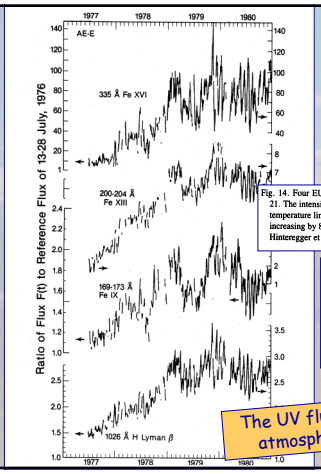
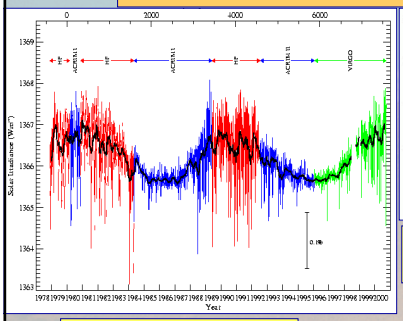


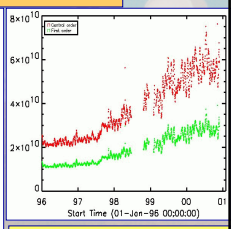
Fig. 14. Four EUV line irradiances from AE-E in the ascending phase and maximum of Cycle 21. The intensity scale is relative to the solar minimum spectrum (Fig. 13) and shows the high-temperature line of Fe XVI increasing by a factor of 100 from minimum to maximum, Fe XIII increasing by 8, Fe IX increasing by 2 and Lyman β by 3 (figure based on measurements from Hinteregger et al. 1981).

Note the strong solar cycle variation of the Sun's UV radiation:
The „hotter" the line, the stronger the modulation

The UV flux heats the Earth's outer atmosphere and lets it „breath"!

Solar irradiance measurements - the Sun as a star



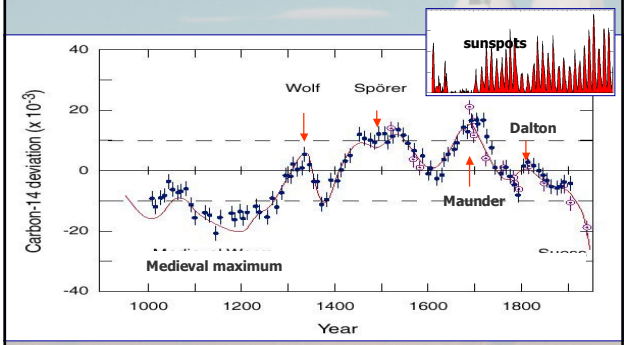


SEM (CELIAS): EUV disk integrated flux from 1-500Å and in 260-340 Å (He II 304 Å)

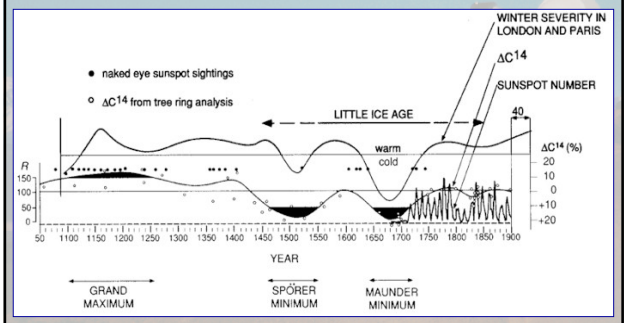
VIRGO - Total solar irradiance

Note: the UV flux varies by factors, rather than by per mille!

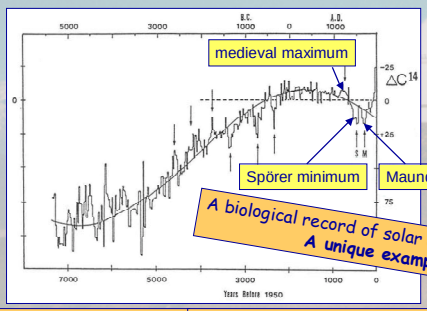
Solar activity from ^{14}C data



Solar cycles and Earth's climate variations



Solar activity, cosmic rays, and tree rings

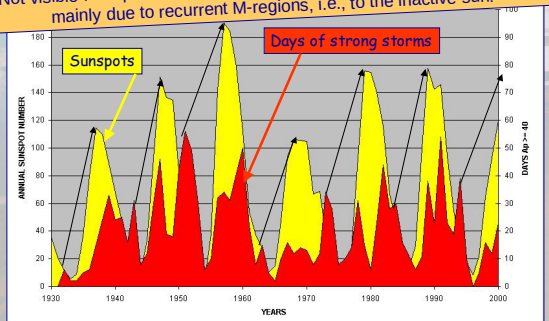


A biological record of solar activity history.
A unique example!

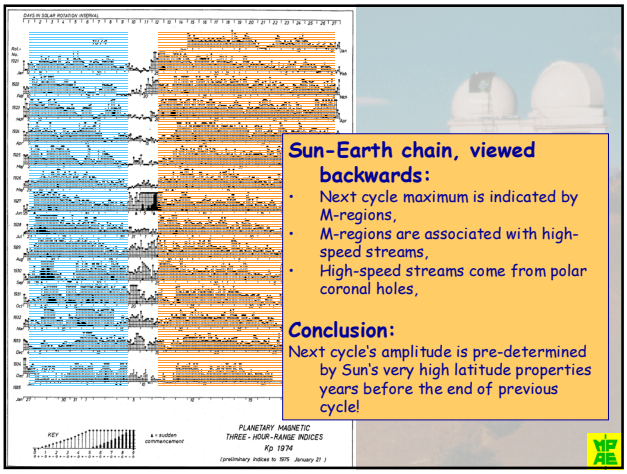
High solar activity causes:
- better shielding of heliosphere against GCRs,
- lower fluxes of GCRs on Earth's atmosphere,
- less production of ^{14}C isotopes in atmosphere,
- less ^{14}C inclusion in tree rings.

Solar cycles and Earth's climate variations

Not visible from plots like this one and often ignored: the second peak is mainly due to recurrent M-regions, i.e., to the inactive sun!



The second peak in the storm occurrence allows to predict next cycle's maximum activity!



Sun-Earth chain, viewed backwards:

- Next cycle maximum is indicated by M-regions,
- M-regions are associated with high-speed streams,
- High-speed streams come from polar coronal holes,

Conclusion:
Next cycle's amplitude is pre-determined by Sun's very high latitude properties years before the end of previous cycle!

Overlap of solar cycles

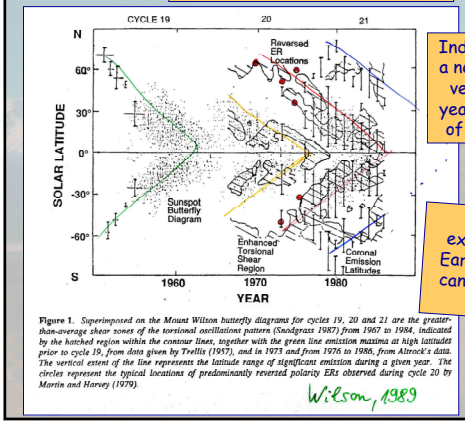


Figure 1. *Superimposed on the Mount Wilson butterfly diagrams for cycles 19, 20 and 21 are the greater-than-average shear zones of the torsional oscillations pattern (Snodgrass 1987) from 1967 to 1984, indicated by the hatched region within the contour lines, together with the green line emission maxima at high latitudes prior to cycle 19, from data given by Trellis (1957), and in 1973 and from 1976 to 1986, from Altrock's data. The vertical extent of the line represents the latitude range of significant emission during a given year. The circles represent the typical locations of predominantly reversed polarity ERs observed during cycle 20 by Martin and Harvey (1979).*

Wilson, 1989

Indeed, first signs of a new cycle appear at very high latitudes years before the end of the previous one!

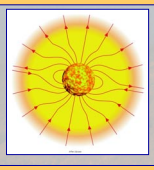
Another nice example for what Earth observations can teach us about the Sun!

Variations in the solar magnetic flux

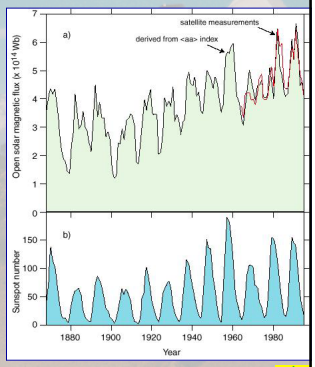
The solar magnetic flux has increased by a factor of 2.3 since 1901

The estimated long term changes in TSI alone can account for:

- 52% of the temperature rise between 1910-1960
- 31% of the rise since 1970

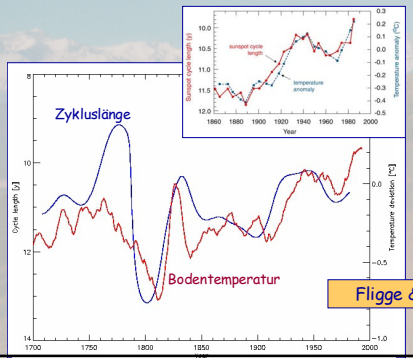


Do GCRs cause increased cloud formation by providing condensation nuclei?



Solar cycle length and temperature on Earth,

A surprising correlation!



Friis-Christensen & Lassen (1991)

Fligge & Solanki (2001)

Clouds on Earth and GCRs

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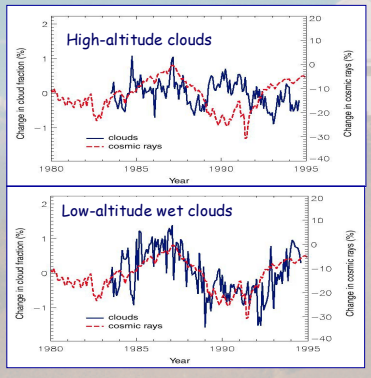
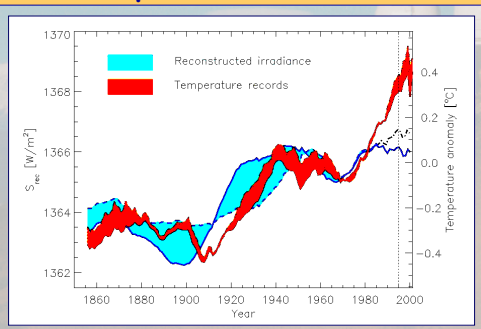


Variations of solar irradiance and temperatures on Earth



Note: from 1980 on another effect takes over: the man-made greenhouse effect!

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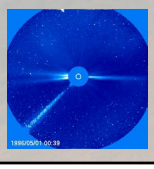

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