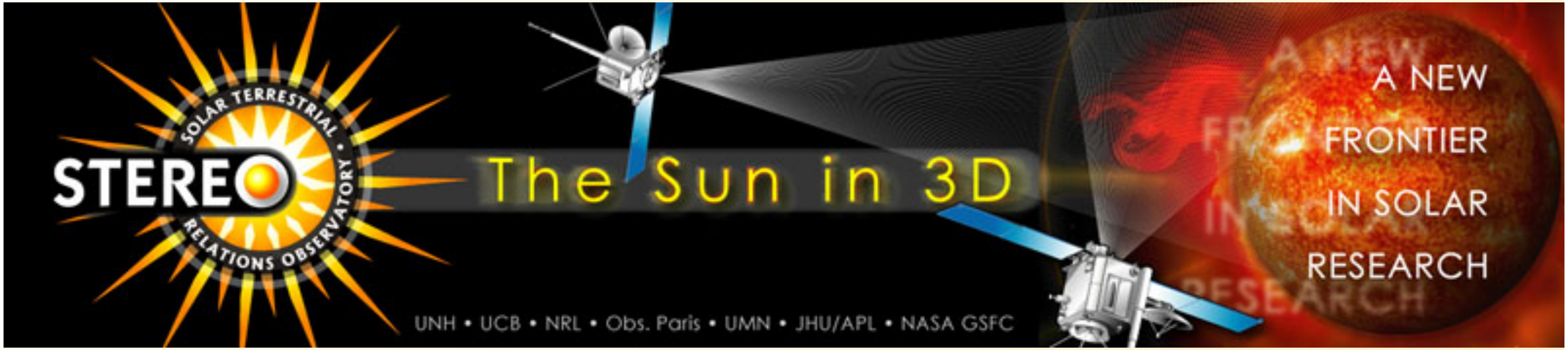
Solar energetic particles



B. Heber[1], N. Dresing[1], R. Gomez-Herrero[1], A Klassen[1], R. Müller-Mellin[1], and W. Dröge[2]
[1]Christian-Albrechts-Universität, Kiel, Germany
[2]Universität Würzburg, Germany

Outline

- **The Sun and the solar cycle**
- The Sun as a Particle Accelerator
  - Photons and Neutrons
  - Flares: Solar Energetic Particles
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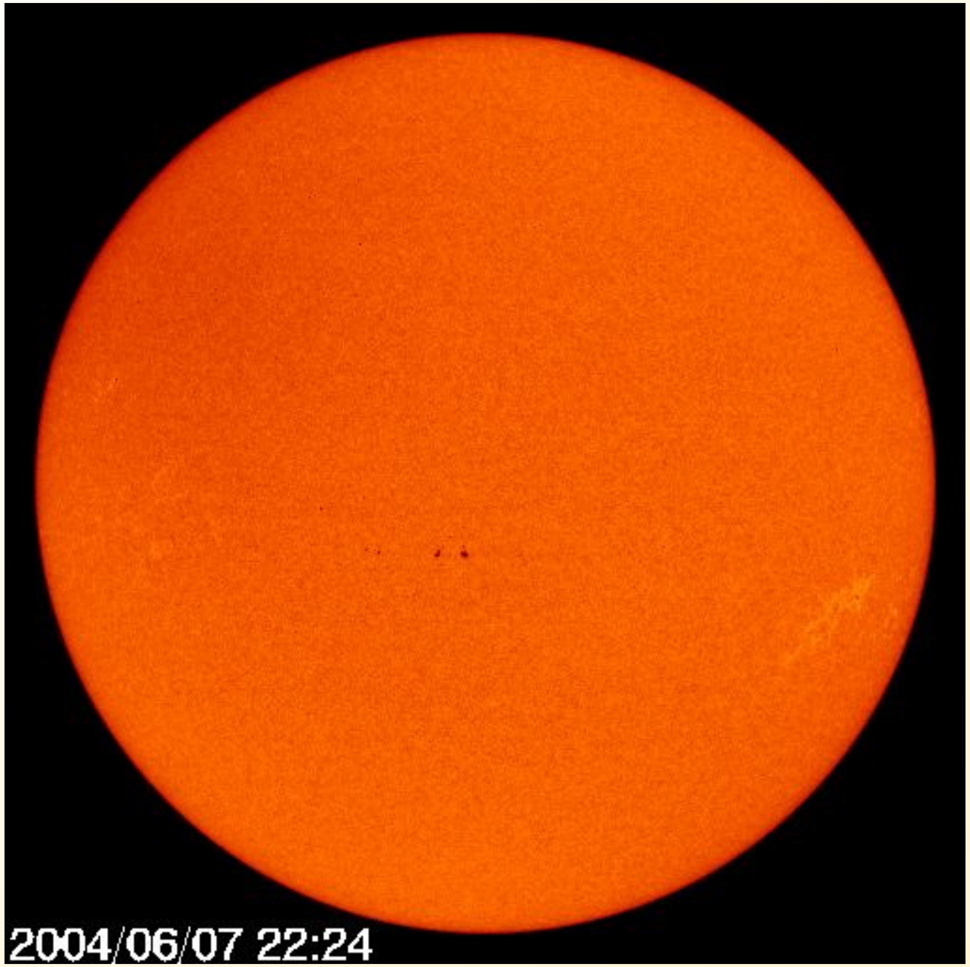
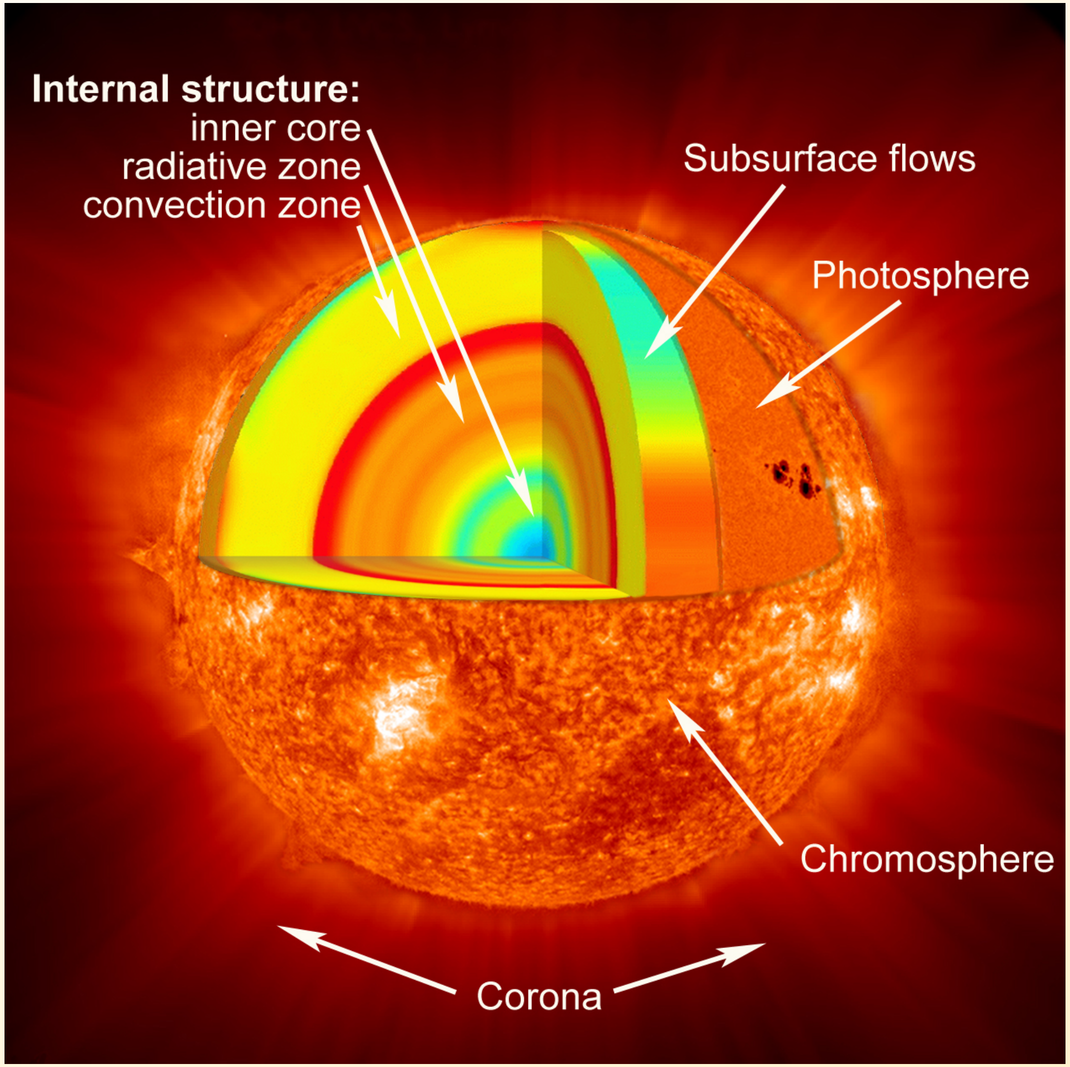
Some Facts about the Sun



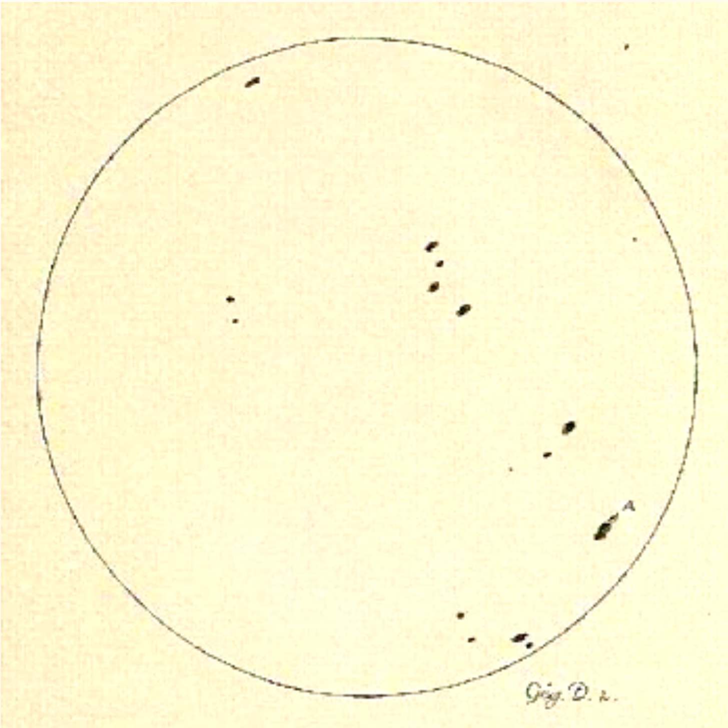
SOHO / ESA

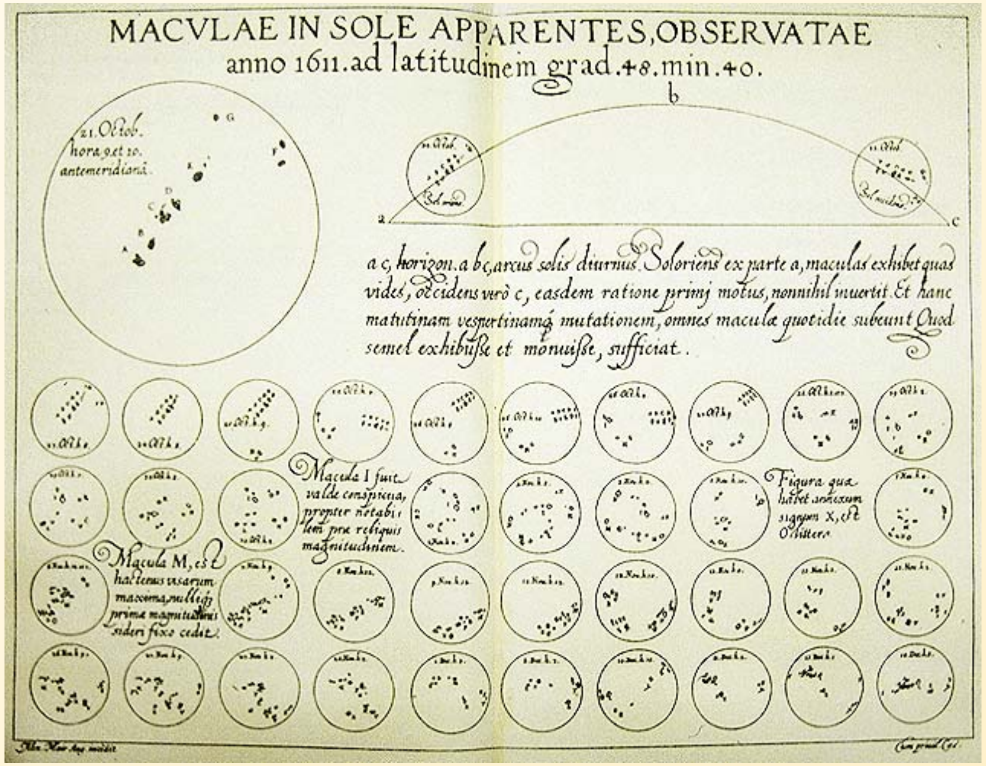
Mass (kg)	$1.989\ 10^{30}$
Mass (Earth = 1)	332830
Radius (km)	695000
Radius (Earth = 1)	108.97
Density (g/cm^3)	1.410
Rotation period (days)	25 – 36
Escape velocity (km/sec)	618.02
Luminosity (W)	$3.827 10^{26}$
at 1AU	1.3 kW/m^2
Mean Temperature at the surface:	5800° K
Corona:	1 - 2x10^6 K
Age (billion years)	4.5
Distance Sun-Earth (km)	150x10^6

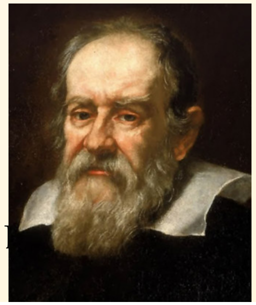
The interior of the Sun



Discovery of the Sunspots







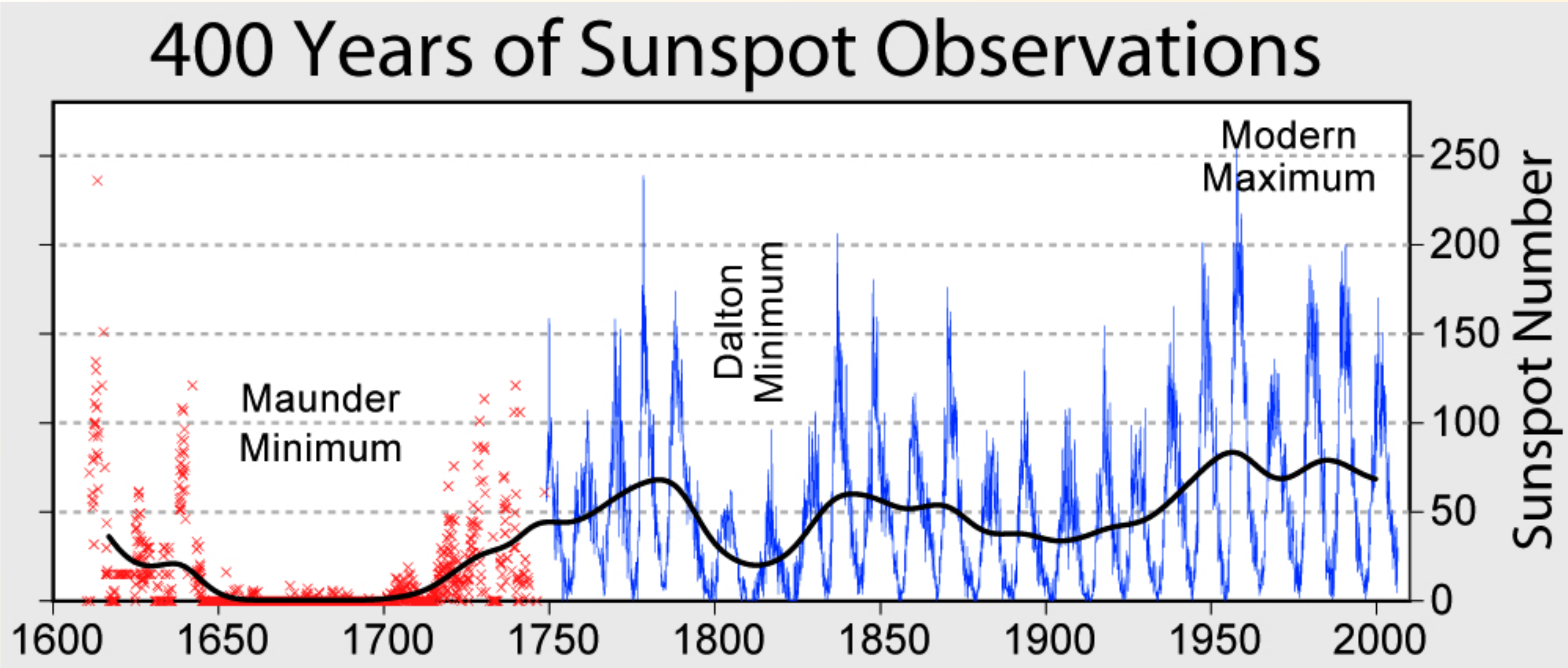
Galileo Galilei

Florenz

Christoph Scheiner

Ingolstadt / Donau

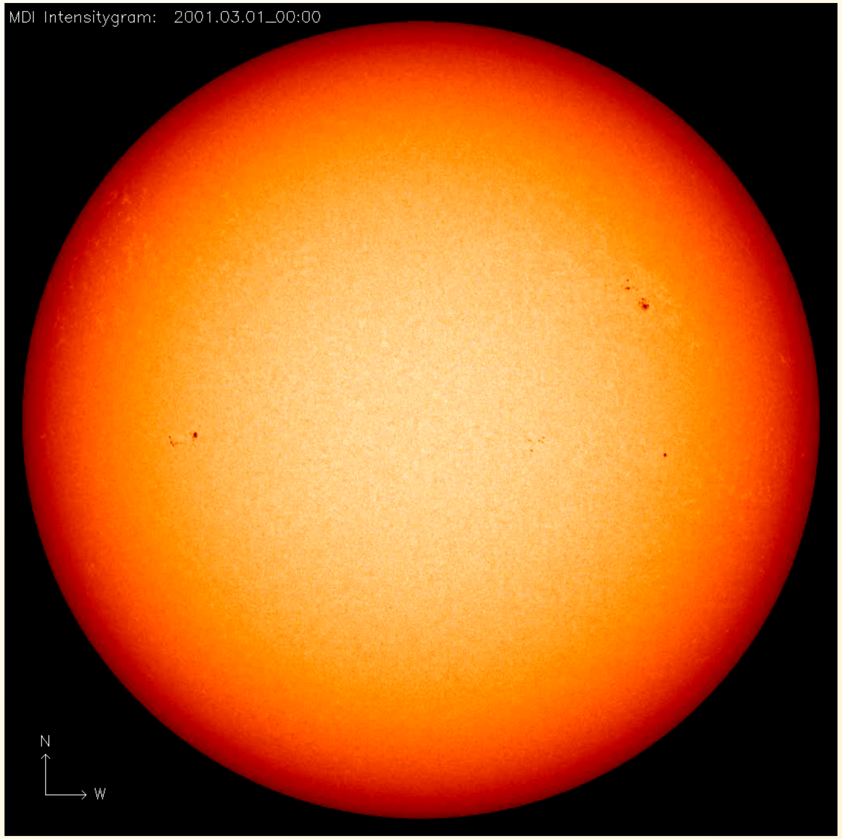
Solar variability in Sunspot numbers



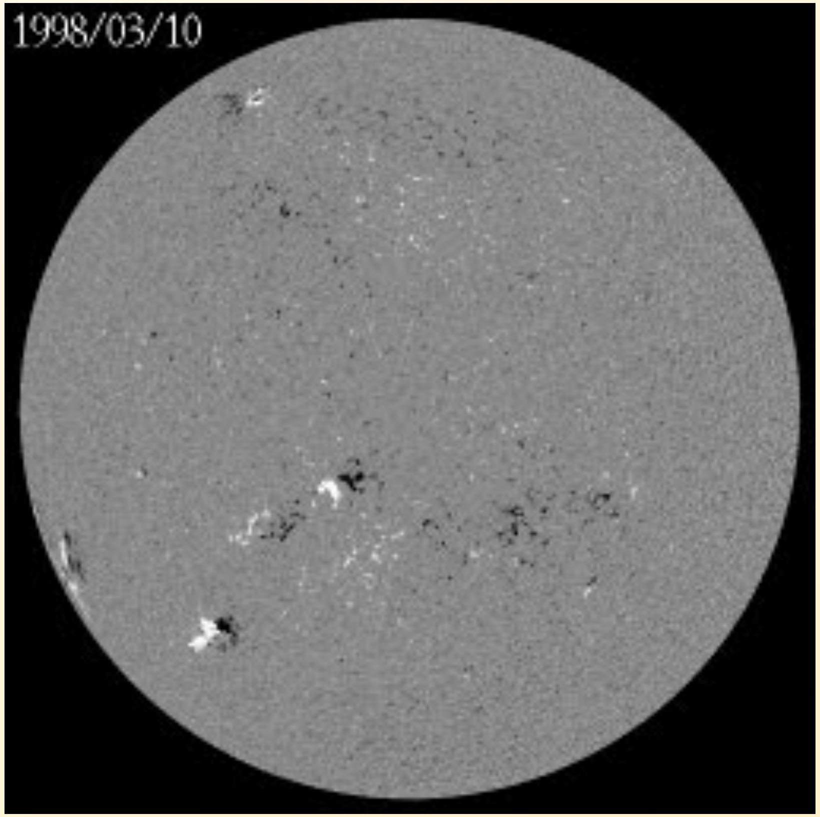
PHOTOSPHERE - CHROMOSPHERE - CORONA

Photosphere

A magnetized Star



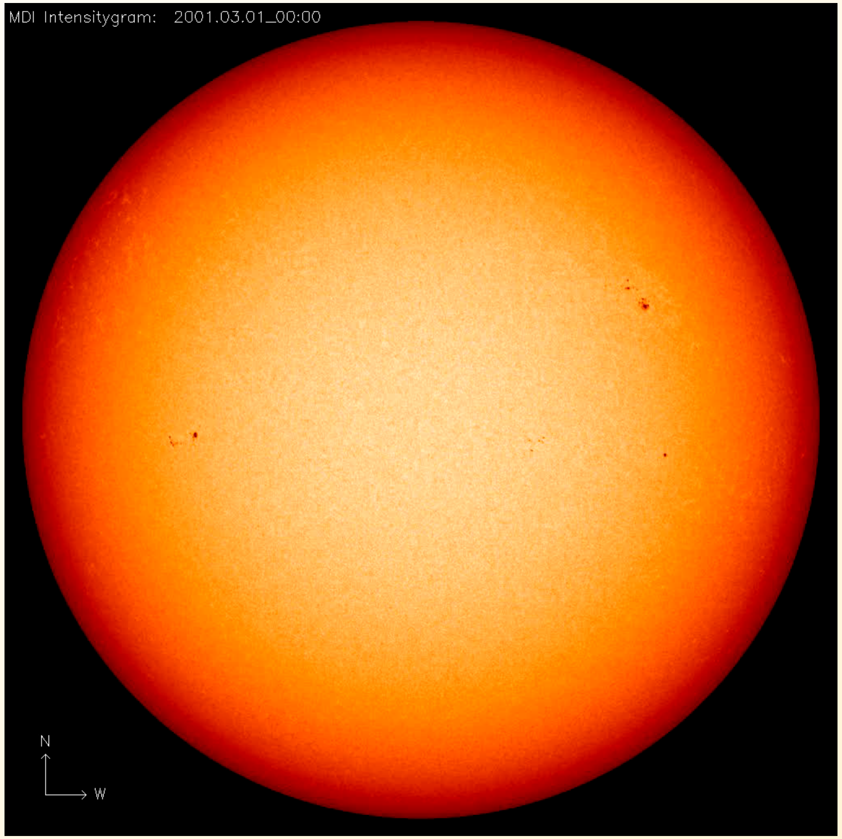
SOHO / ESA



SOHO / ESA

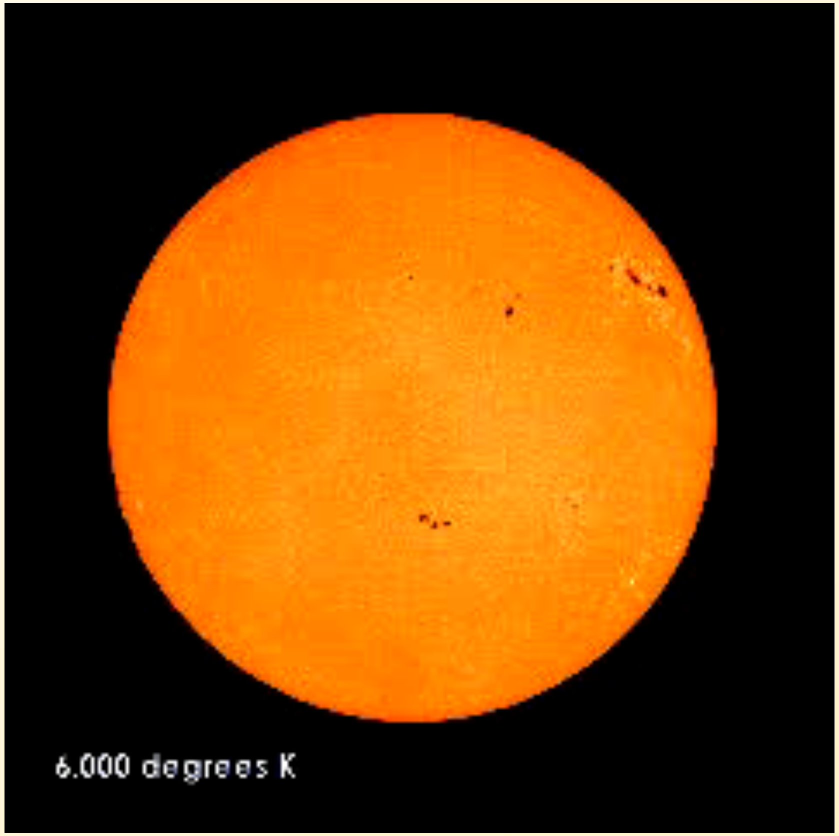
PHOTOSPHERE - CHROMOSPHERE - CORONA

Photosphere



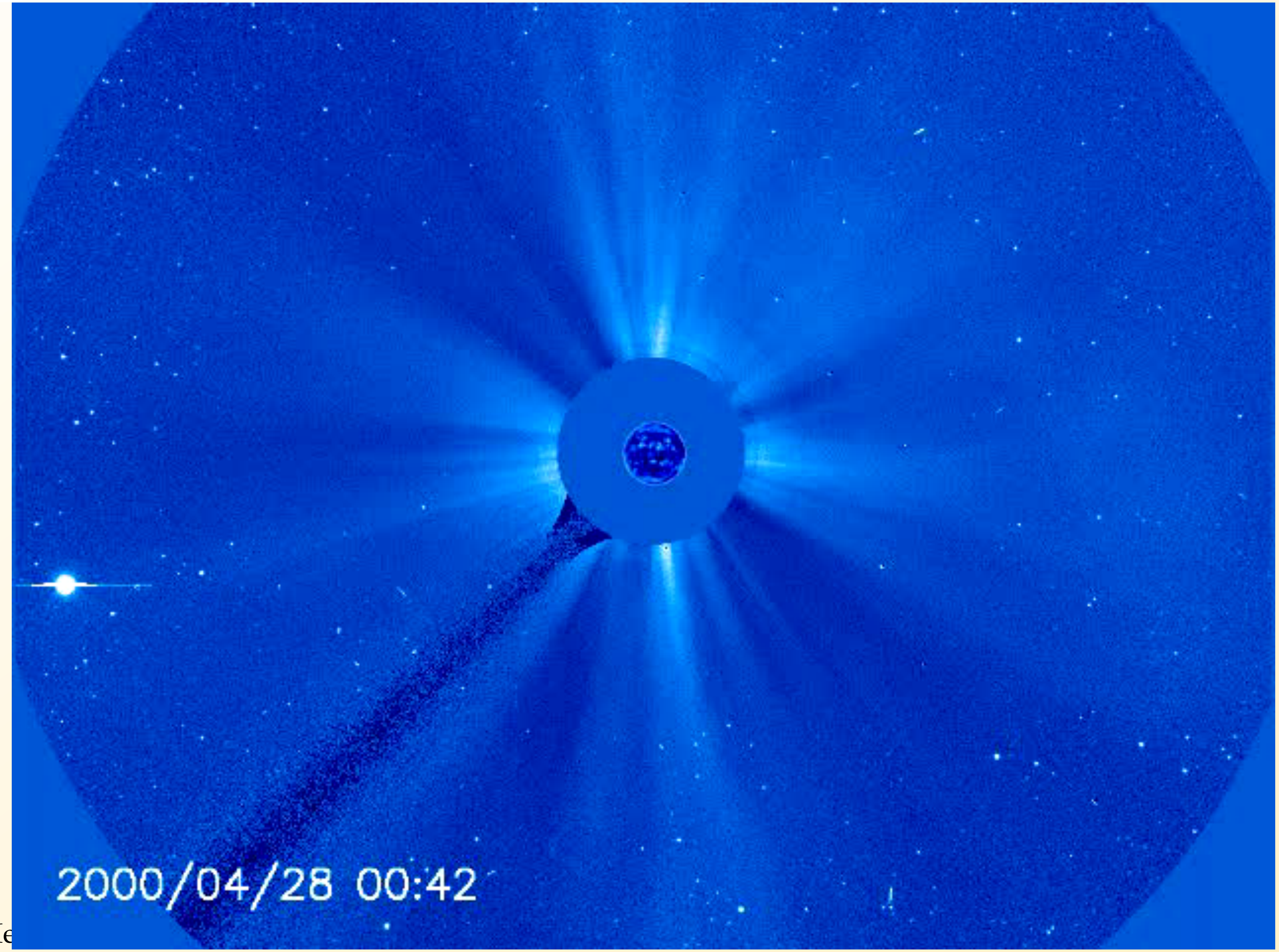
SOHO / ESA

Chromosphere and Corona



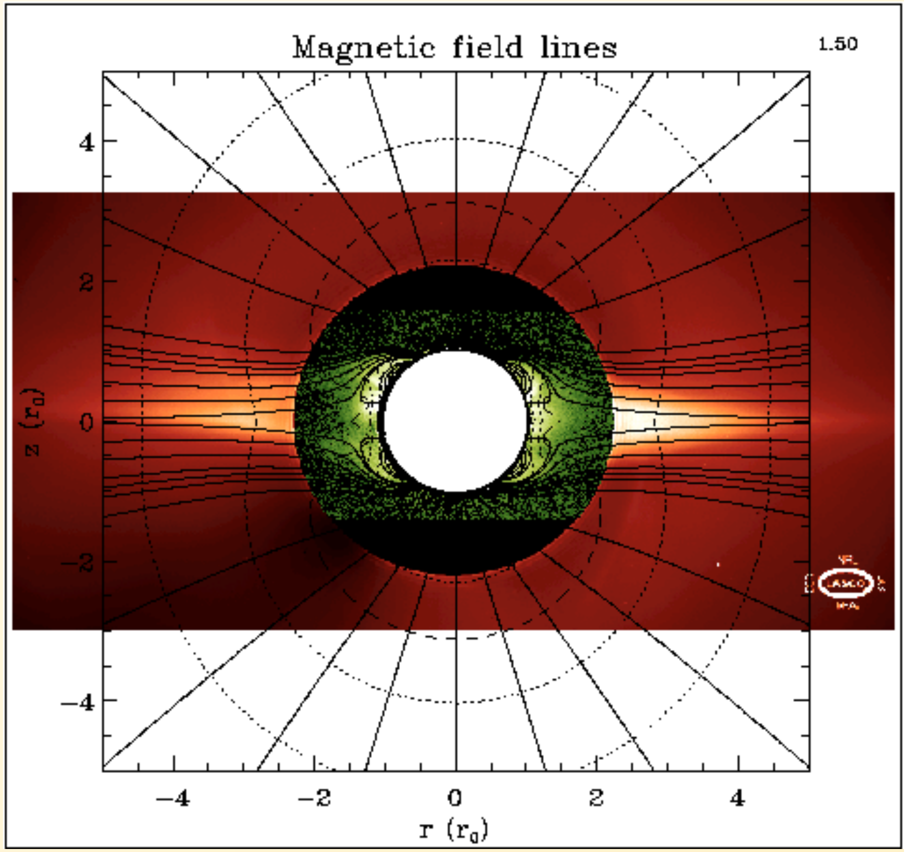
SOHO / ESA

The expansion of the solar atmosphere – the solar wind (Biermann, Parker,...)



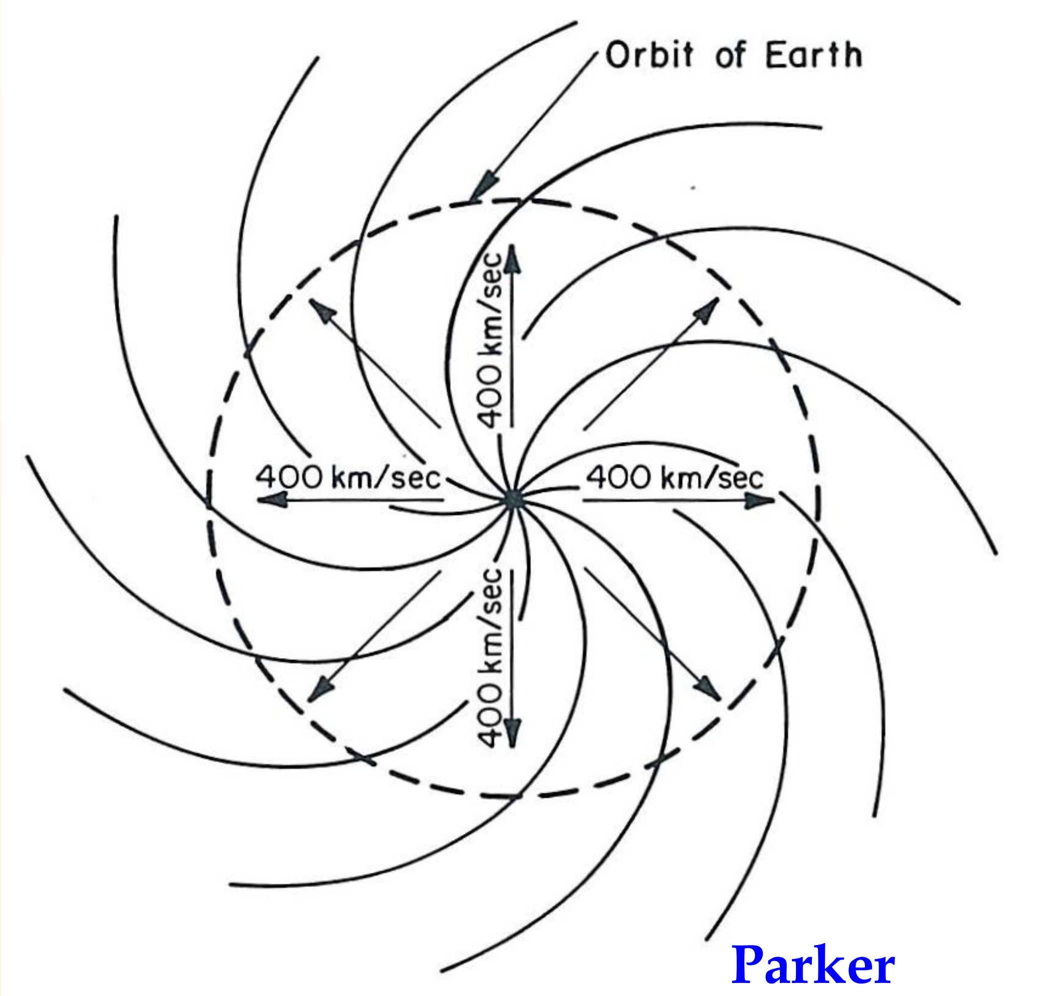
The heliospheric magnetic field

- The heliospheric magnetic field is a result of the Sun's magnetic field being carried outward, frozen in to the solar wind.
- Within the corona, the magnetic field forces dominate the plasma forces.
- As the field strength decreases with distance, beyond the Alfvén radius at a few solar radii, the plasma flow becomes dominant, and the field lines are constrained to move with the solar wind.



The Parker Spiral Field

- The solar magnetic field is frozen in to the radial outflowing solar wind. Thus, due to the Sun's rotation, the magnetic field lines adopt an Archimedean spiral configuration.
- The angle to the radial direction of the magnetic field depends on distance, latitude and the local solar wind velocity.



Parker (1963)

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The Sun as a Particle Accelerator: Energetic photons and neutrons

- Detection of energetic protons from the Sun with ground based neutron monitors (~1942) in association with solar flares.
- Observations of the Sun as a radio emitter since ~ 1942: (Hey, 1942;1946)
- emission from energetic electrons (> 10 keV) , noise storms(1950)
- The Sun predicted to be γ-ray emitter in the late 60's (Lingenfelter, Ramaty and co-workers)

The Sun as a Particle Accelerator: Energetic photons and neutrons

- First detection of solar γ-ray line spectrum in 1972 (OSO-7 and Prognoz)

- First detection of neutrons > 100 MeV by SMM/ GRS in 1980 (Chupp et al, 1982) and first detection by ground level monitors of primary > 200 MeV solar neutrons in 1982 (Debrunner et al, 1983) (since then ~15 neutron events observed)

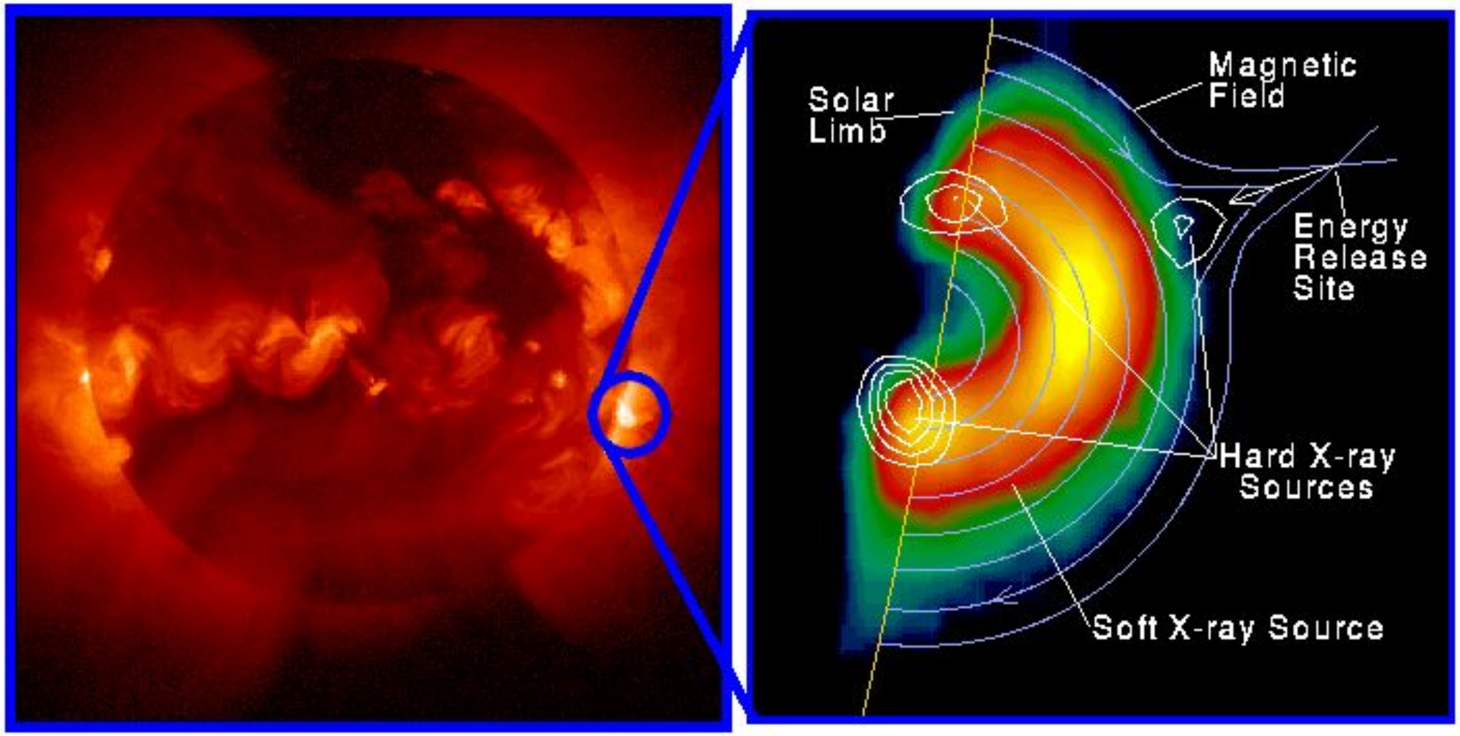
THE ACTIVE SUN
Flares

TRACE / NASA

Solar Flare

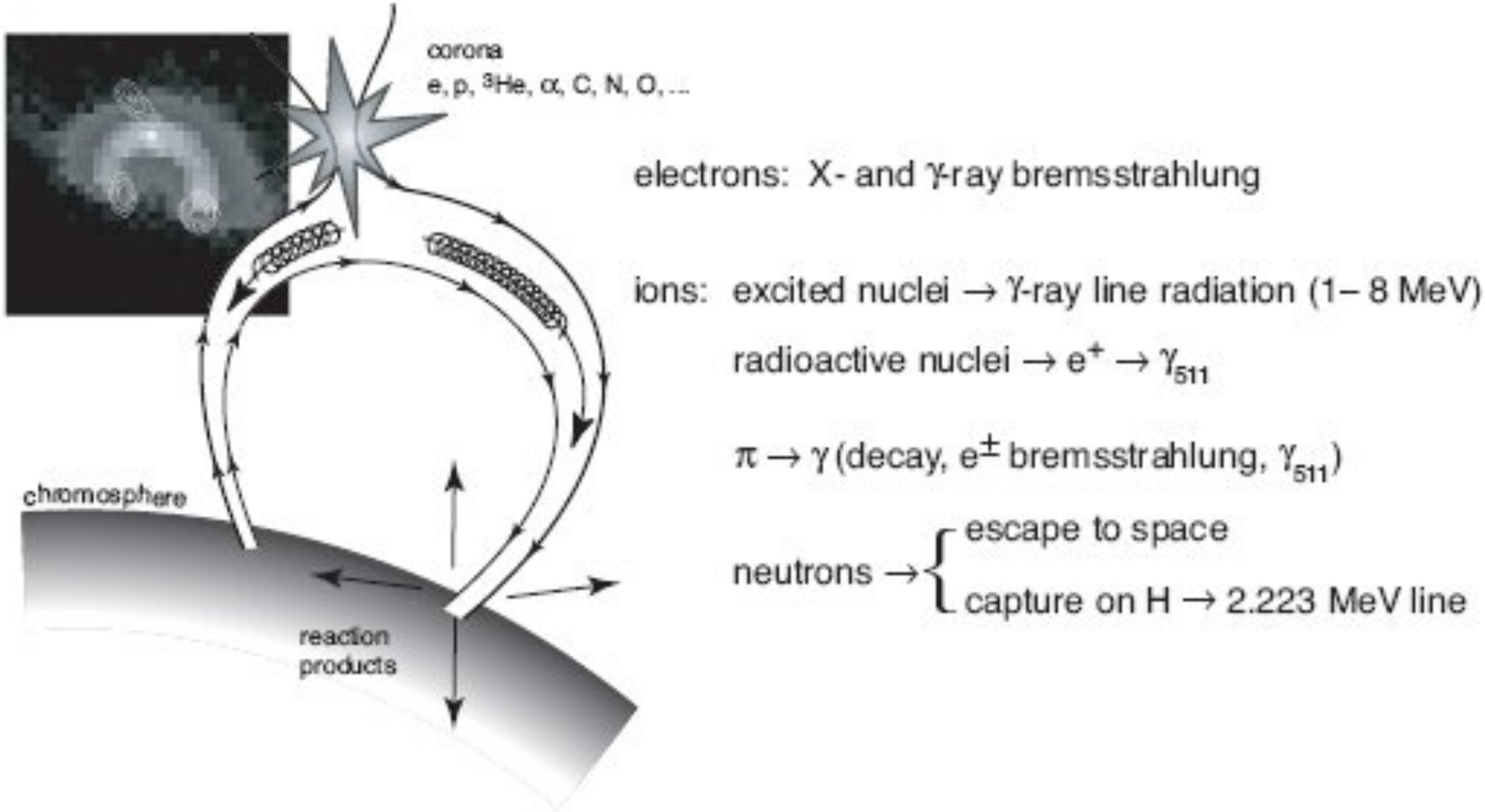
Energy: ~ 10^{25} Ws

The Sun as a Particle Accelerator: Energetic photons and neutrons

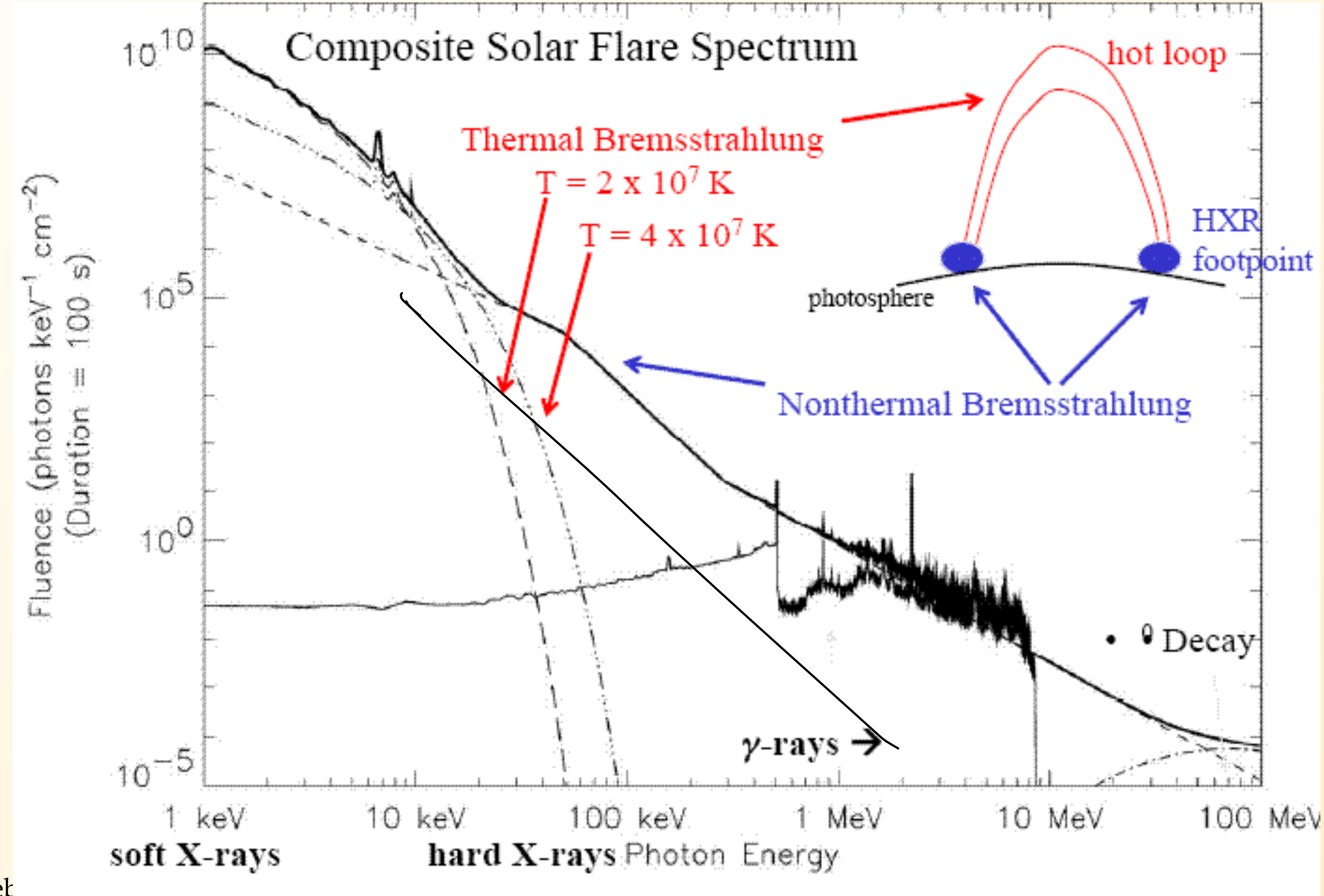


Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.

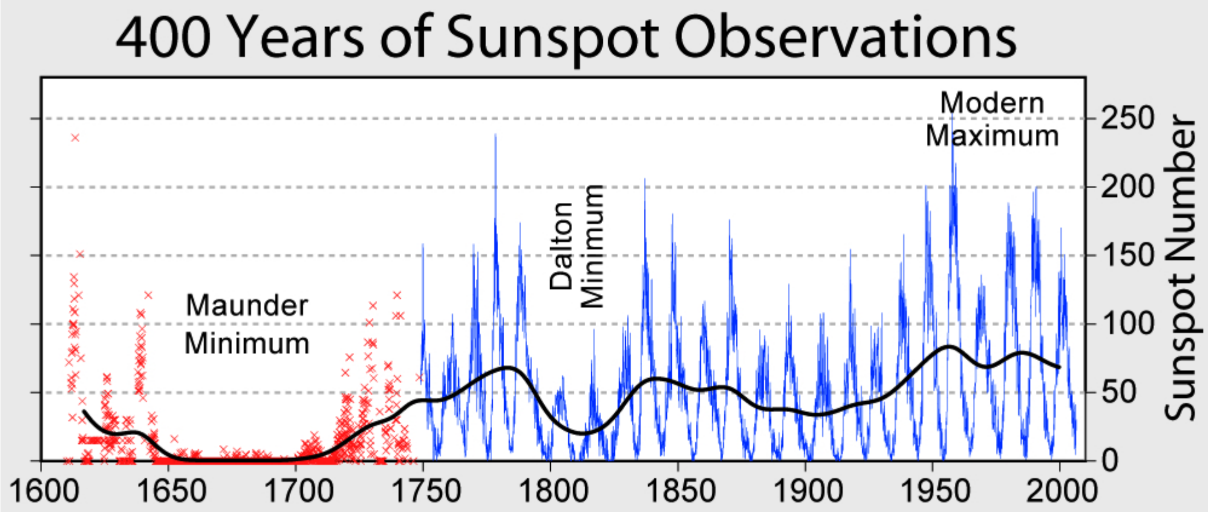
The Sun as a Particle Accelerator: Energetic photons and neutrons

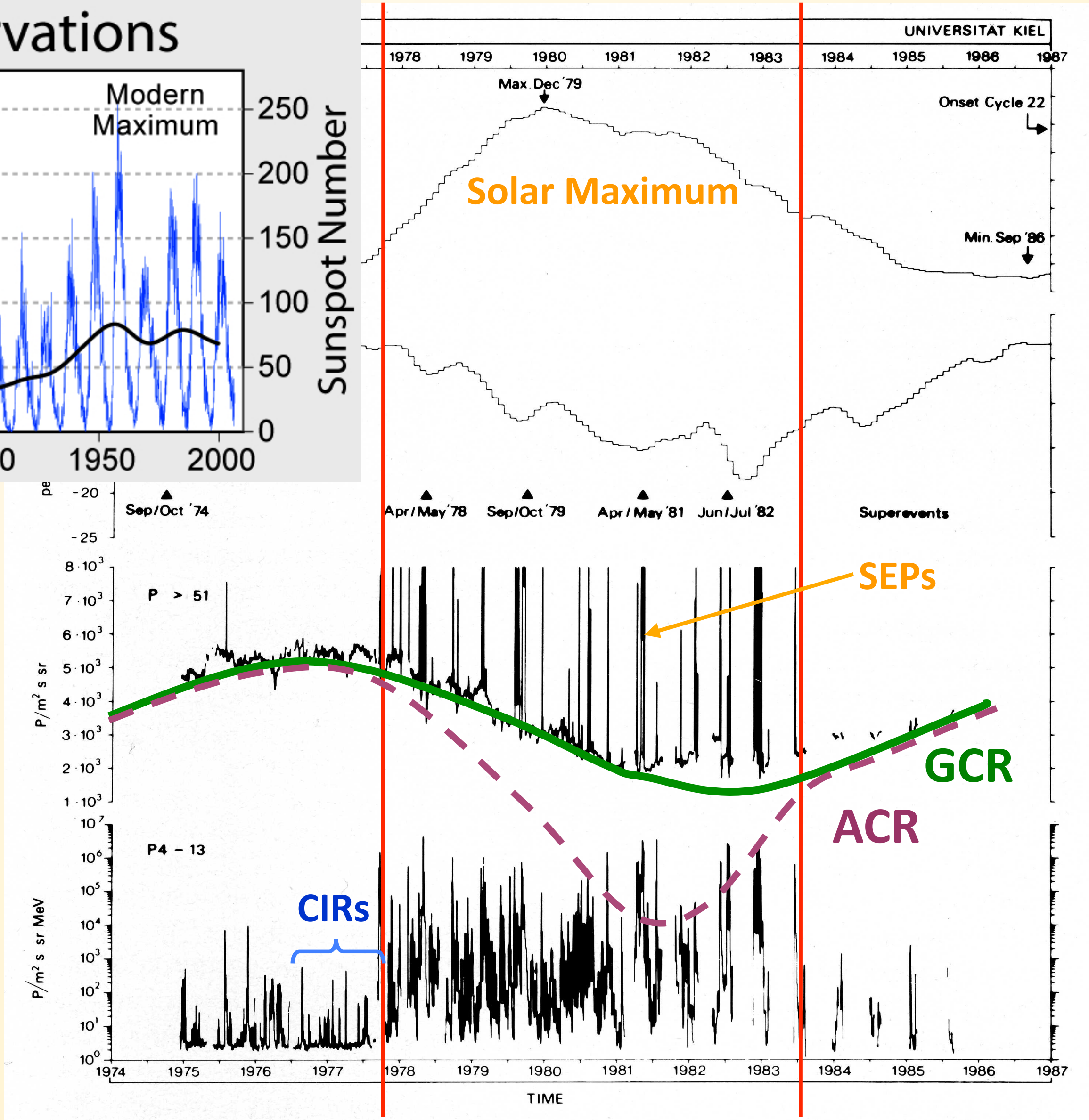


The Sun as a Particle Accelerator: Energetic photons



Solar variability in Sunspot numbers, and in Cosmic Rays





Consequences:

Modulation of Galactic and Anomalous Cosmic Rays

Solar Energetic ParticleEvents (SEPs)

B. Heber

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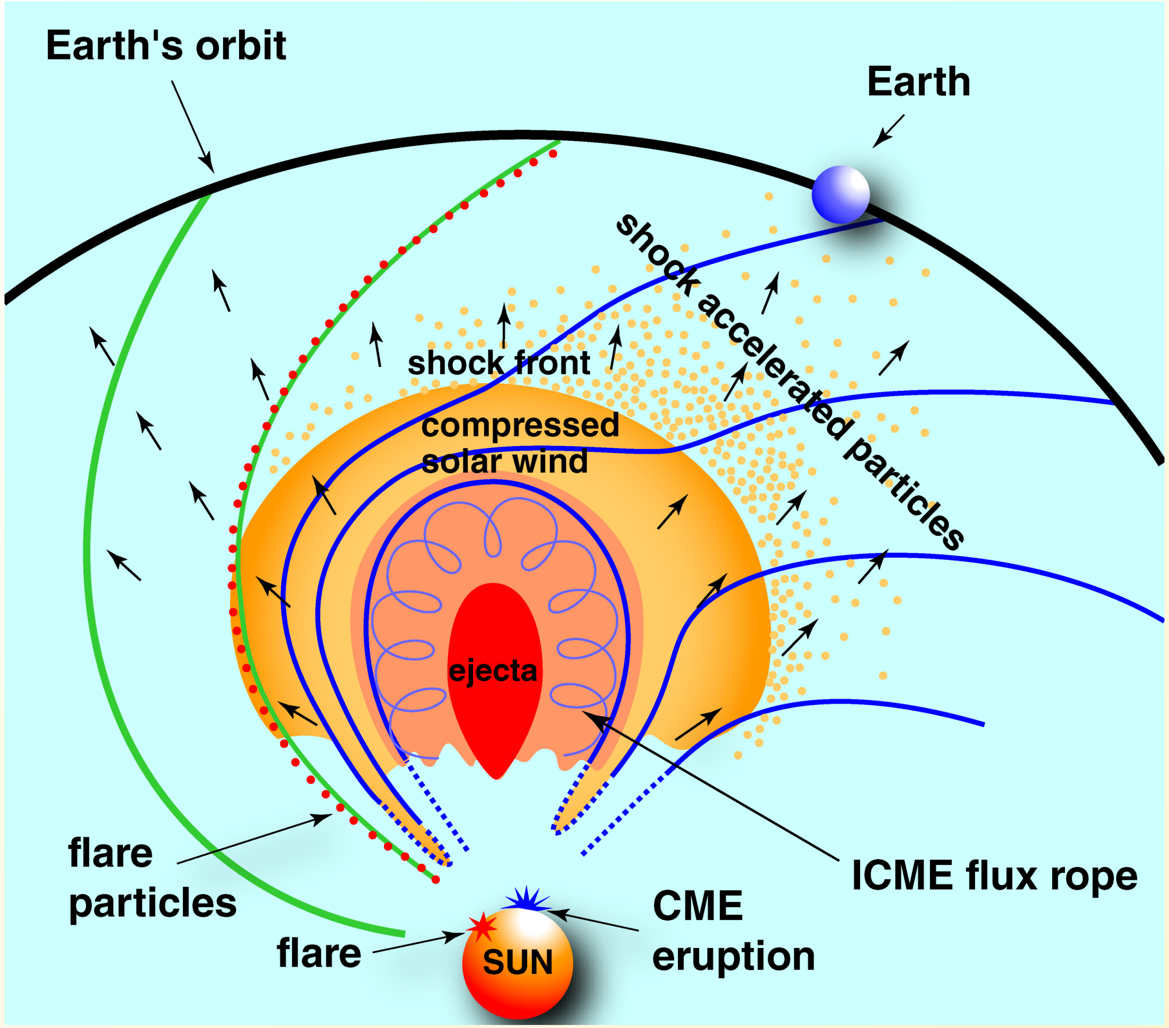
Solar Energetic Particles (SEPs)

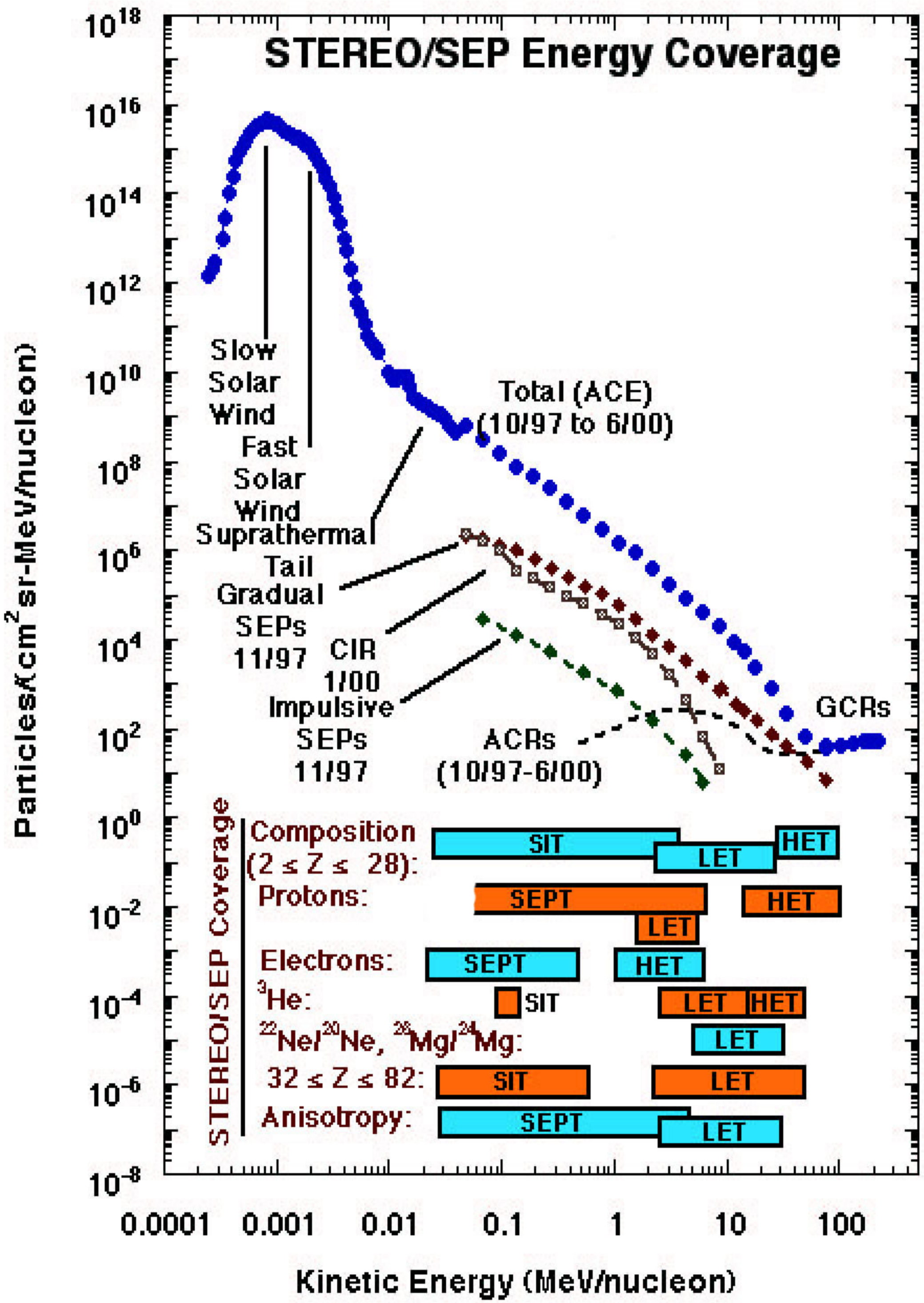


Impulsive Events (Flares):

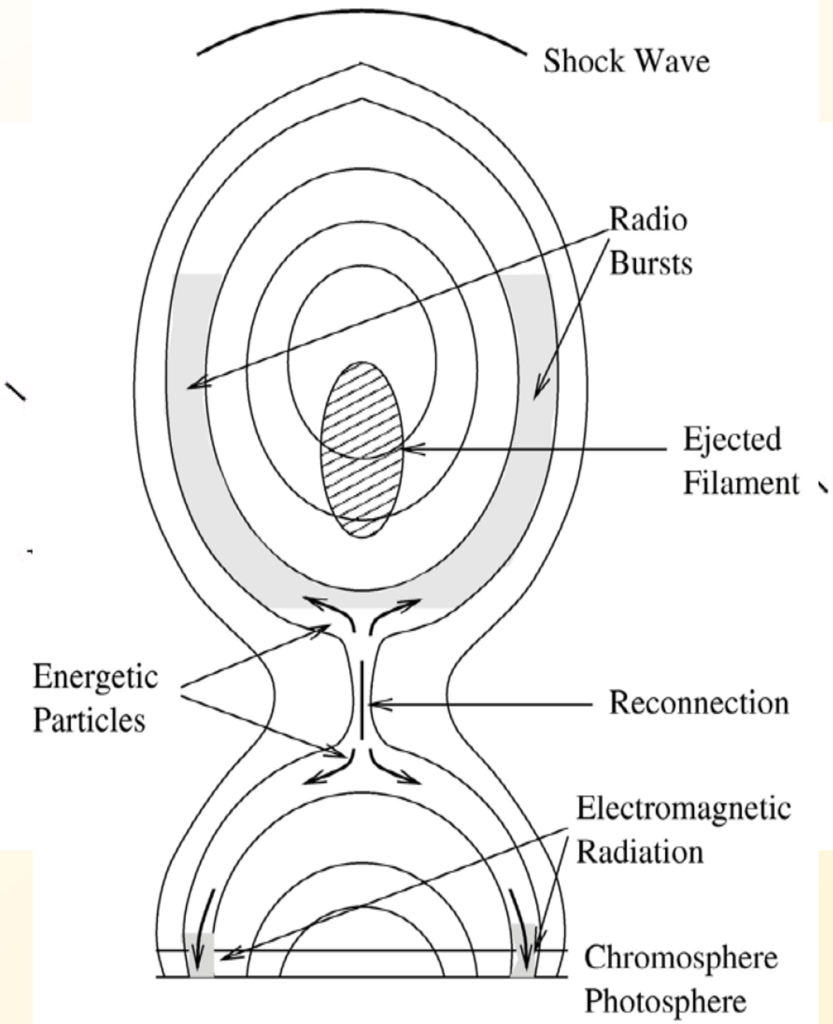
Particles are restricted to a small longitudinal range; (relative) low Intensities and energies

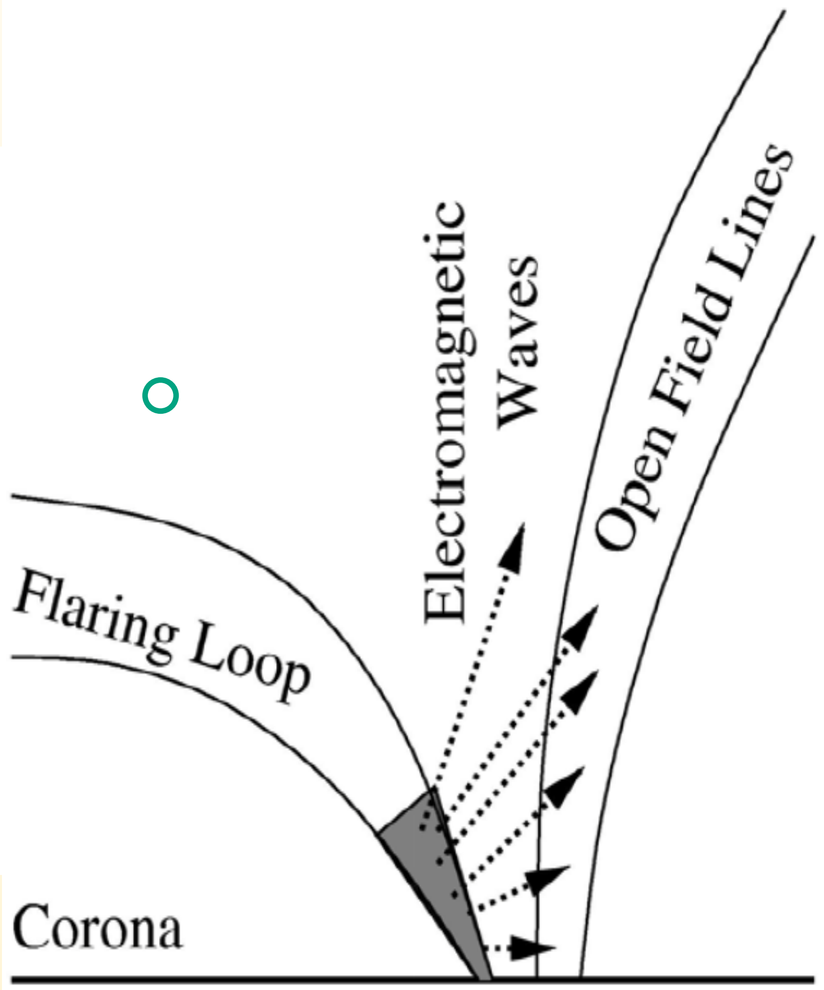
Composition: **H, ^{3}He, ^{4}He, C, N, O, Ne, Mg, Si, Fe**

Charge states: High (e.g.. Fe^{+20}; Source < 1 R_S


STEREO/SEP Energy Coverage
Particles/(cm² sr-MeV/nucleon)
Kinetic Energy (MeV/nucleon)
Slow Solar Wind
Fast Solar Wind
Suprathermal Tail
Gradual SEPs 11/97
CIR 1/00
Impulsive SEPs 11/97
Total (ACE) (10/97 to 6/00)
ACRs (10/97-6/00)
GCRs
STEREO/SEP Coverage
Composition (2 ≤ Z ≤ 28):
Protons:
Electrons:
3He:
22Ne/20Ne, 26Mg/24Mg:
32 ≤ Z ≤ 82:
Anisotropy:
SIT
LET
HET
SEPT

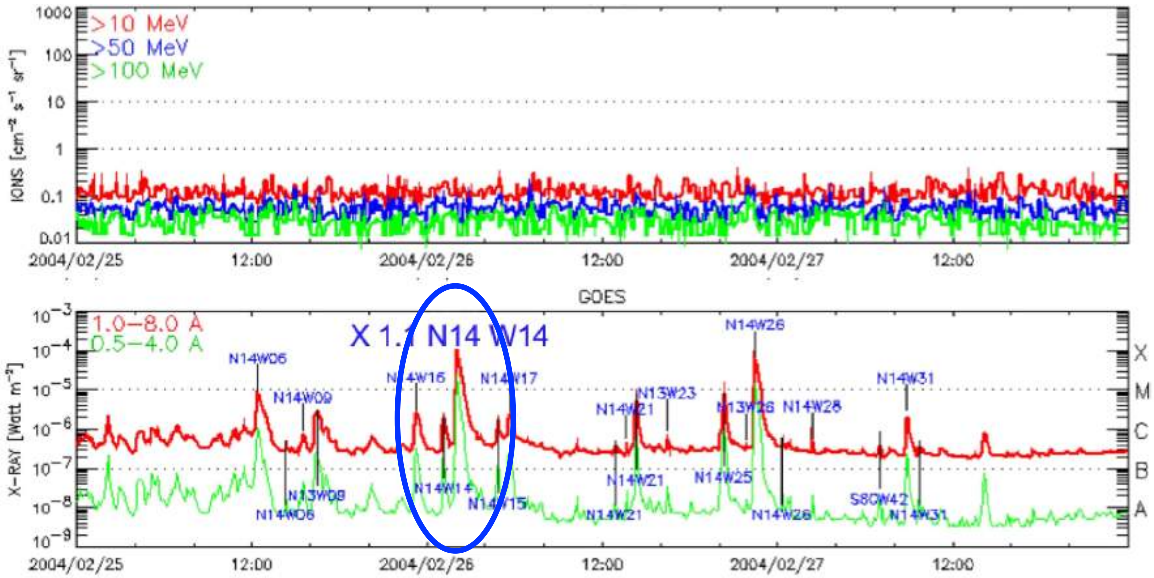
Flares and SEP: the role of magnetic confinement (Klein et al., 634)

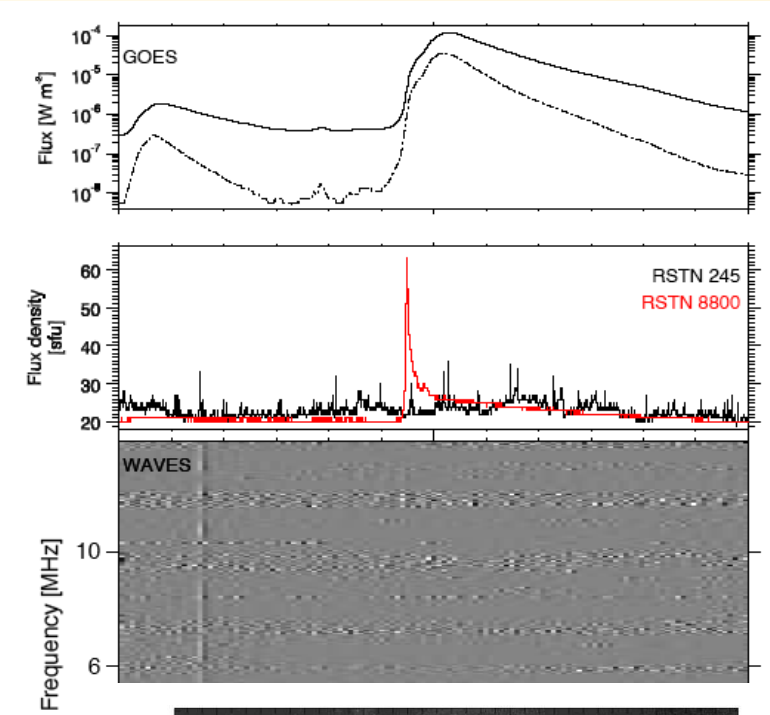


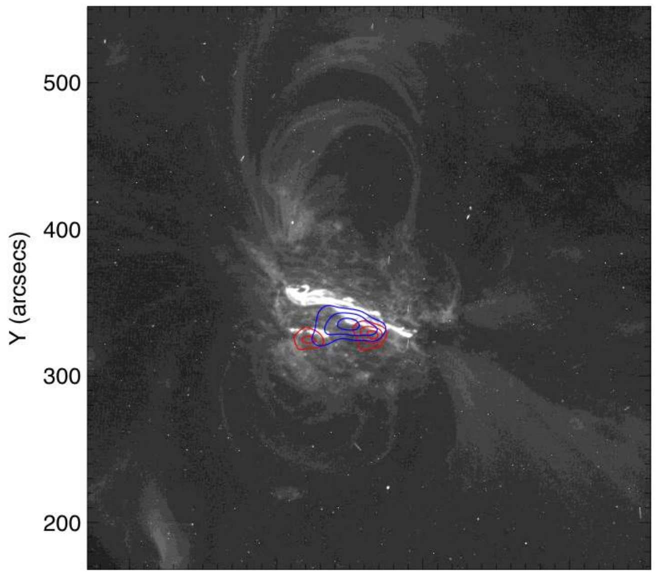


***Reames, Space Sci. Rev., 90*, 413, 1999**

Flares and SEP: the role of magnetic confinement (Klein et al., 634)





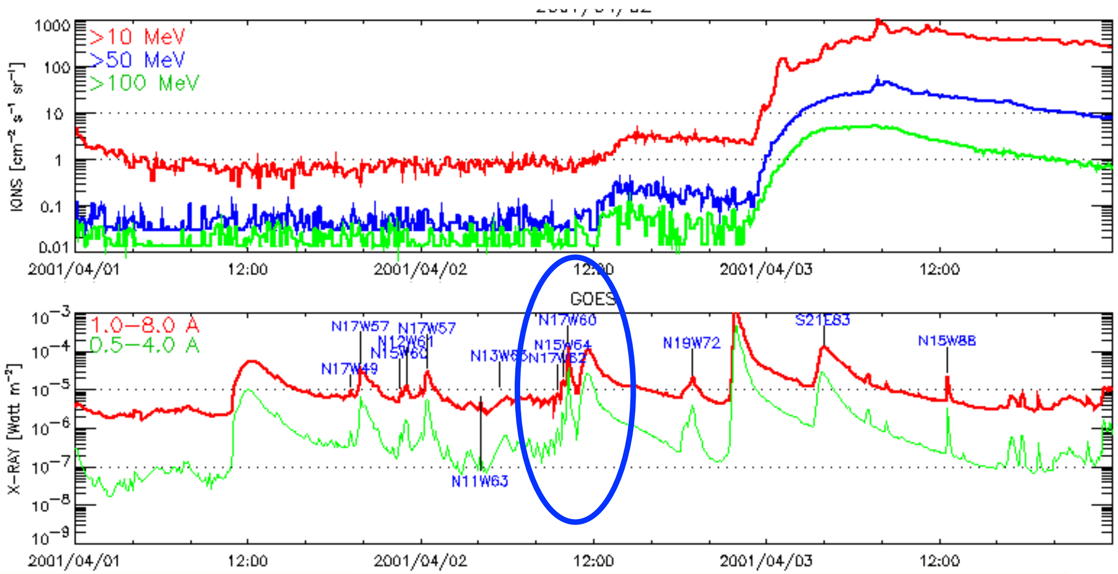


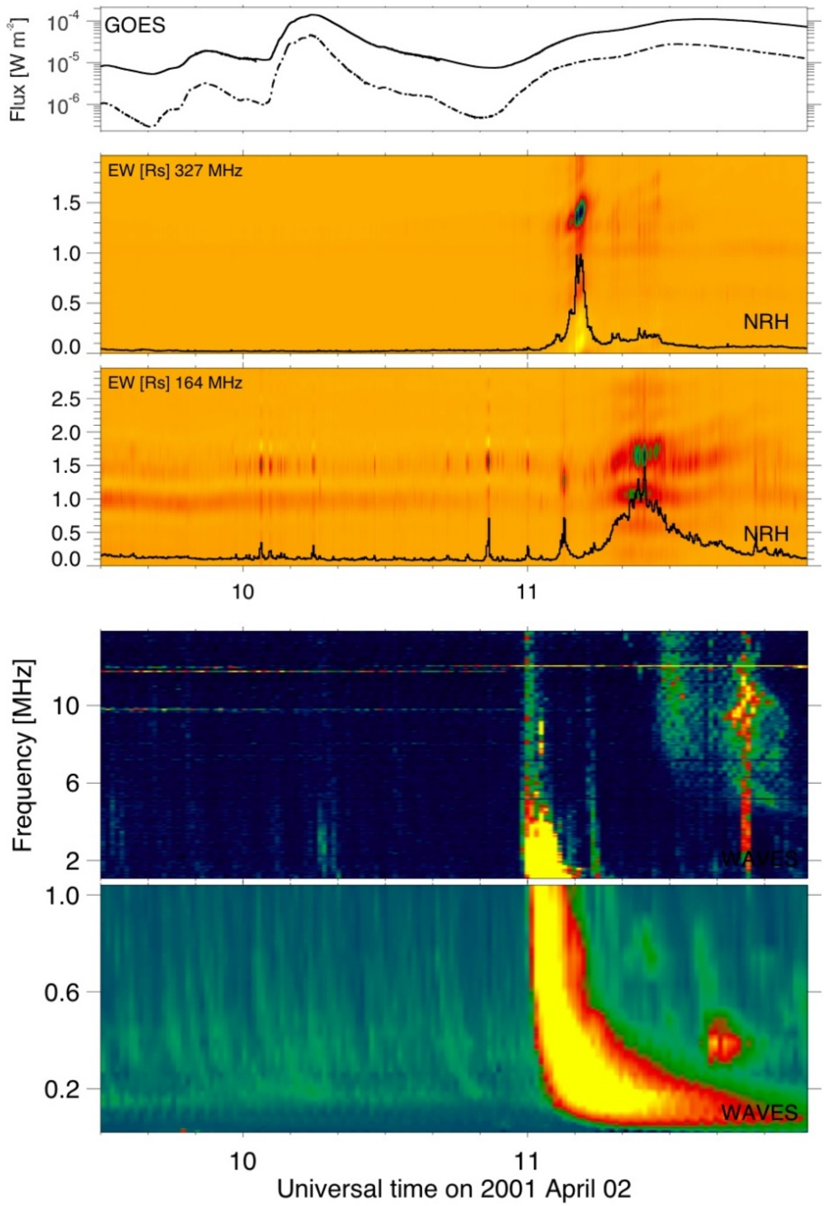
CME-less flare 2004 Feb 26:

- Particle acceleration in the corona (Nobeyama: µwave burst→35 GHz), RHESSI HXR burst
- These particles remain confined in the (low) corona:
  - Cutoff at dm-m-λ, no type III
  - confined HXR source

=> no SEP (no particle escape)

Flares and SEP: the role of magnetic confinement (Klein et al., 634)





CME-less flare 2001 Apr 02 was followed by

- an 'eruptive' flare from a neighbouring AR
- Radio dm-m-λ: moving IV
- strong type III (particle escape to IP space)

=> SEP (GOES)

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Transport equation for solar energetic particles with large anisotropy from Zhang et al. (2010)

$$\frac{\partial f(t,\mathbf{r},p,\mu)}{\partial t} = \nabla\cdot\kappa_\perp\cdot\nabla f \qquad \leftarrow \text{cross-field diffusion}$$

$$-(\mathbf{V}_{sw} + \mathbf{V}_d + v\mu\hat{\mathbf{b}})\cdot\nabla f \qquad \leftarrow \text{convection, drift and streaming}$$

$$+\frac{\partial}{\partial\mu} D_{\mu\mu}\frac{\partial f}{\partial\mu} \qquad \leftarrow \text{pitch angle diffusion}$$

Visser et al. (2010)

$$+\left[\frac{(1-\mu^2)v}{L_B} - \frac{\mu(1-\mu^2)}{2}(\nabla\cdot\mathbf{V}_{sw} - 3\hat{\mathbf{b}}\hat{\mathbf{b}}:\nabla\mathbf{V}_{sw})\right]\frac{\partial f}{\partial\mu} \qquad \leftarrow \text{focusing}$$

$$+p\left(\frac{1-\mu^2}{2}(\nabla\cdot\mathbf{V}_{sw} - \hat{\mathbf{b}}\hat{\mathbf{b}}:\nabla\mathbf{V}_{sw}) + \mu^2\hat{\mathbf{b}}\hat{\mathbf{b}}:\nabla\mathbf{V}_{sw}\right)\frac{\partial f}{\partial p} \qquad \leftarrow \text{adiabatic cooling}$$

Stochastic differential equation solver

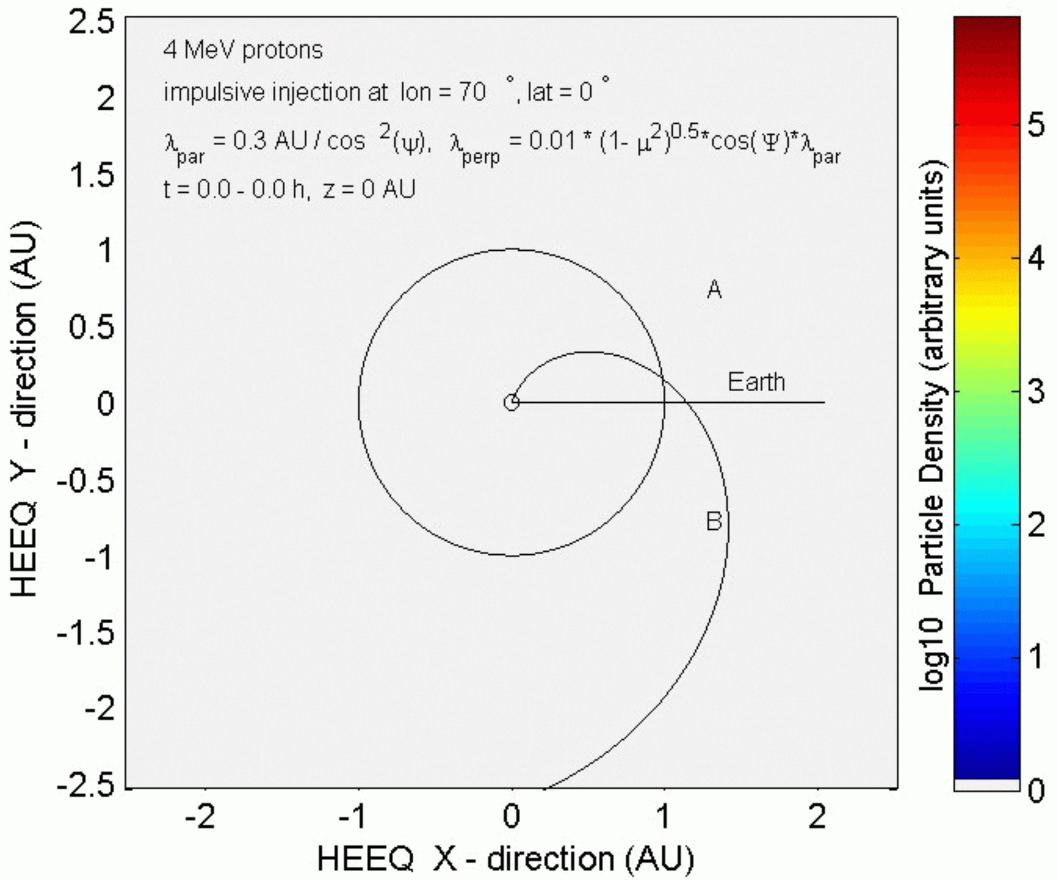
$$d\mathbf{x} = \sqrt{2\boldsymbol{\kappa}_\perp}\,d\mathbf{w}(s) + (\nabla\cdot\boldsymbol{\kappa}_\perp - \mathbf{V}_{sw} - \mathbf{V}_d - v\mu\hat{\mathbf{b}})ds$$

$$dp = \left[\frac{1-\mu^2}{2}(\nabla\cdot\mathbf{V}_{sw} - \hat{\mathbf{b}}\hat{\mathbf{b}}:\nabla\mathbf{V}_{sw}) + \mu^2\hat{\mathbf{b}}\hat{\mathbf{b}}:\nabla\mathbf{V}_{sw}\right]p\,ds$$

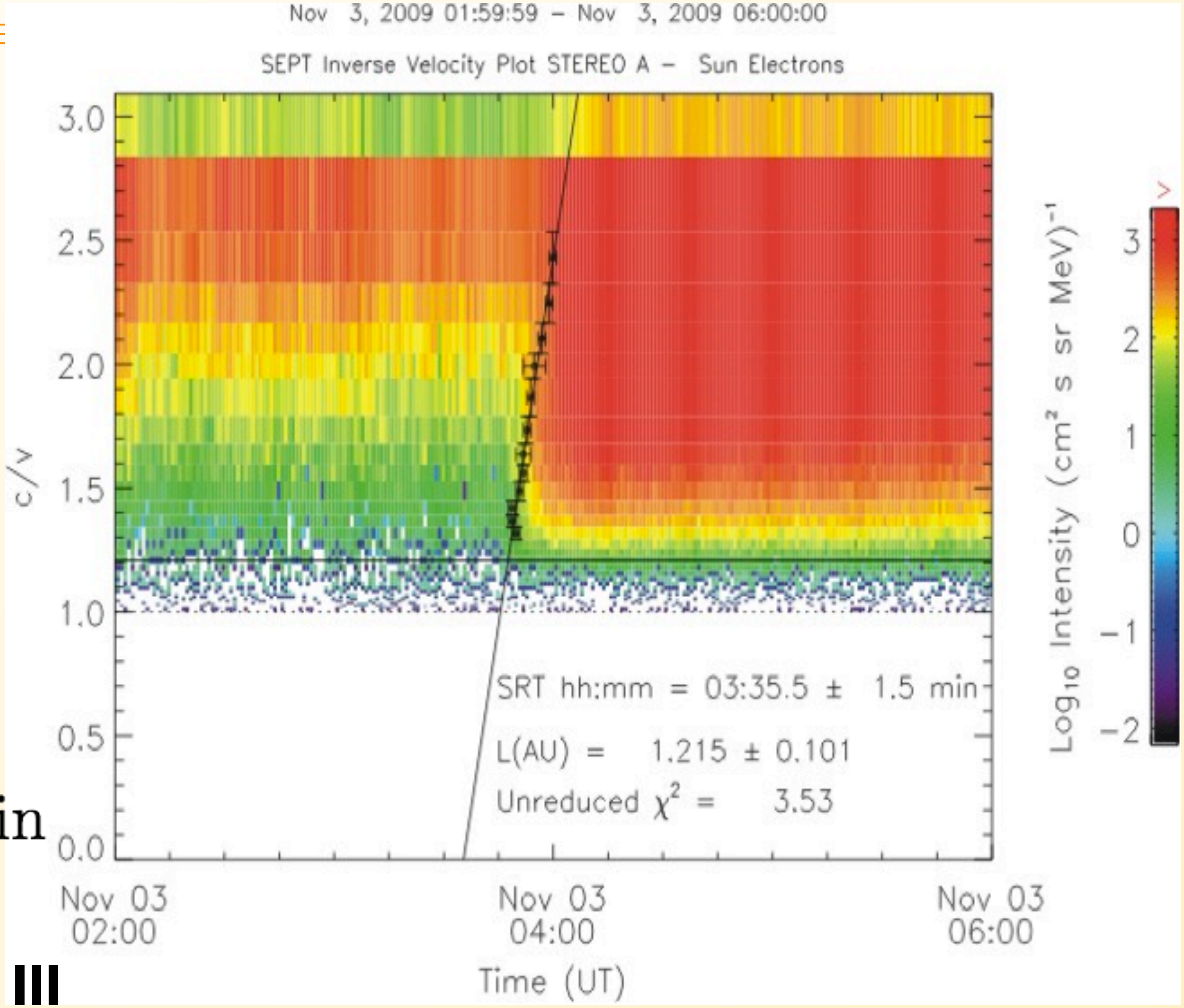
$$d\mu = \sqrt{2D_{\mu\mu}}\,dw(s) + \left[\frac{\partial D_{\mu\mu}}{\partial\mu} + \frac{(1-\mu^2)v}{2L_B} - \frac{\mu(1-\mu^2)}{2}(\nabla\cdot\mathbf{V}_{sw} - 3\hat{\mathbf{b}}\hat{\mathbf{b}}:\nabla\mathbf{V}_{sw})\right]ds$$

High Light SH-2: 3-D Particle Propagation – The role of perpendicular Transport

- Solution of the modified Roelof equation using SDEs (Dröge et al., 2010)



Electron velocity dispersion observed by SEPT during Nov. 3, 2009 (first) SEP event



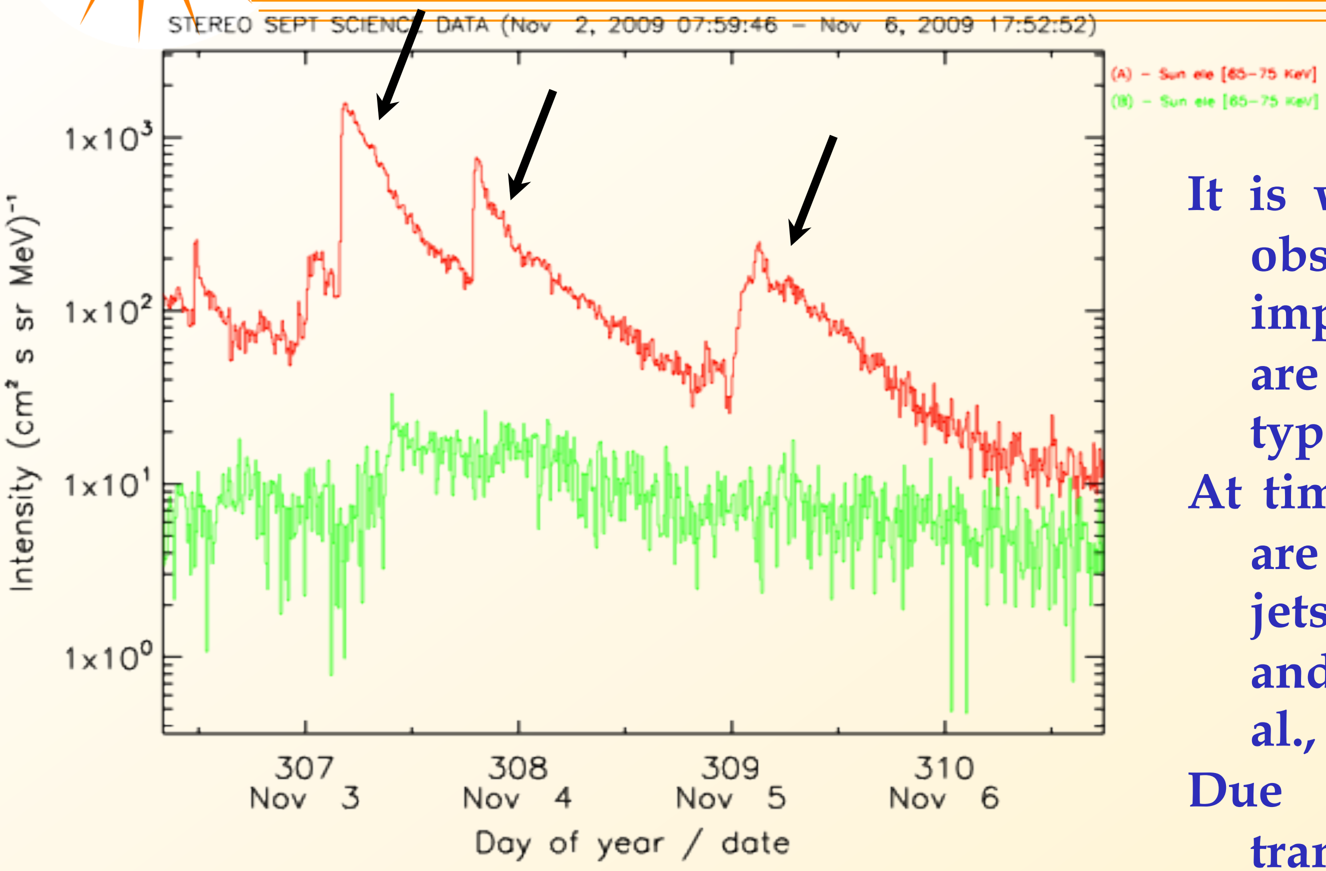
Onset time vs Inverse velocity technique (e.g. Lin et al, 1981) provides an estimation of the injection time at the Sun and the path length:

$$L=1.2\pm0.1\ \mathrm{AU}$$

$$t_0=03{:}44\ \mathrm{UT} \pm 2\ \mathrm{min}$$

12 min delay wrt type III radio burst

Electron measurements at 1 AU



- It is well known that in-situ observed near-relativistic impulsive electron events are well correlated with type III radio bursts.
- At times type III radio bursts are associated with X-ray jets (e.g. Aurass et al., 1994) and EUVI jets (e.g. Wang et al., 2006).
- Due to interplanetary transport "normal" SEP event observation last hours.

Short delay of (1-2 min) between spikes onset and the corresponding type III bursts

Spike characteristics:

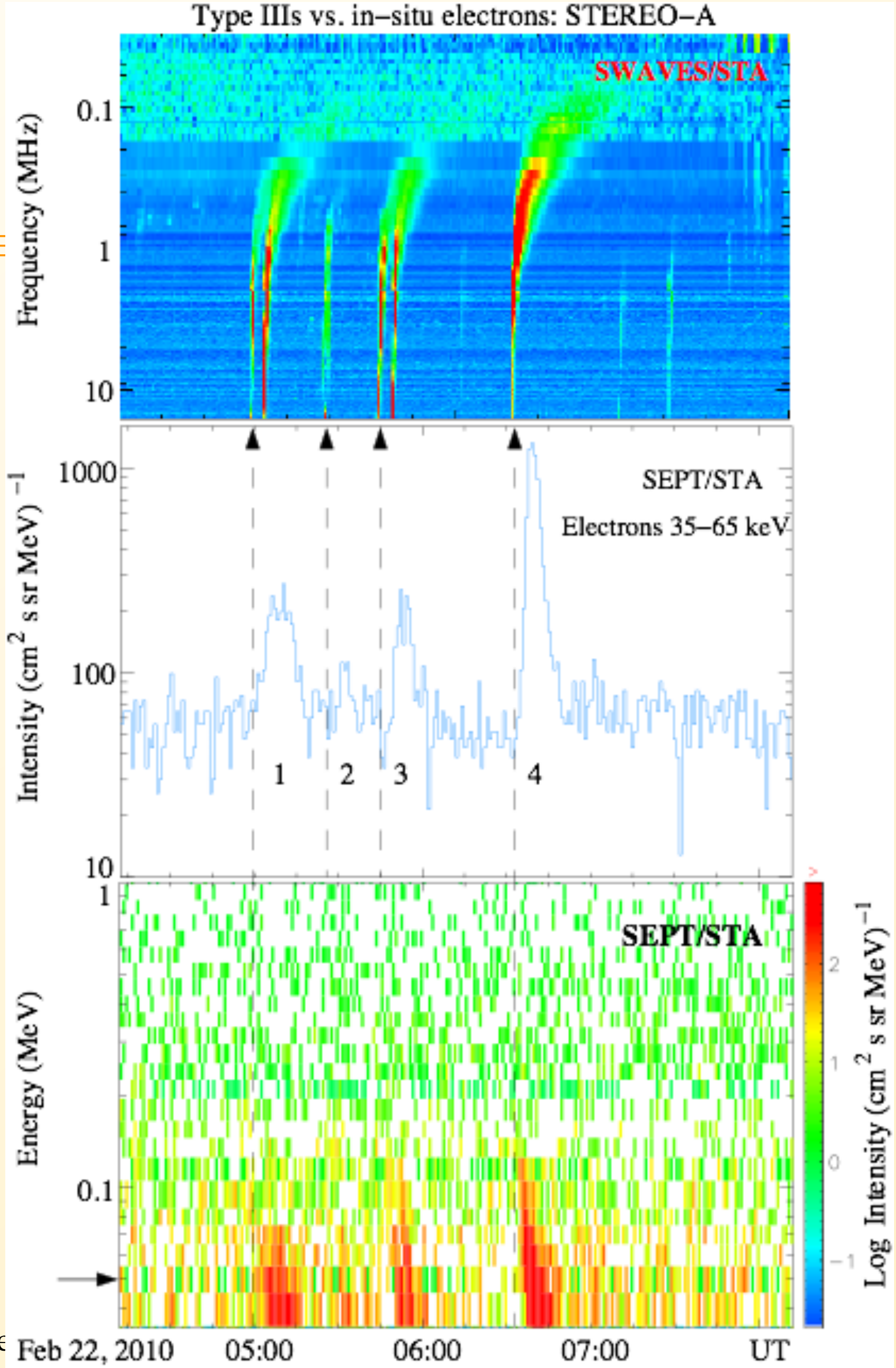
- Symmetric profile (~Gaussian)
- Very short duration (FWHM <= 5 min)
- Velocity dispersion
- Energy range up to 120 keV

The sharp peak and the short duration required an upper limit on the duration of the electron injection into IP medium of <= 2 min.

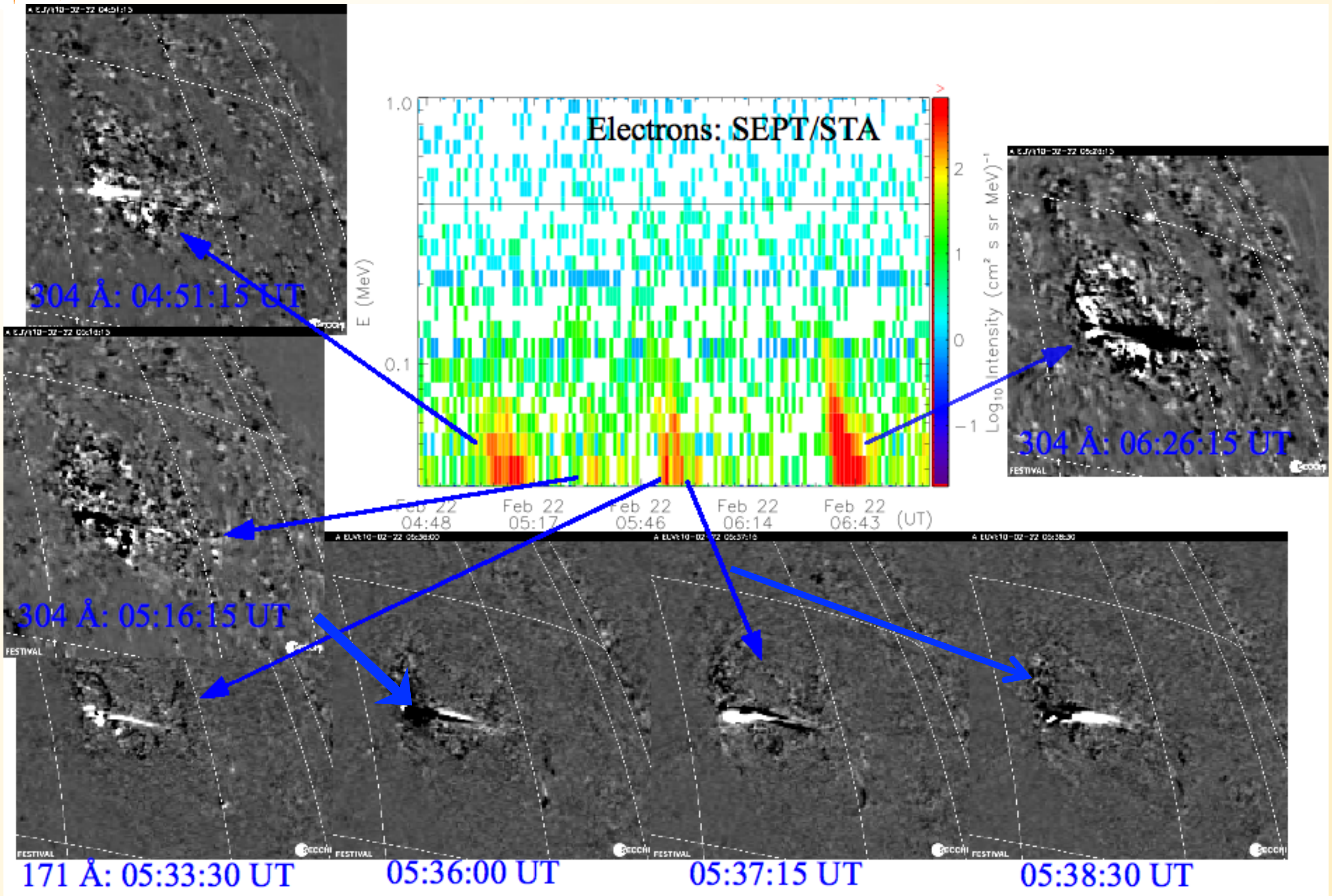
The two double type III bursts are associated with two double spikes (number 1 & 3).

All type IIIs were observed only at STA (not at STB & very weak at WIND).

Each spike is associated with an EUVI jet.



Electron spikes and EUVI jets



B.

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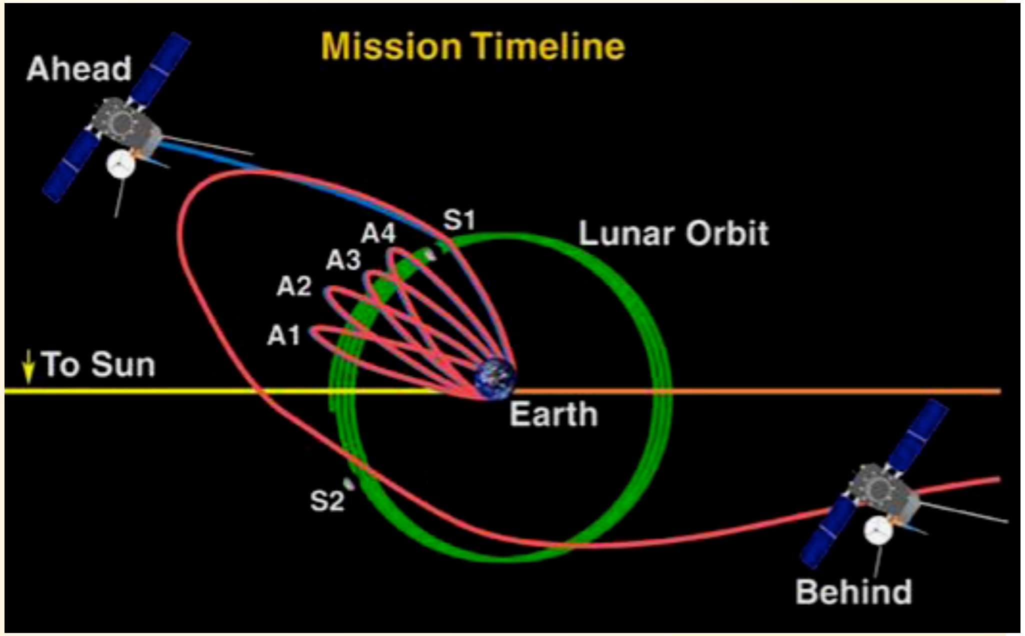
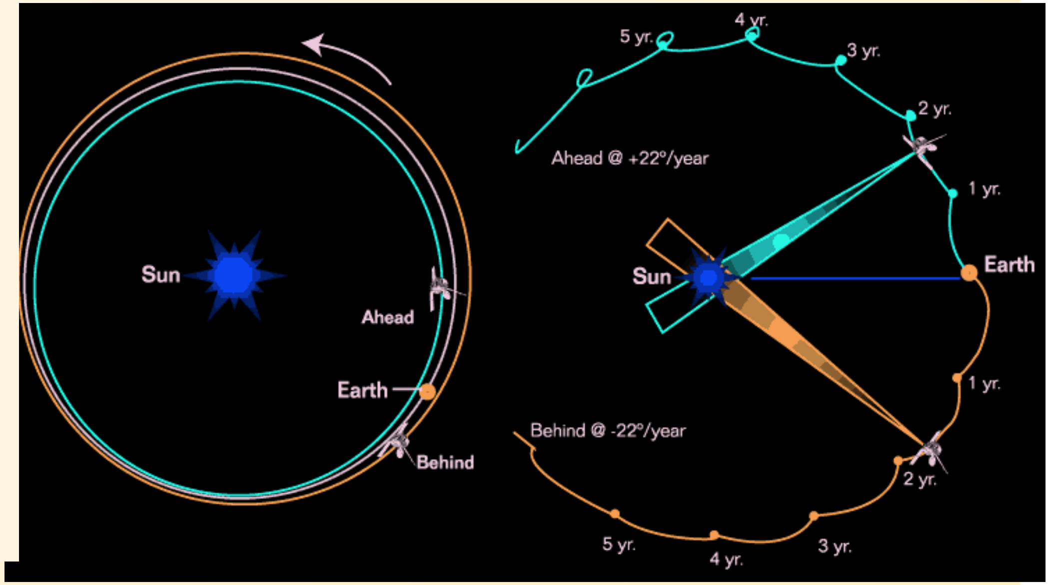
STEREO Orbit

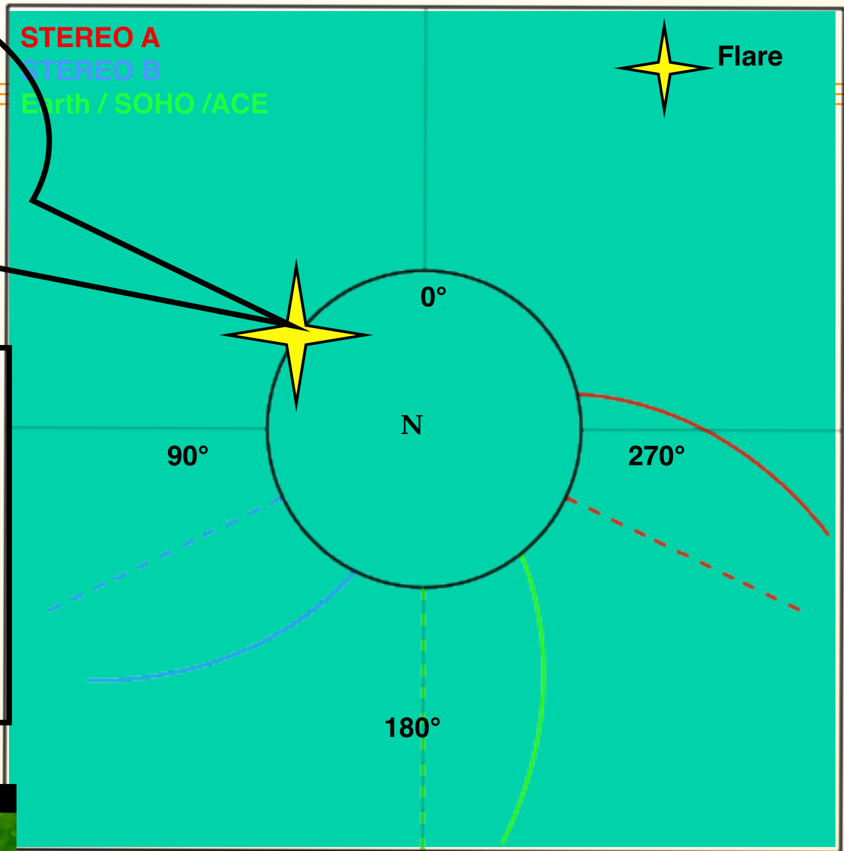
- Launched on Oct 25, 2006
- SEPT B and A switched-on on Nov. 13 and 14, 2006
- Separation after lunar swing-by S1 on Dec. 15, 2006
- SEPT-A doors opened on Dec. 14, 2006
- SEPT-B doors opened on Jan. 16, 2007
- Final orbit:
  - Near ecliptic, following Earth (0.95-1.09 AU)
  - Growing azimuthal separation 22°/year
  - Heliographic latitude from -7.3 to +7.3 degrees





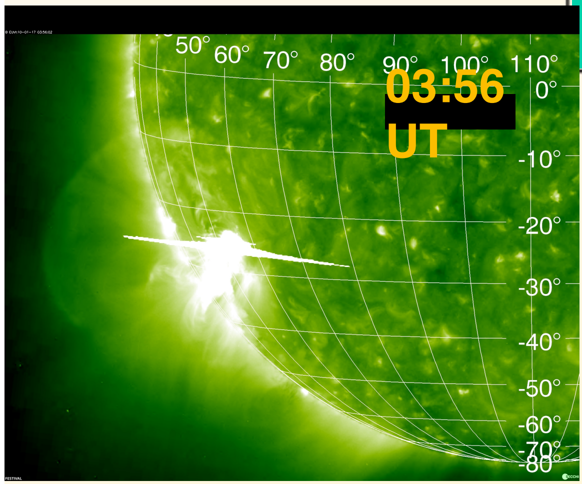
January 17, 2010

Flare onset: 3:51
Lat: -25°
Carr long: 55°



STB
OT 4:54 UT
long-sep: 108°
HG lat: 4°

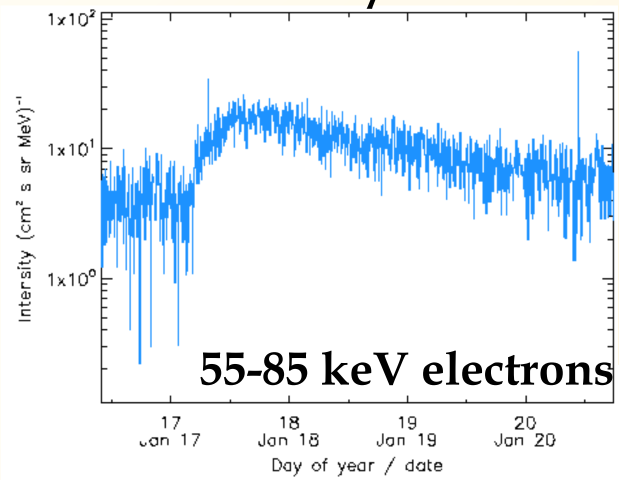
STA
OT 5:13 UT
long-sep: 118°
HG lat: -7°

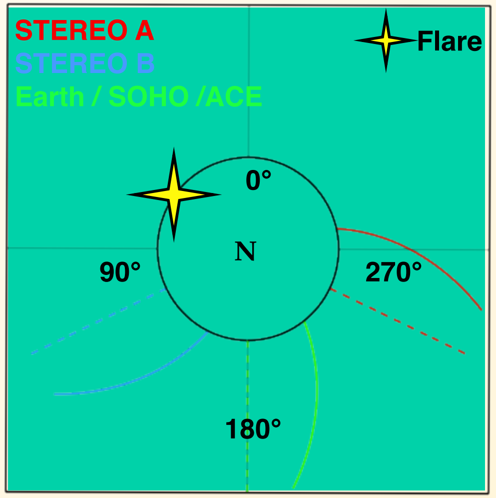


SOHO
OT 6:20 UT
long-sep: 169°
HG lat: -5°

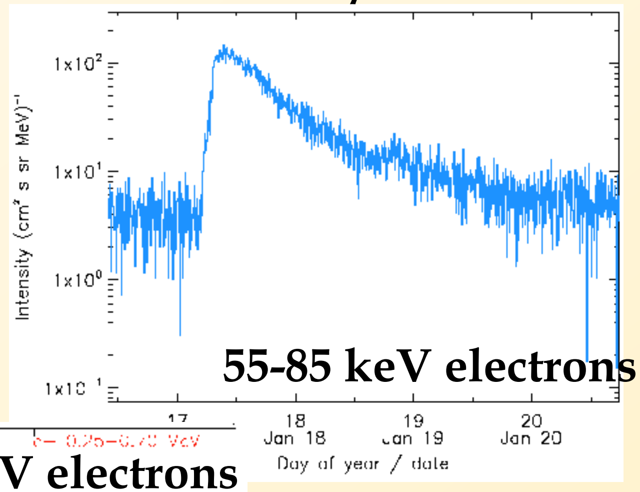
January 17, 2010

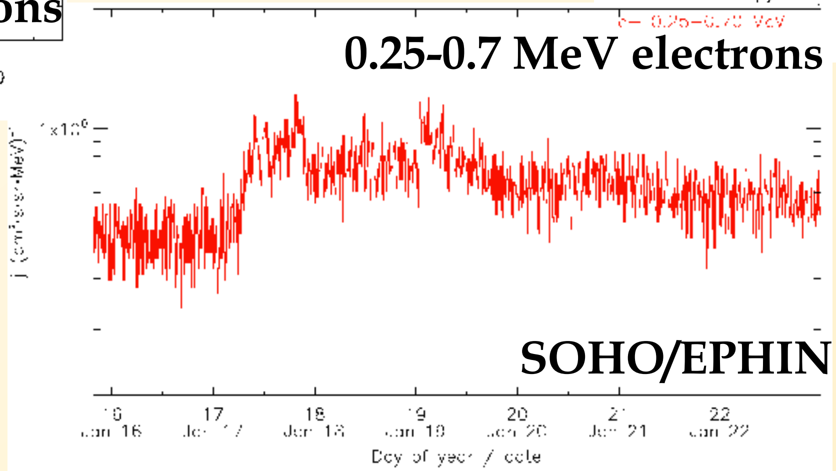
STEREO/SEPT B





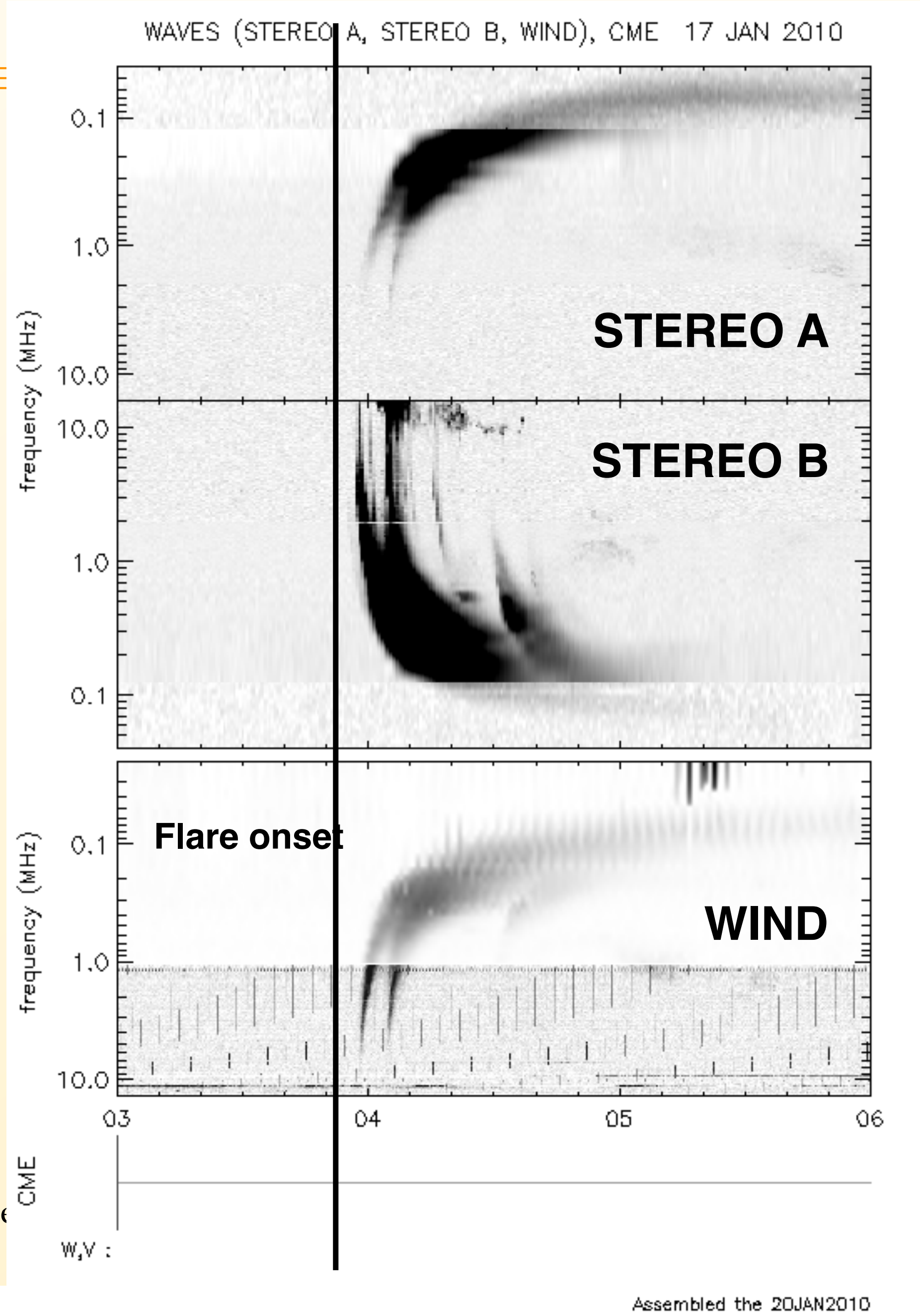
STEREO/SEPT A



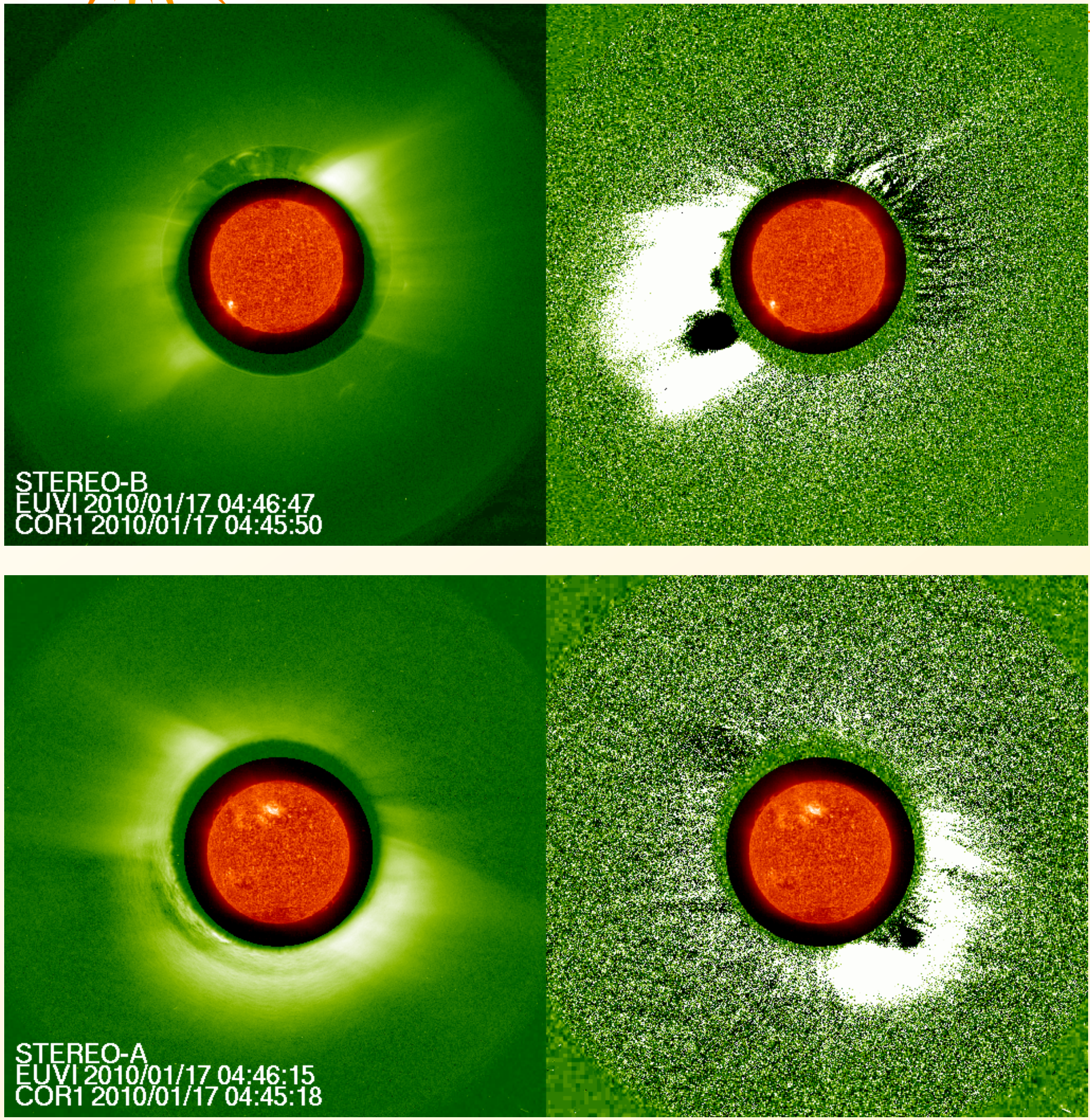


Radio observations

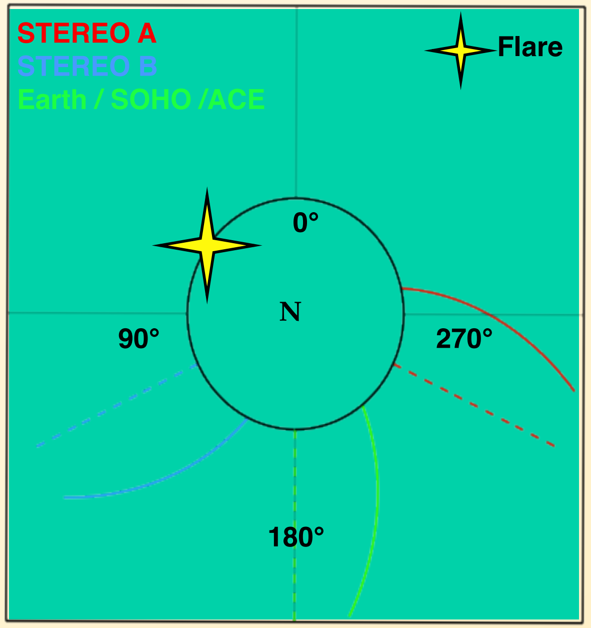
- Type III seen by STA and STB and WIND/WAVES
- Occulted for STA
- Type II seen by STB
- Type II also reported by HIRAISO radio station



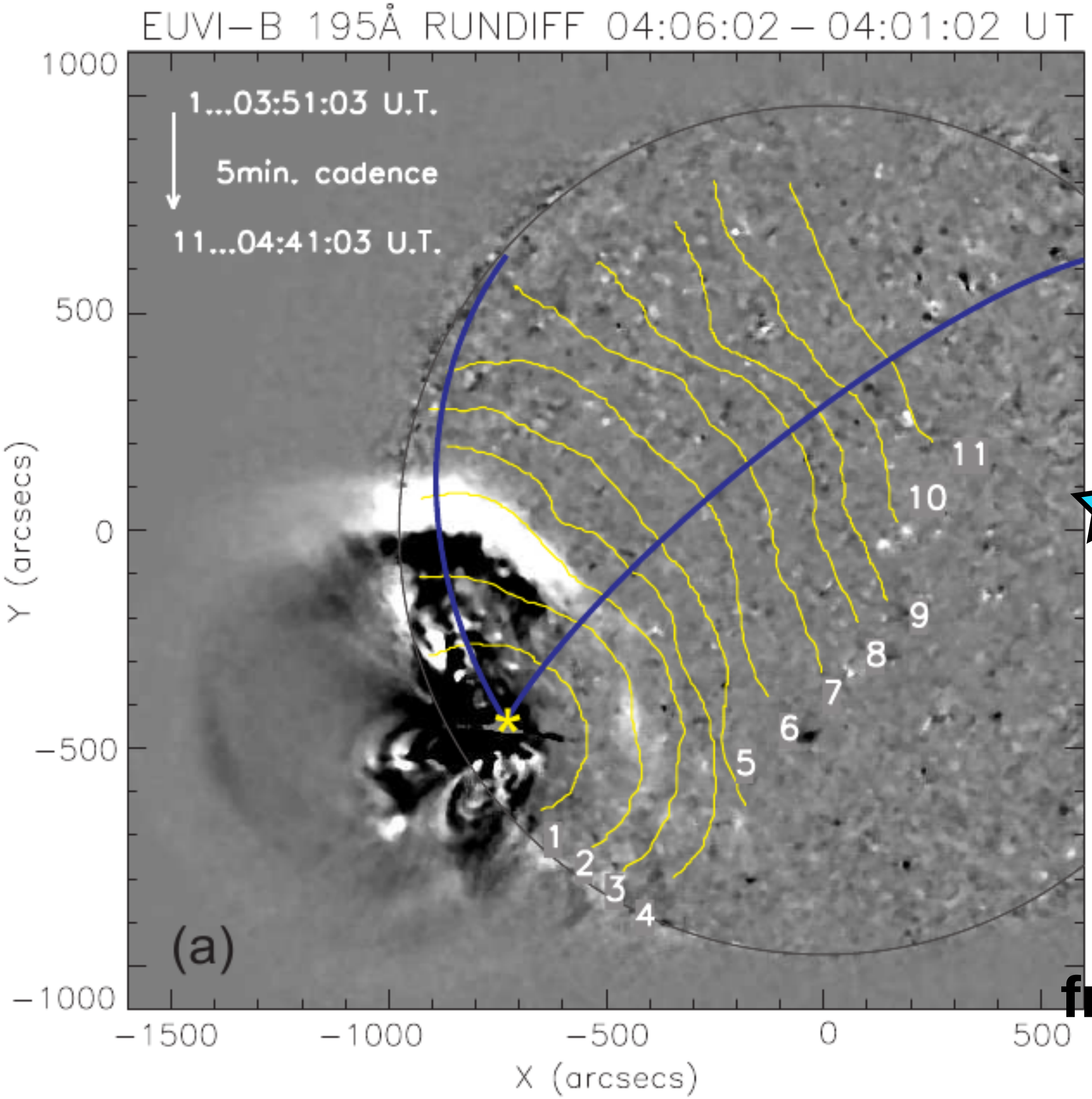
CME observations



At 4:10 UT COR 1 coronagraphs onboard both STEREO observed a CME.
SE limb for STB
SW limb for STA



EIT wave



EIT wave seen only by STEREO B is propagating with v~280 km/s

STB magnetic foot point

from Veronig et al. 2010

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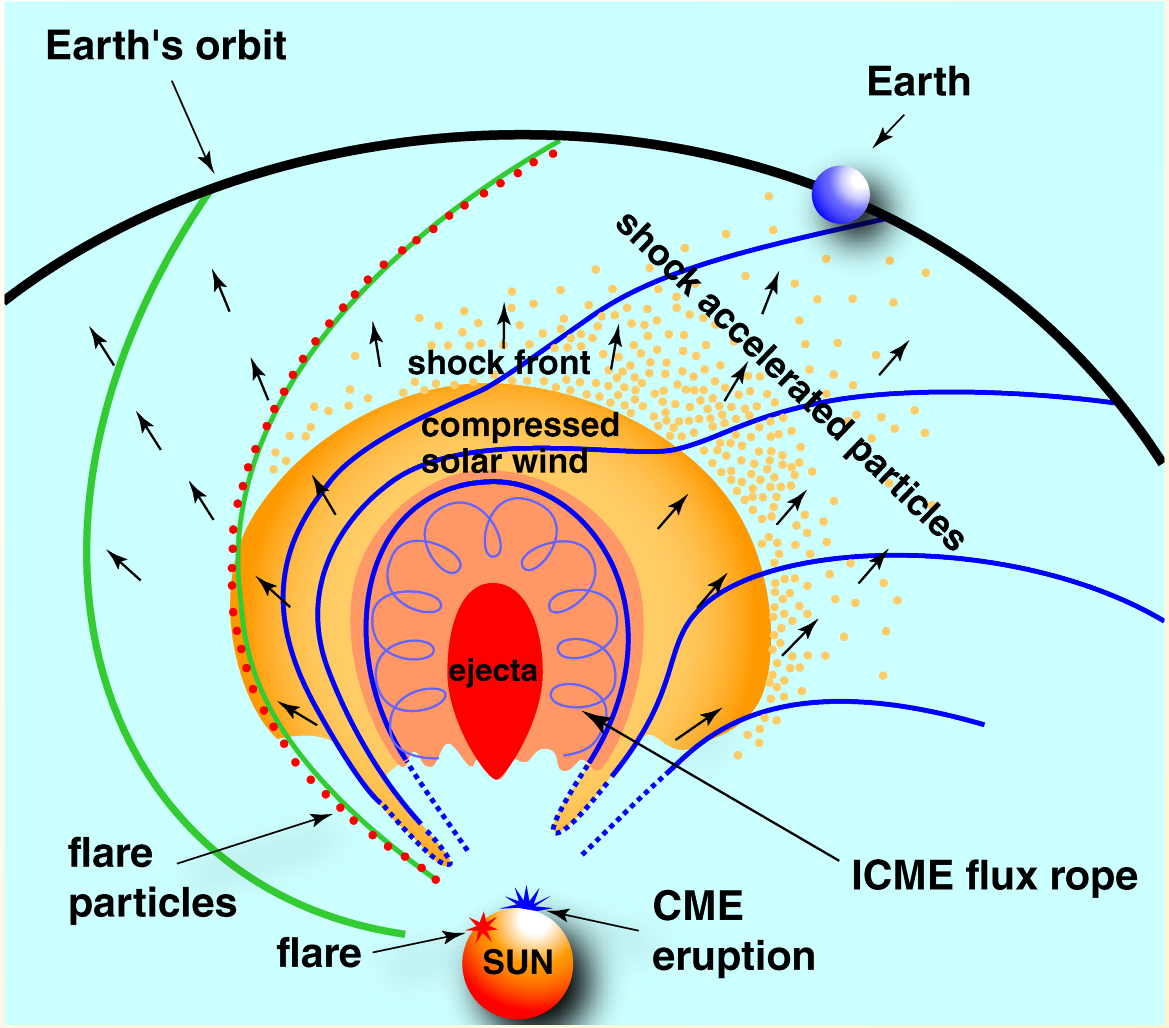
  - **Flares: Solar Energetic Particles**
- **Energetic particle transport in the inner heliosphere**
- **Multi spacecraft events**
- **Ground Level Events (extreme events)**
- Summary and Outlook

Gradual Solar Energetic Particles (SEPs)

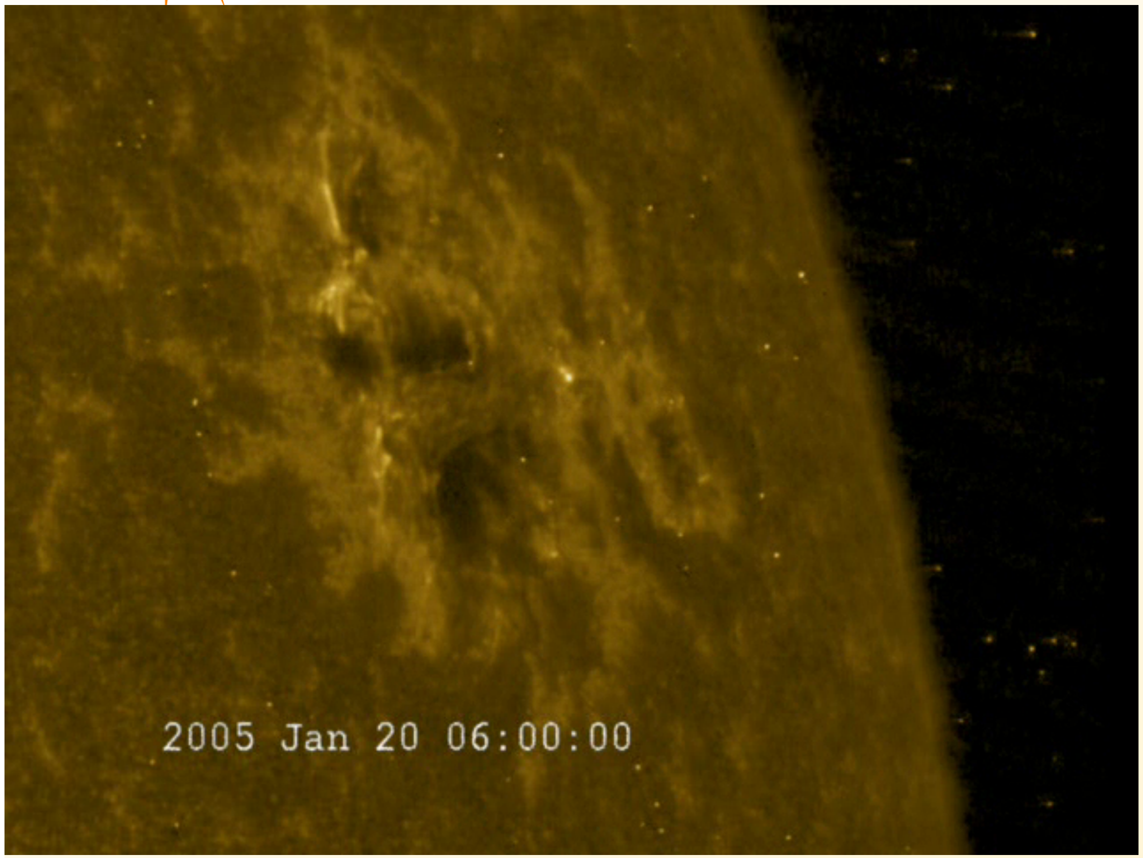


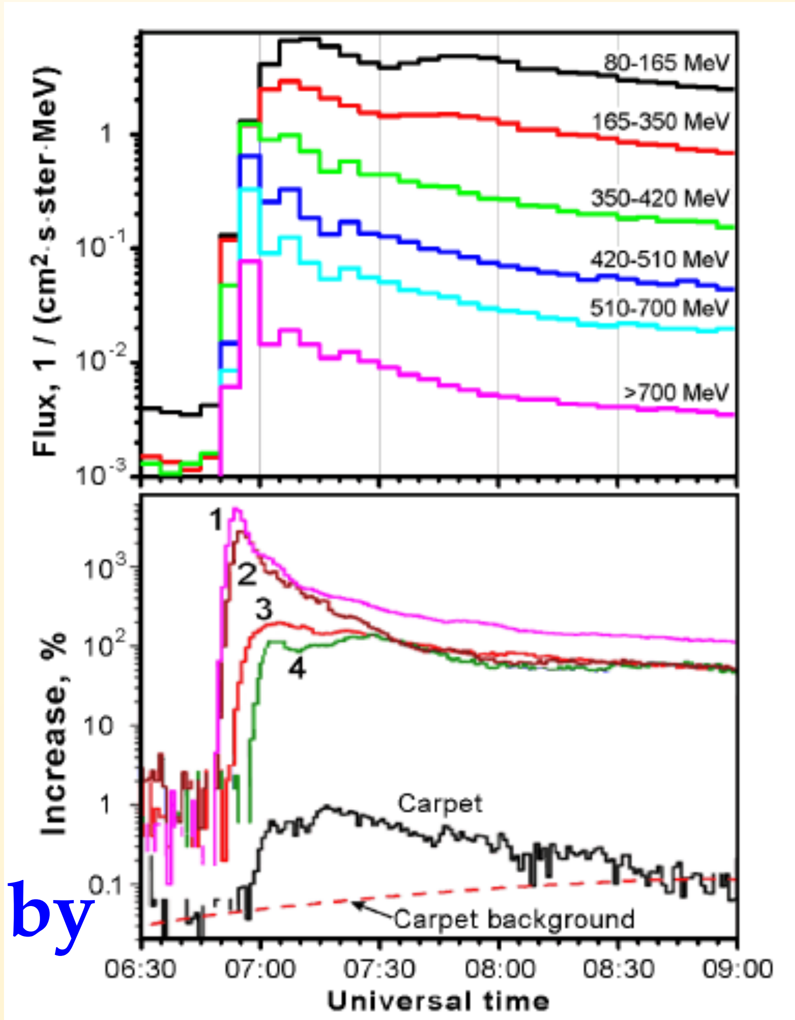
Coronal / Interplanetary Shocks:

Particles are seen over a broad longitudinal range; (relative) high Intensities and energies

Composition as for the solar wind

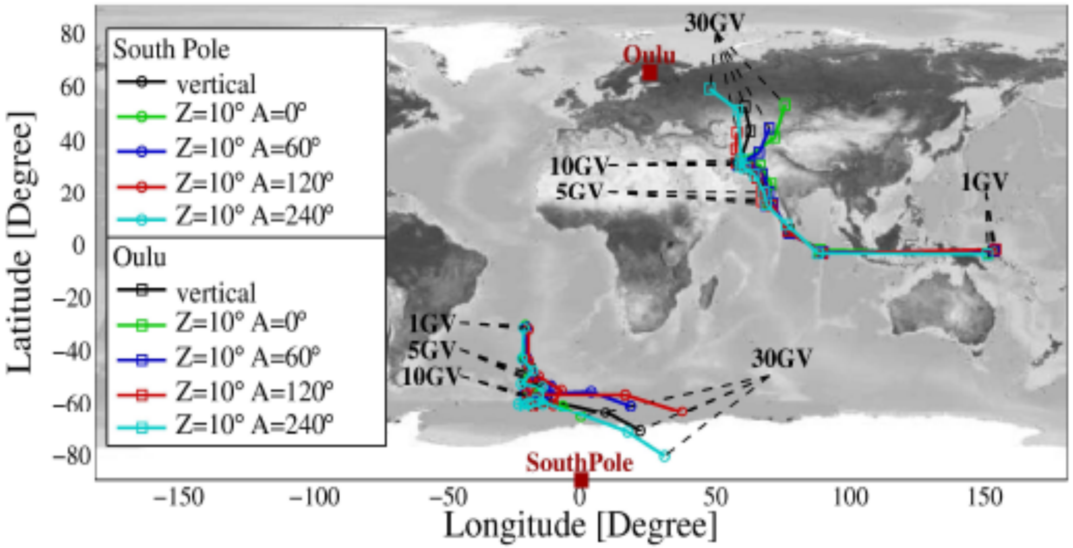
Ground Level enhancements

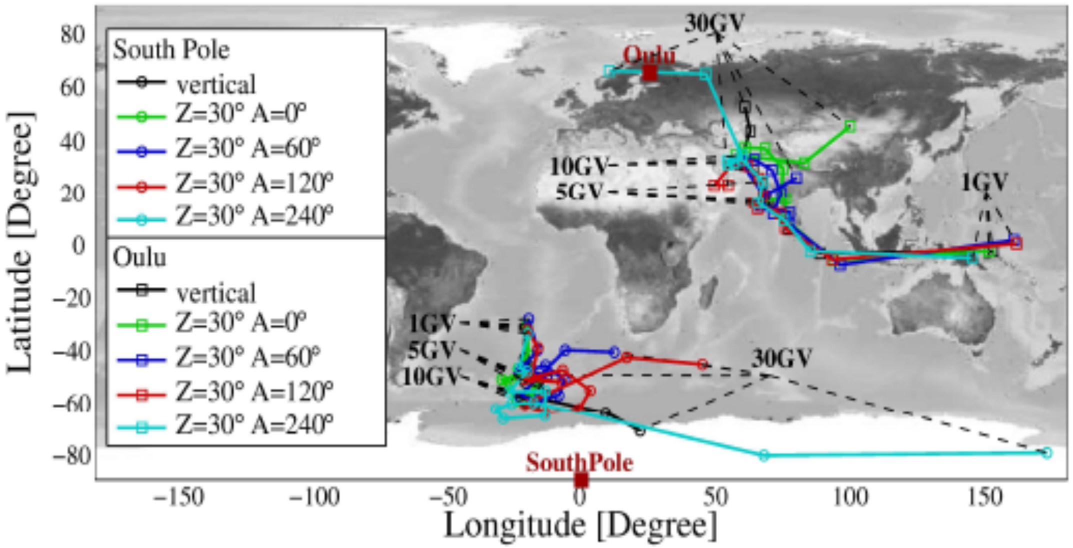


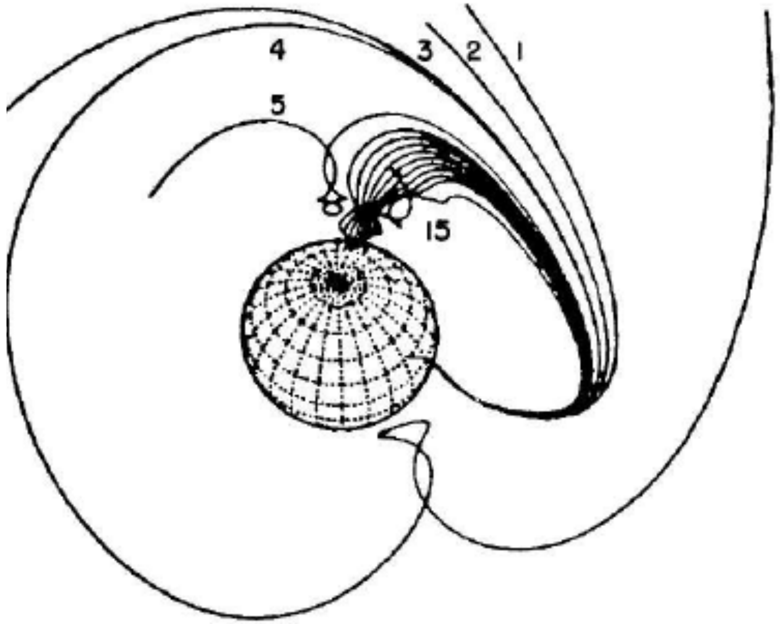


The SEP from 20.01.2005 as seen by Trace and in energetic particle measurements.

Ground Level Enhancements - Measurements of energetic particles



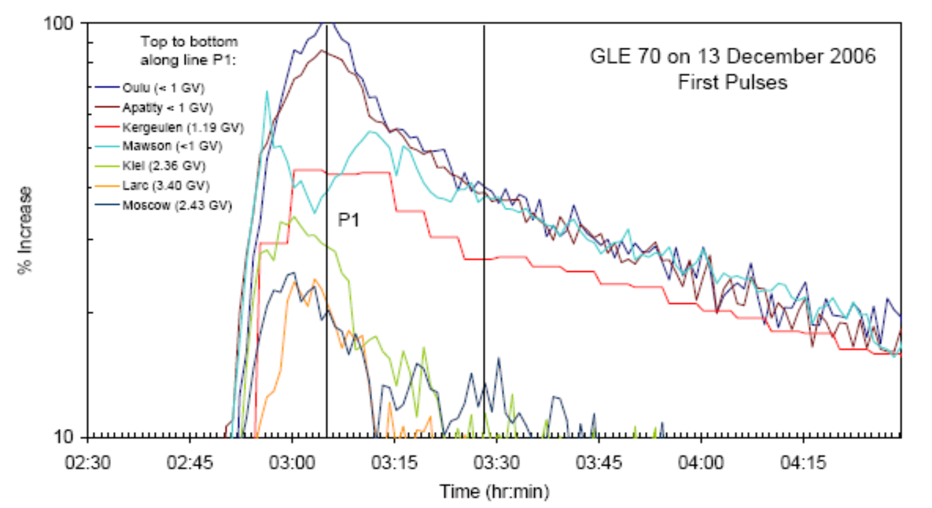


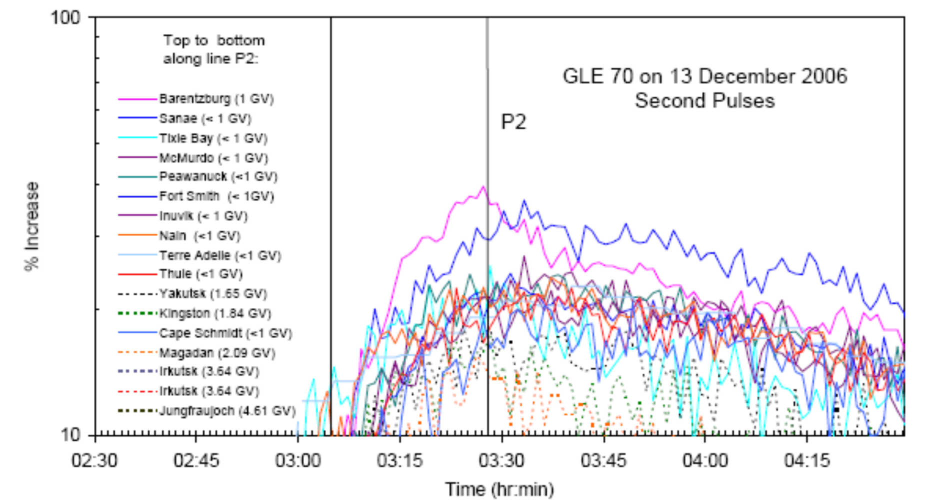


Charged Particle trajectories in the Earth magnetic field.

Rigidity dependent asymptotic direction

Ground Level Enhancements – Interpretation (e.g. Moraal et al., 1553)

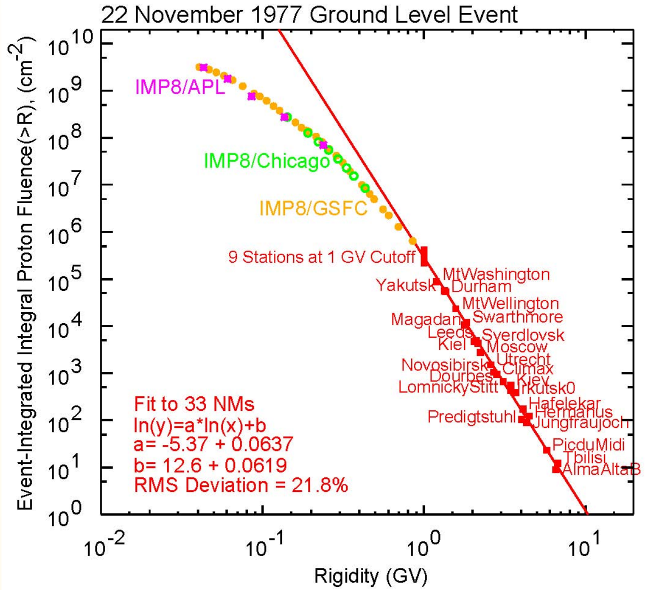


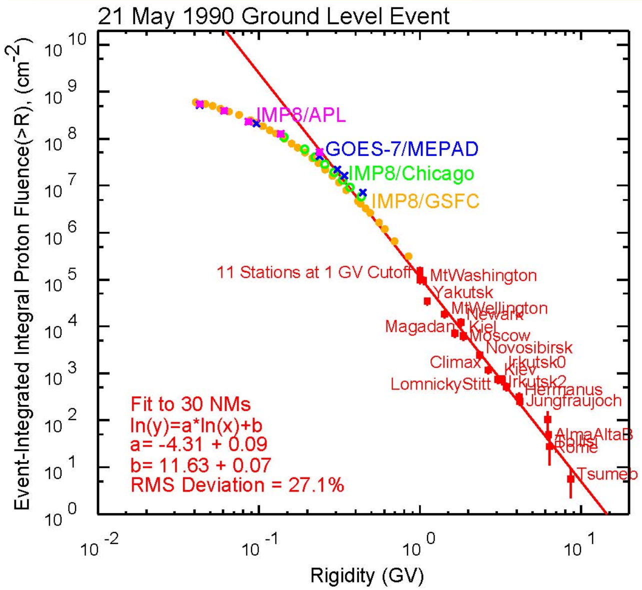


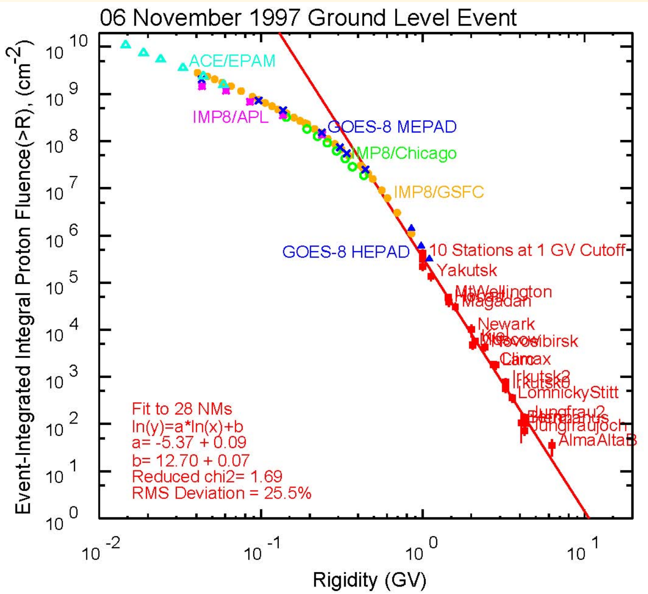
Rigidity dependent asymptotic direction requires a carefully analysis and the use of several stations and other facilities (Iakovleva et al., 894, Belov et al., 894,1004, Gvozdevsky (1149, Ryan et al., 807, Vashenyuk et al., 1171 Tylka et al., 273, Mewaldt et al, 783, Andriopoulou et al, 1529)

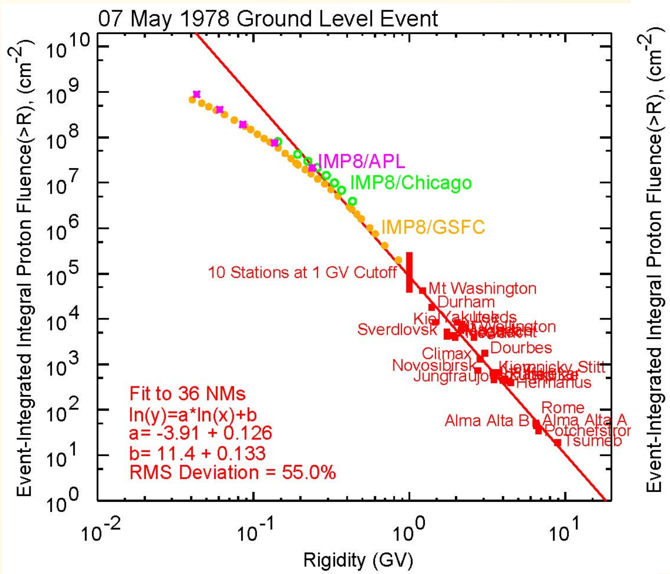
Active Sun

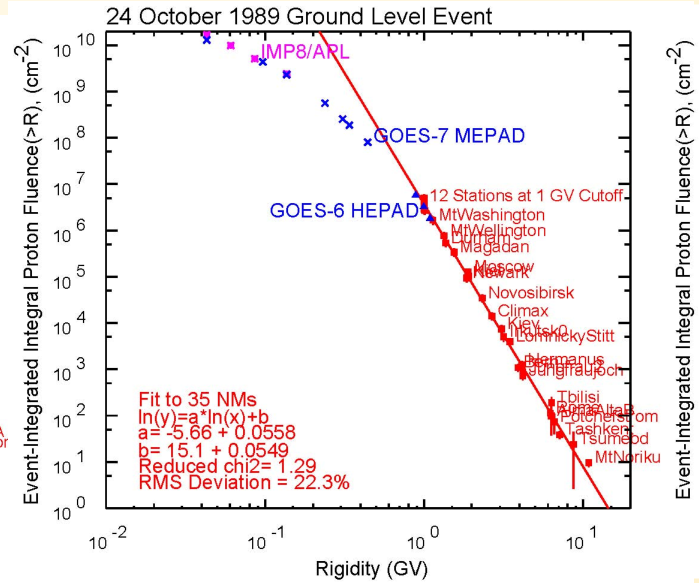
Comparisons with Satellite Spectra: Examples from Solar Cycles 21, 22, and 23 (Tylka et al.,273)

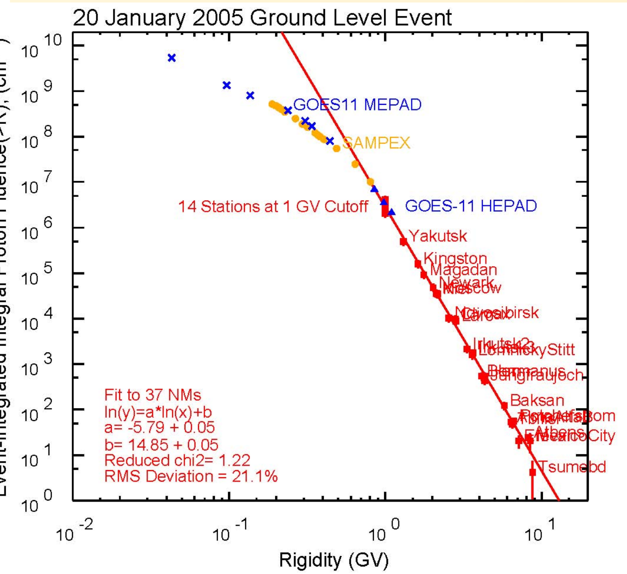




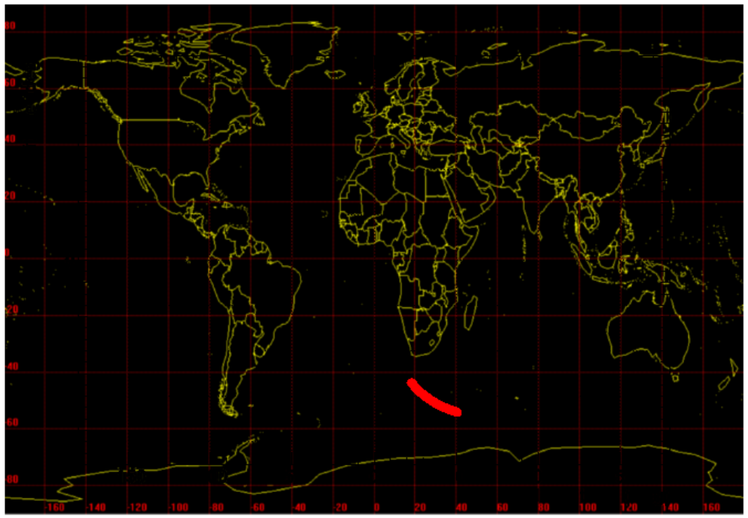


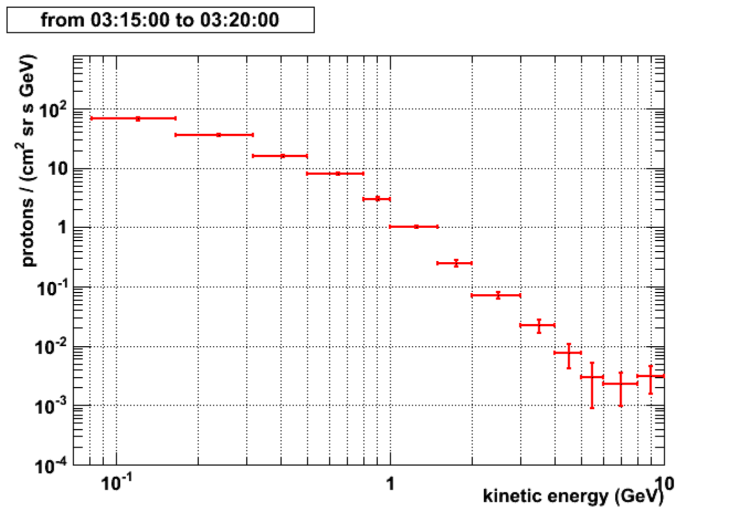






The Earth magnetic field as a spectrometer (De Simone et al., 794)





Outline

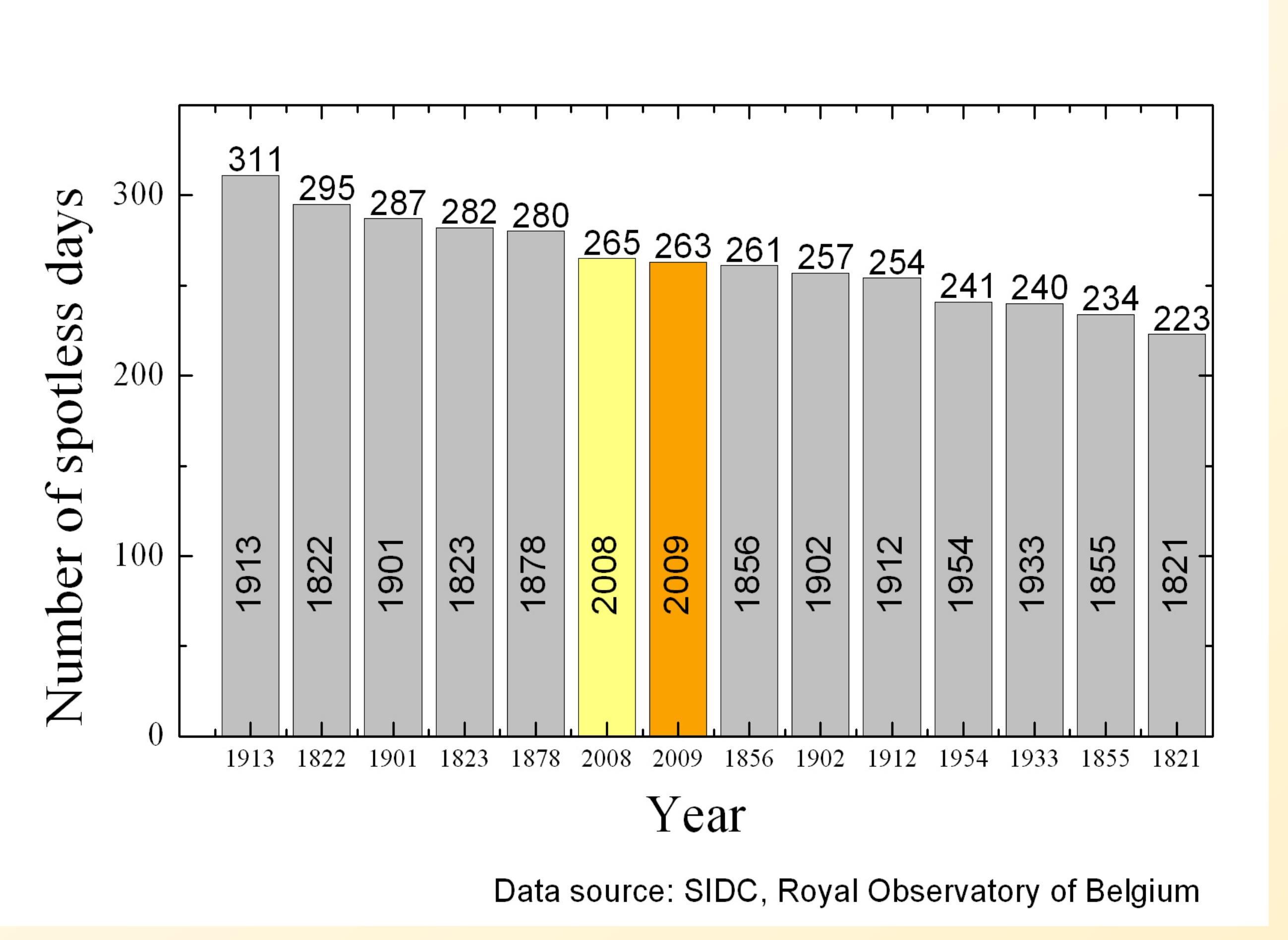
- The Sun and the solar cycle
- The Sun as a Particle Accelerator
  - Photons and Neutrons
  - Flares: Solar Energetic Particles
- Energetic particle transport in the inner heliosphere
- Multi spacecraft events
- Ground Level Events (extreme gradual events)
- Summary and Outlook

Summary

- The Sun is an active, magnetized Star, producing energetic photons and particles during energetic particles events
- Proton and electron measurements reflect the solar activity with
- Modeling of particle acceleration and interplanetary transport is improving thanks to new computing power, better understanding of transport parameters and adaption to SDEs
- Observations of solar electron spike events suggests that three phenomena: the electron spikes, type IIIs and jets are a consequence of reconnection processes in small flares.
- Multi spacecraft events have been measured clearly since the rising activity with very large longitudinal separation (>100 degrees). Thanks to the instrumentation detailed analysis for the wide spread is in progress
- Ground Level events result in a radiation exposure harmful to astronauts

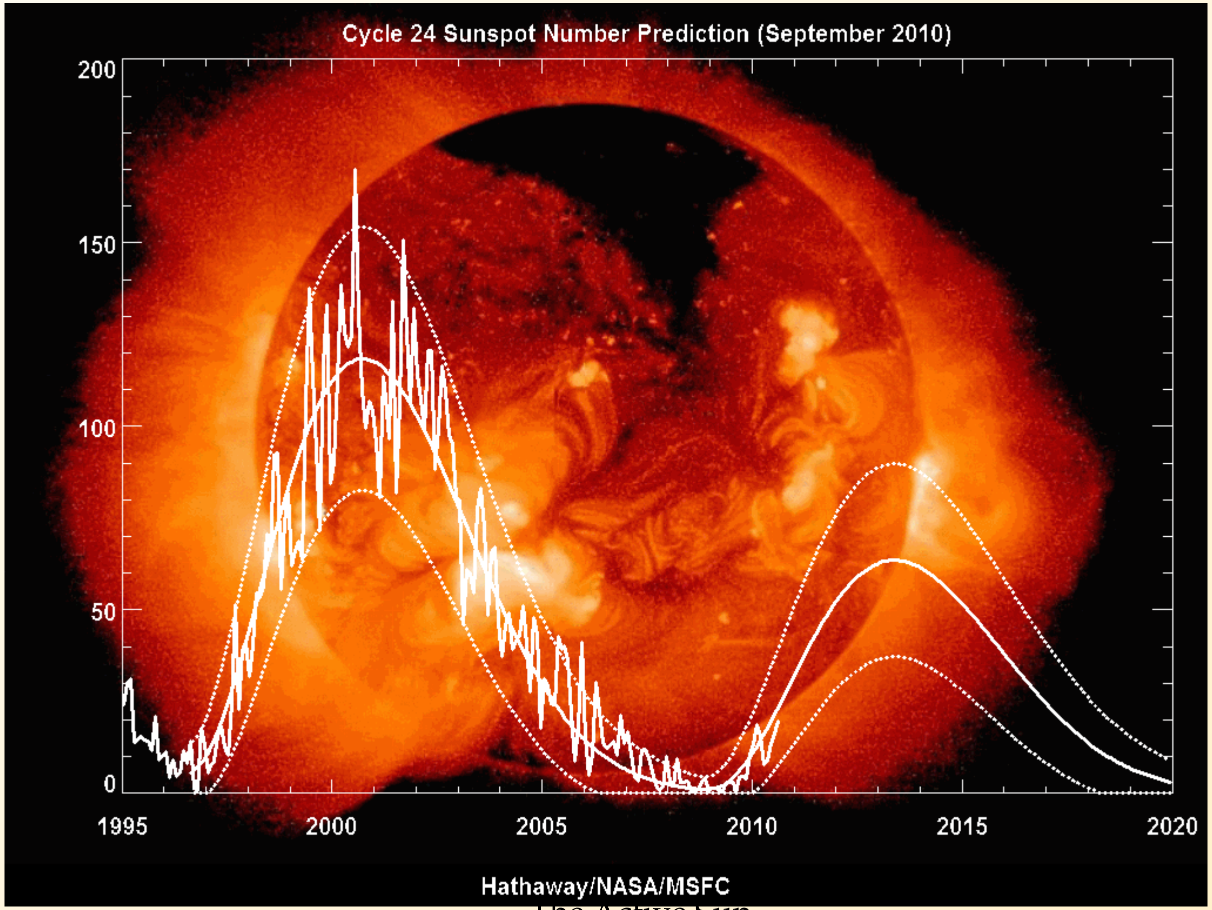
Solar Cycle 23/24

- **The solar minimum has been exceptionally long, but …**



Solar Cycle 23/24

- … the activity showed some increase during 2010



2010: The rising phase of SC24