RADSAGA

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Space weather and the variable radiation environment in space

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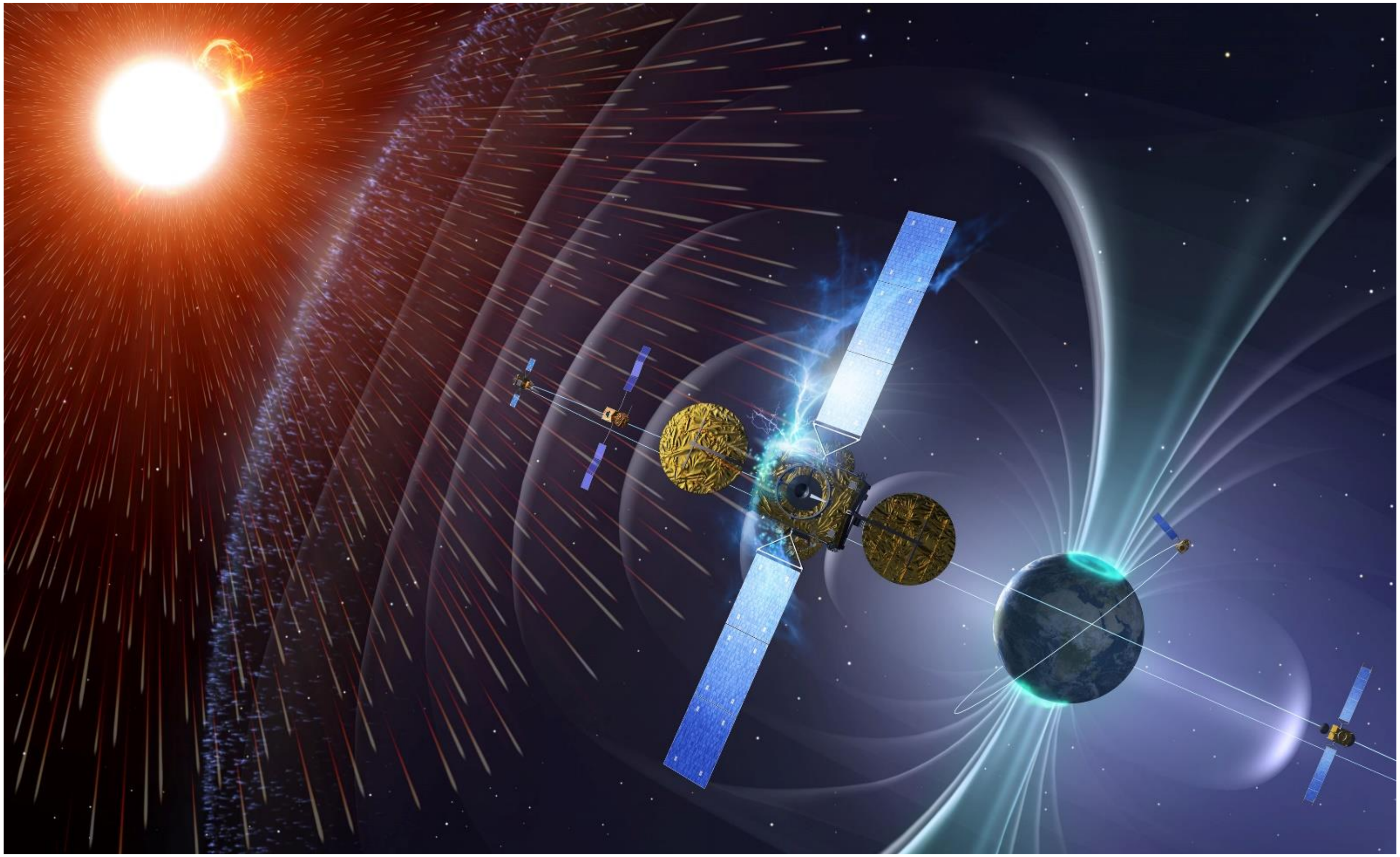
RADSAGA

Outline

- Brief introduction to space radiation
- Long term variations
  - Earth´s magnetic field
  - Solar cycle
- Short term variations
  - Brief introduction to space weather
  - Solar particle events

RADSAGA

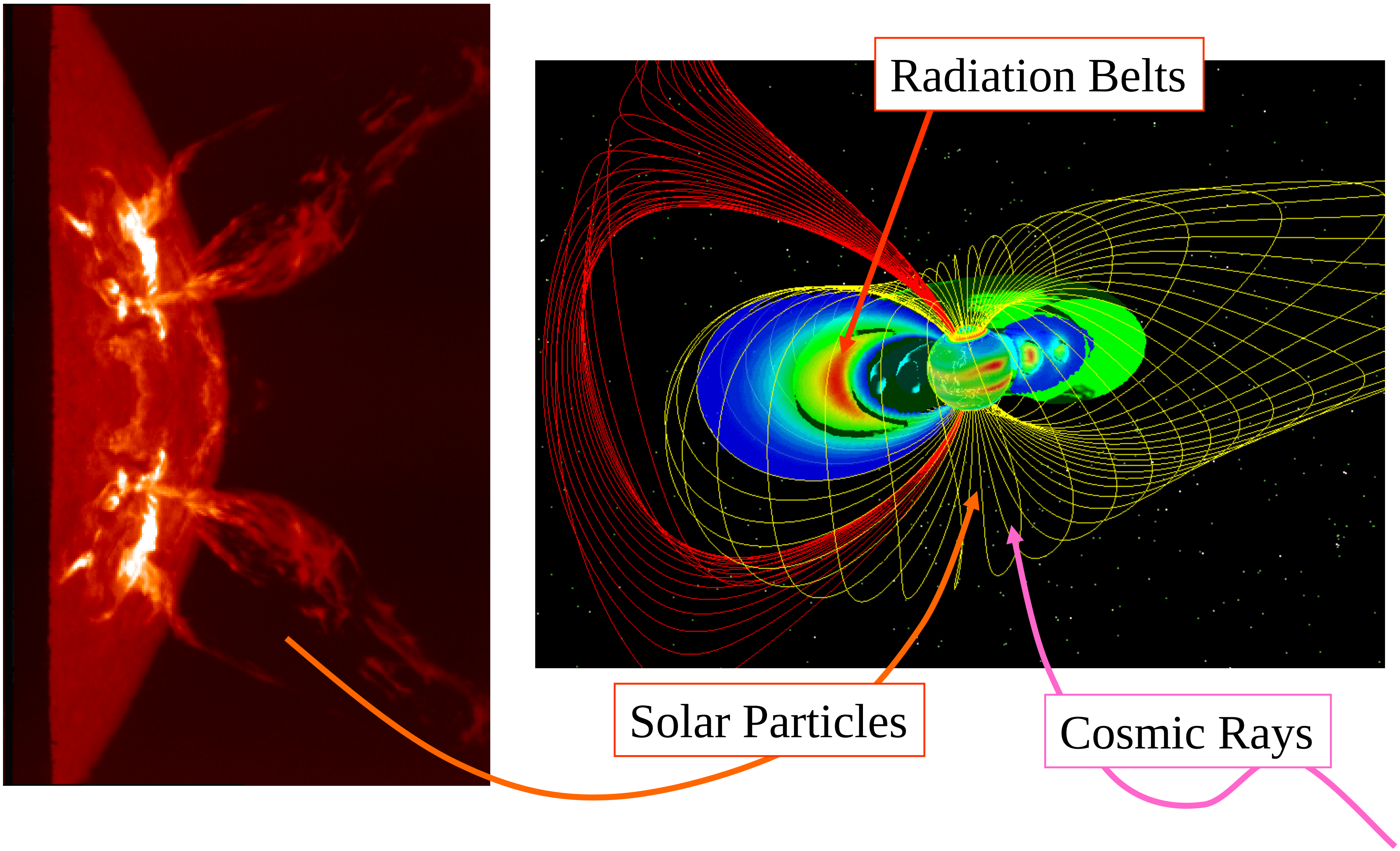
Radiation and Space Weather



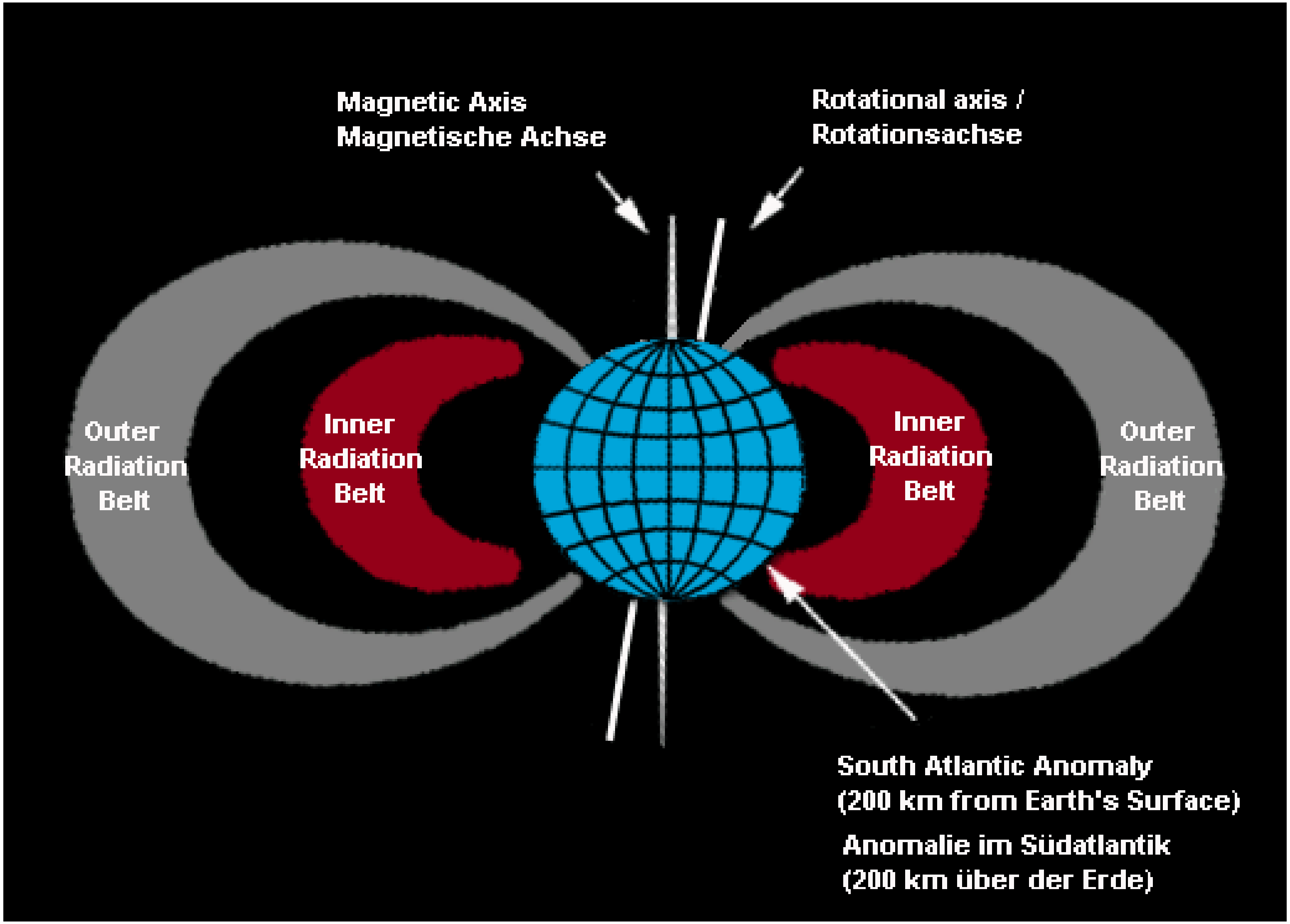
Overview: particle energy ranges

Galactic cosmic rays	GeV- 10^{x} GeV
Solar event particles	10s MeV - GeV
Trapped particles e, p	100 KeV- 10s MeV
Plasma	eV- 100 KeV
Atmospheric particles	eV

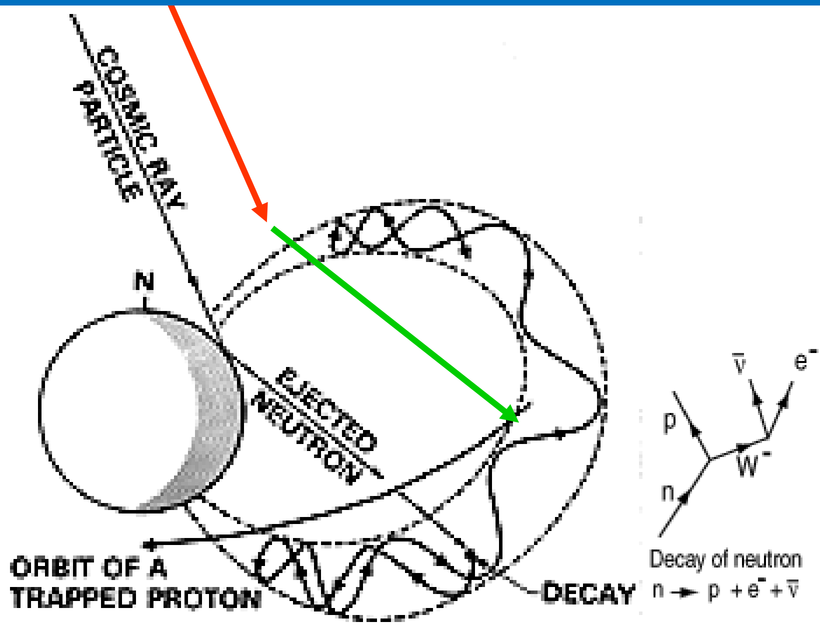
Radiation in space

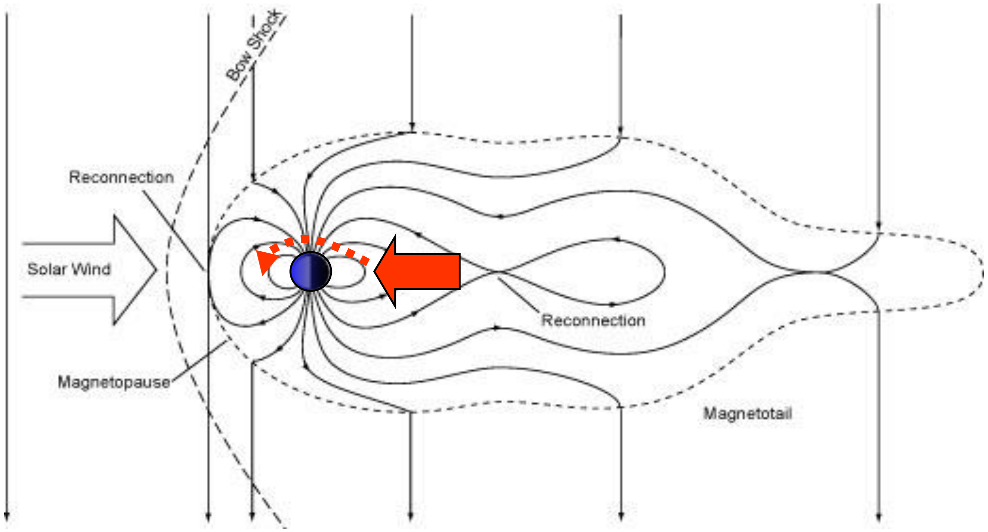


Trapped radiation belts (Van Allen belts)



Radiation belt sources





High Energy Protons (Inner Belt)

Cosmic Ray Albedo Neutron Decay

- Nuclear interaction in atmosphere
- Some products are upward travelling neutrons
- Decay (half life ~10min) into p, e^-
- Results in very stable population
- Lower energy protons can be inserted via the magnetospheric tail

High Energy Electrons (Outer Belt)

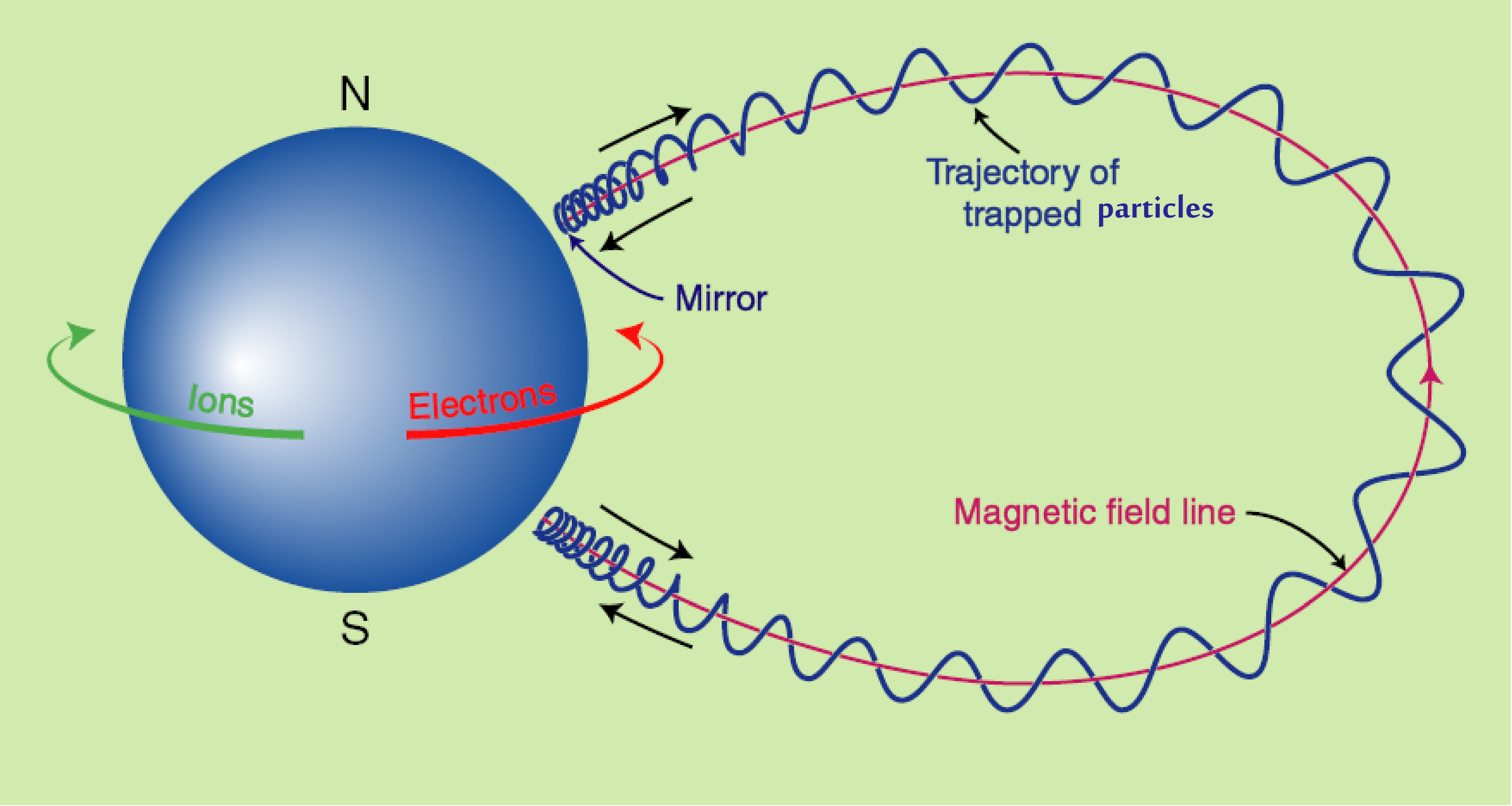
Geomagnetic Storms

- Geomagnetic Tail loaded
- Reconnection results in earthward propagation & acceleration
- Subsequent acceleration through wave-particle interactions
- Transport through radial diffusion
- Loss in storms
- Results in very dynamic population

Trapped particles

Three Motions

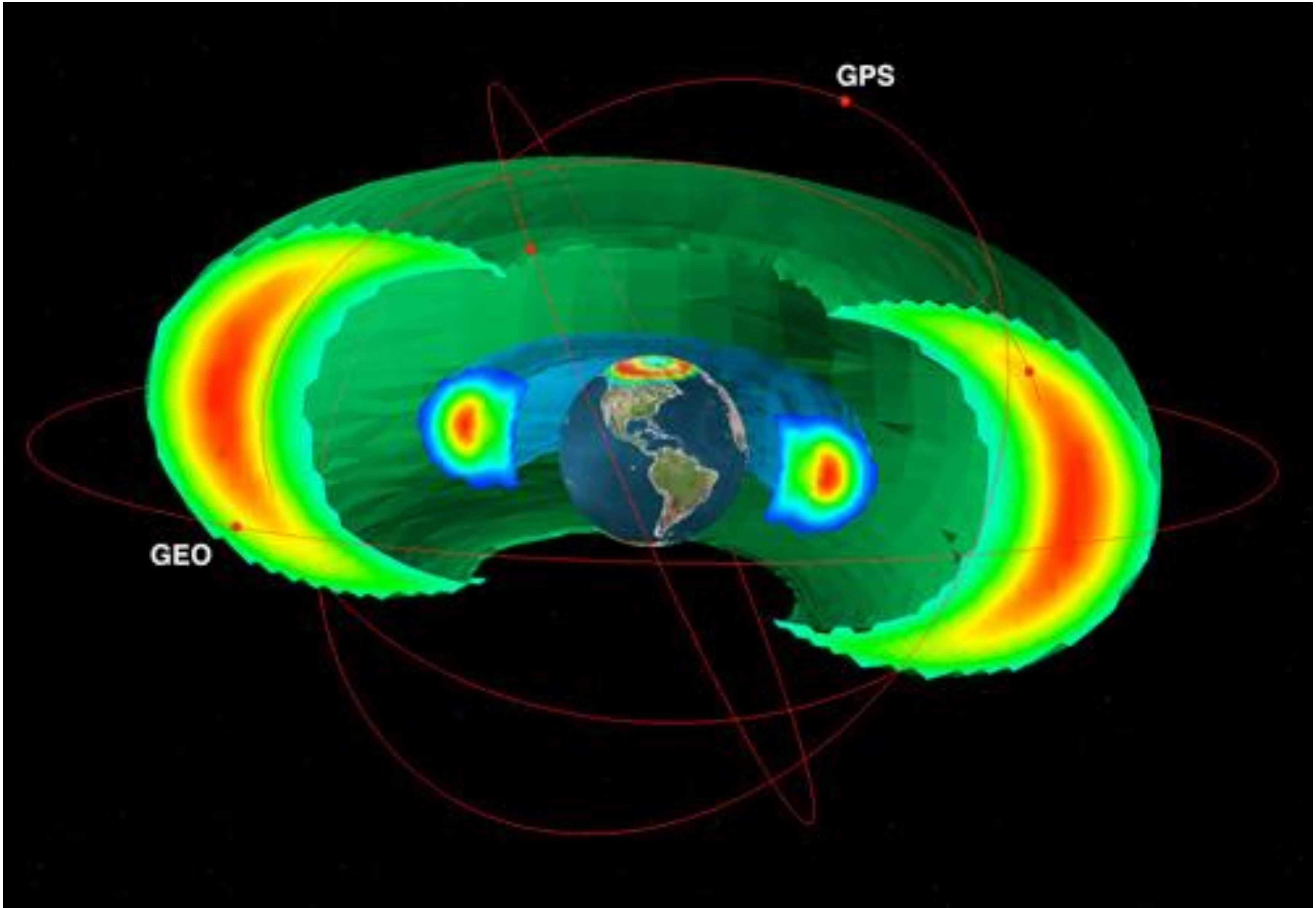
gyration; bounce; drift



Typical parameters of trapped radiation

	Particle	
	1 MeV Electron	10 MeV Proton
Range in aluminium (mm)	2	0,4
Peak equatorial omnidirectional flux ($cm^{-2} s^{-1}$)	4×10^6	3.4×10^5
Radial location (L) of peak flux (Earthradii)	4.4	1.7
Radius of gyration (km)		
@ 500 km @ 20 000 km	0.6 10	50 880
Gyration period (s)		
@ 500 km @ 20 000 km	10^{-5} 2×10^{-4}	7×10^{-3} 0.13
Bounce period (s)		
@ 500 km @ 20 000 km	0.1 0.3	0.65 1.7
Longitudinal drift period (min)		
@ 500 km @ 20 000 km	10 3.5	3 1.1

Radiation belts and satellite orbits



Trapped radiation belts (Van Allen belts)

Lifetimes

- **Proton belt:**
  - **Very stable**
  - **Trapping times can be 10s of years**
- **Electron belt:**
  - **Highly dynamic, trapping times: days or weeks**
  - **Always refilled vis solar-terrestrial interactions**
- **Proposals have been made to destroy the proton belt by scattering from long electromagnetic tethers with high charge**

Cosmic rays

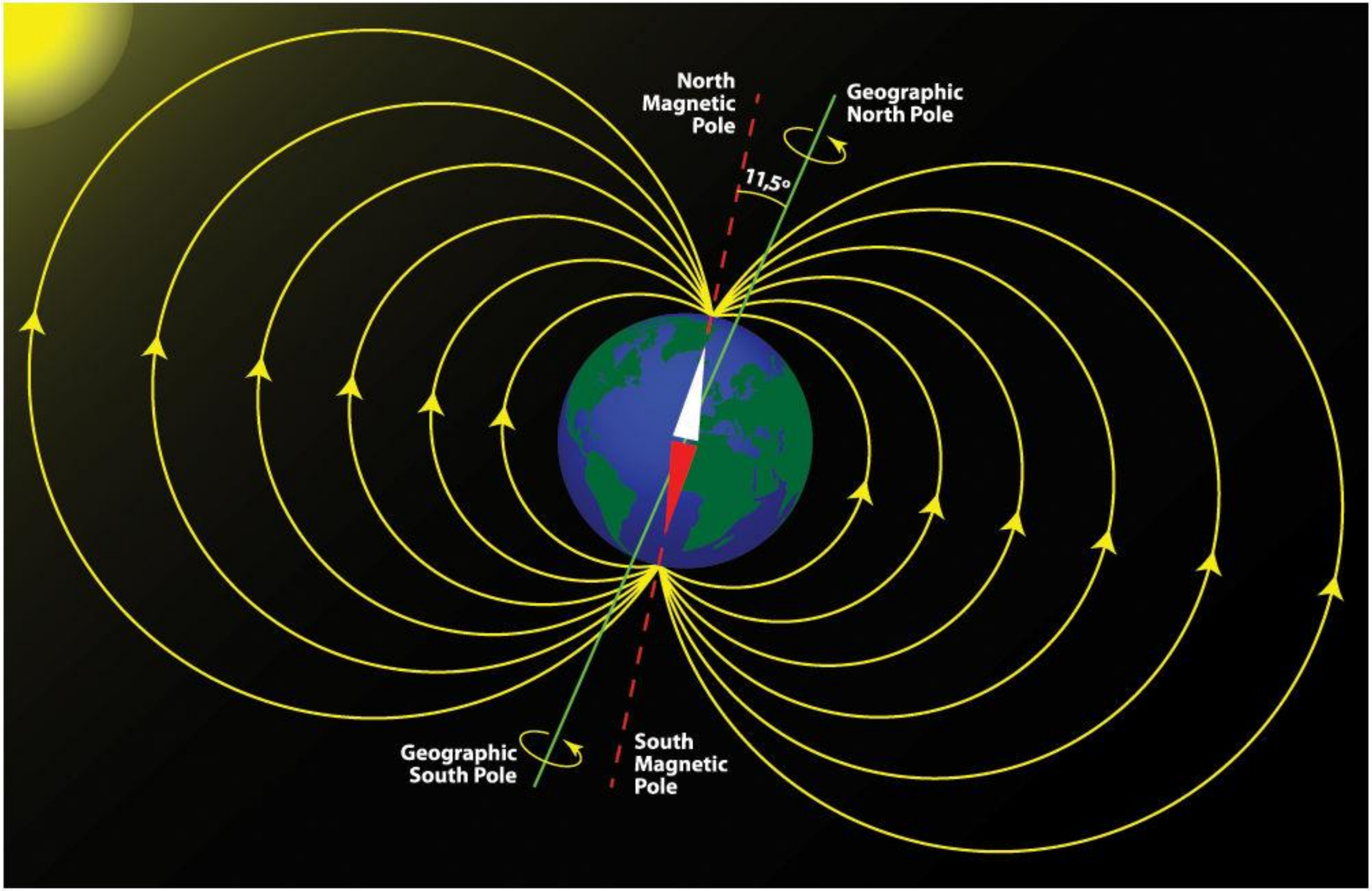
Galactic cosmic rays are very energetic protons and ions originating outside of our solar system

When they reach Earth they interact with atmospheric atoms creating cascades of secondary particles

Long term variations of the radiation environment in space

- Earth´s magnetic field
- Solar cycle

Earth magnetic field



Earth magnetic field

- **To the first approximation and when seen from larger distances the magnetic field is a dipole.**
- **The field strength of an ideal dipole is given by:**

$$B = M_d R^{-3} (1+3 \cos^2 \theta)^{1/2}$$

where

M_d: magnetic dipole moment,

R: radial component in Earth radii,

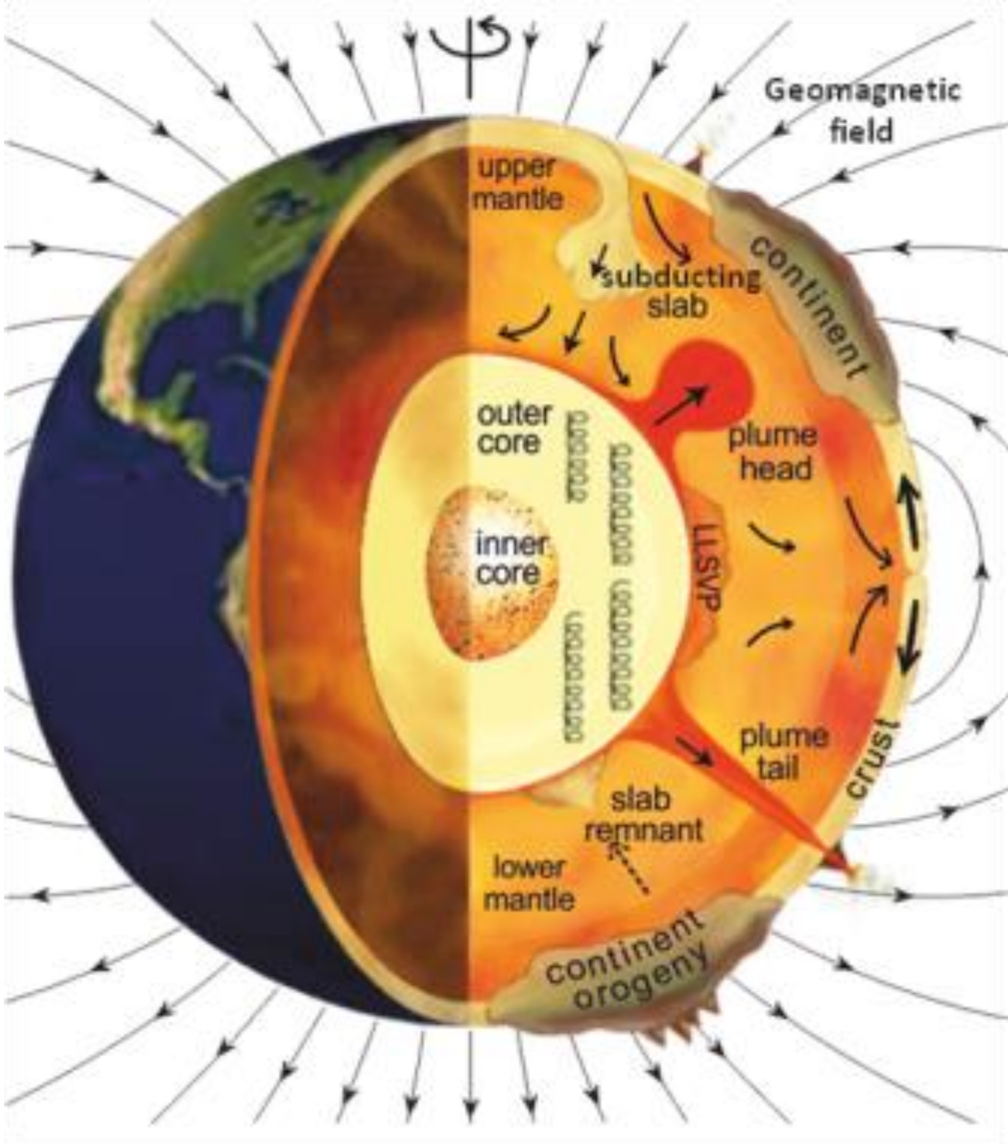
θ: magnetic latitude measured from the magnetic pole

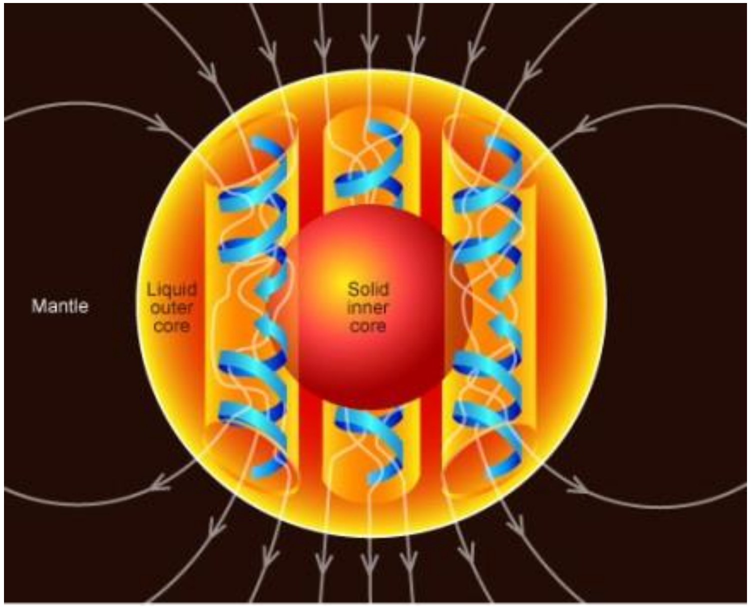
Earth magnetic field

- The magnetic field of Earth is mainly (to > 90%) caused by a magneto-hydrodynamic dynamo operating in the liquid outer core of Earth.
- External components from the ionosphere and the magnetosphere contribute as well.

- The magnetic field axis differs from Earth´s rotation axis
- The magnetic field changes, both in position and strenght

Origin of Earth magnetic field

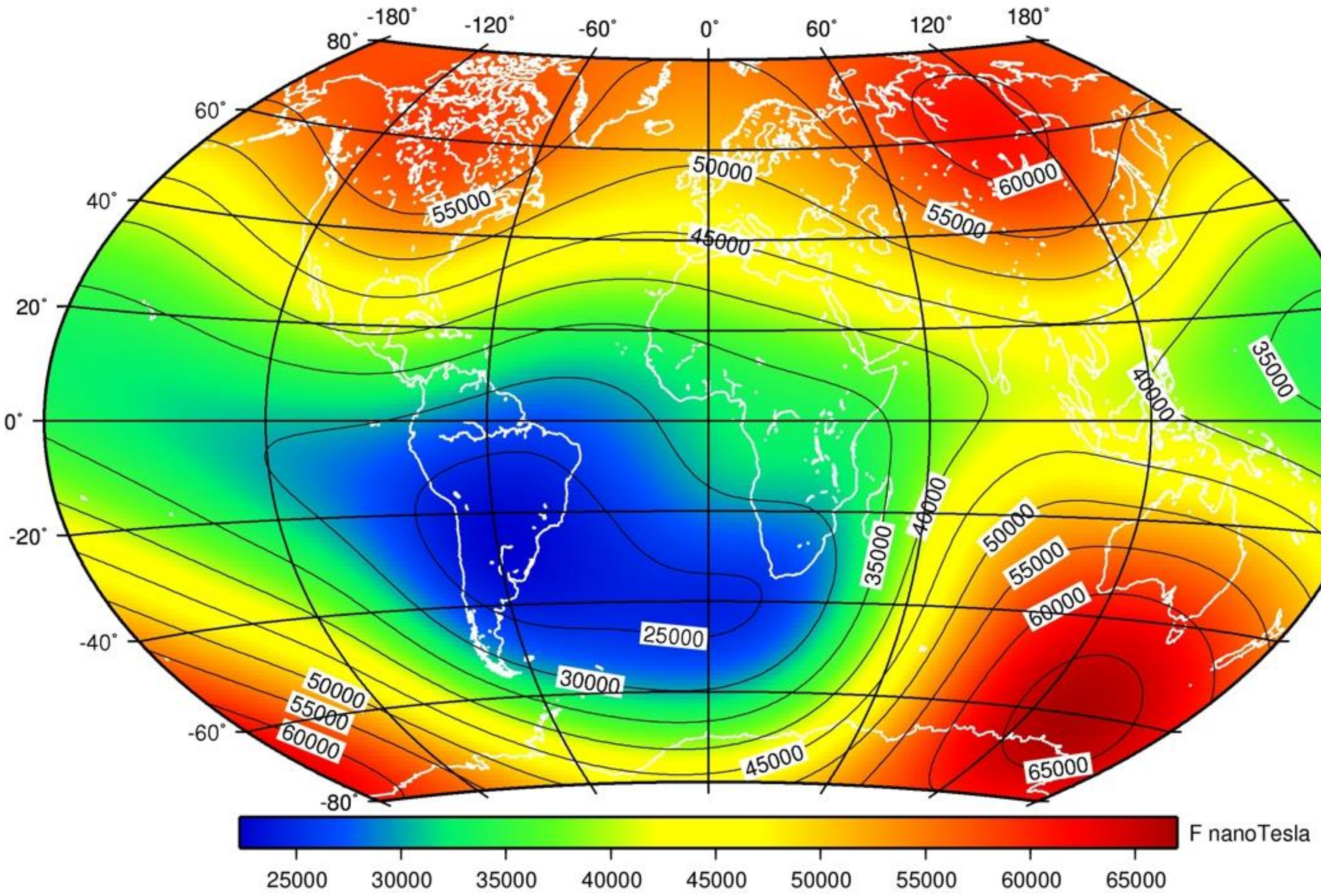




Earth magnetic field

- **Earth magnetic field is:**
  - **tilted relative to the rotation axis (by about 11°)**
  - **offset from the center of Earth (by about 560 km)**
- **The magnetic field was weakening by about 6 % during the last 110 years.**
- **Recent studies indicate an increase of the weakening up to ca 5% per decade (TBC)**
- **The offset is presently increasing by 10 -15 km per 5 years**
- **The magnetic field is changing its polarity at irregular intervals of a few hundred thousand to million years**
- **During such a reversal it does not vanish completely**

Earth magnetic field

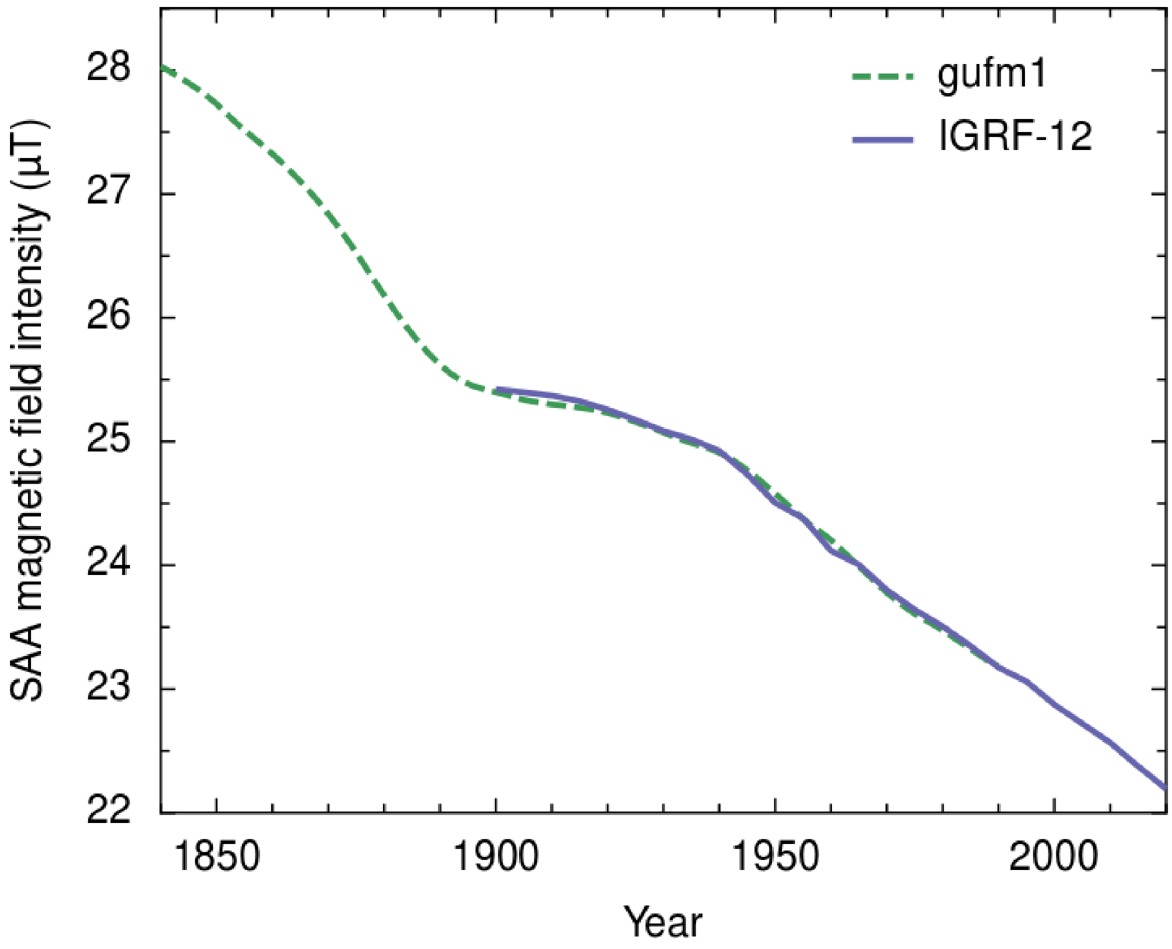


Changes in Earth magnetic field
From ECSS Space Environment Standard

Epoch	M_d (nT R_e^3)	Dipole tilt (Deg)	Offset from Earth centre (km)
1900	32 176	11.39	331
1930	31 433	11.47	378
1960	31 043	11.49	442
1990	30 318	10.86	515
2010	29 973	10.06	563

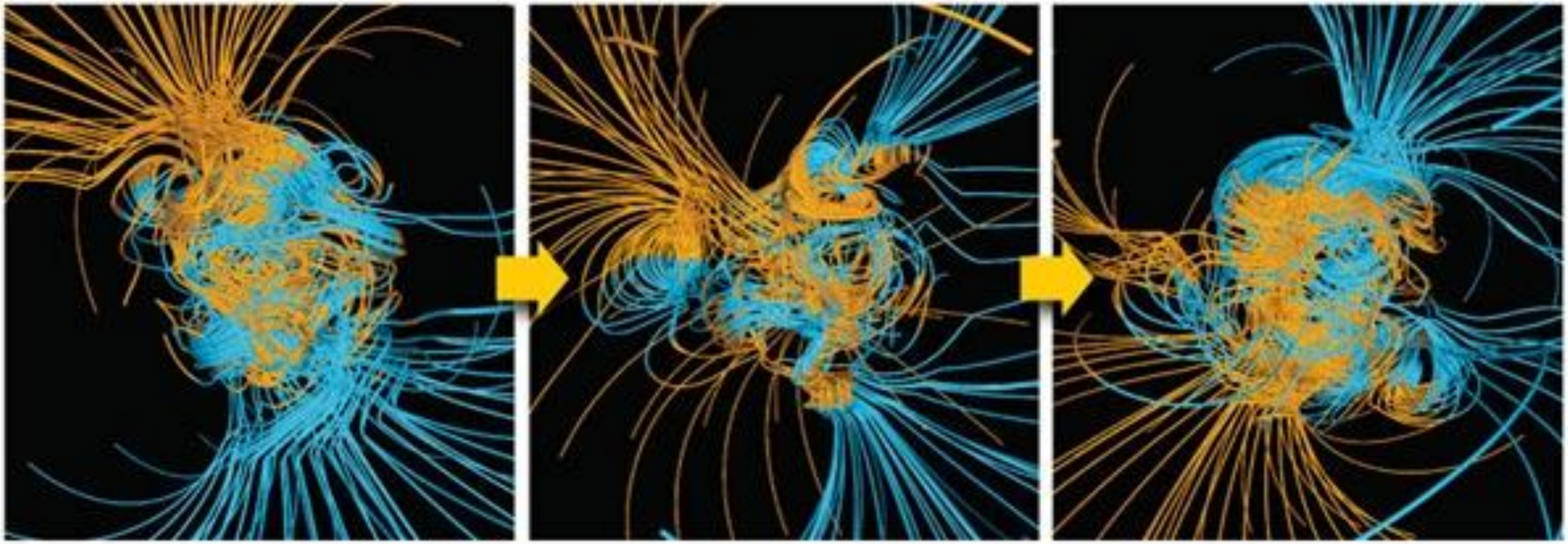
The Earth magnetic field in the SAA

gufm1: historic model for 1590 - 1990
IGRF: International Geomagnetic Reference Field

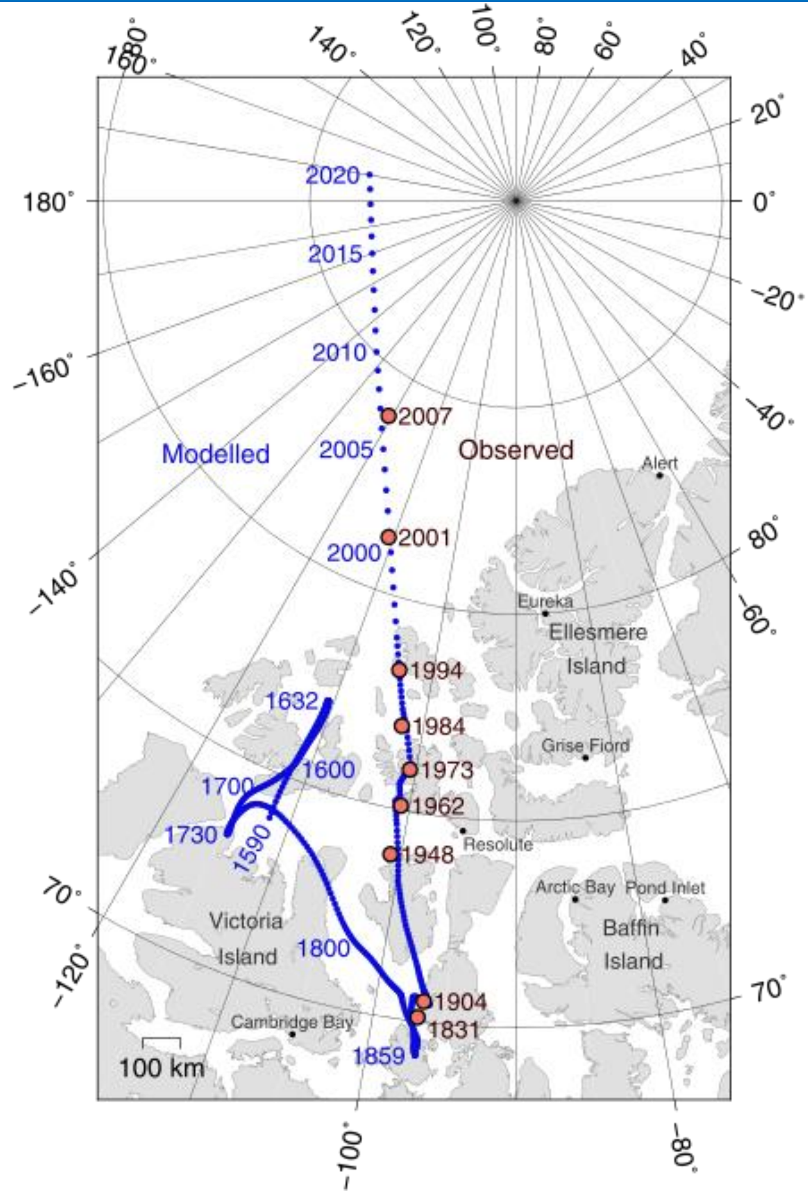


The changing Earth magnetic field
Source: NASA

Simulation: the magnetic field before, during and after reversal



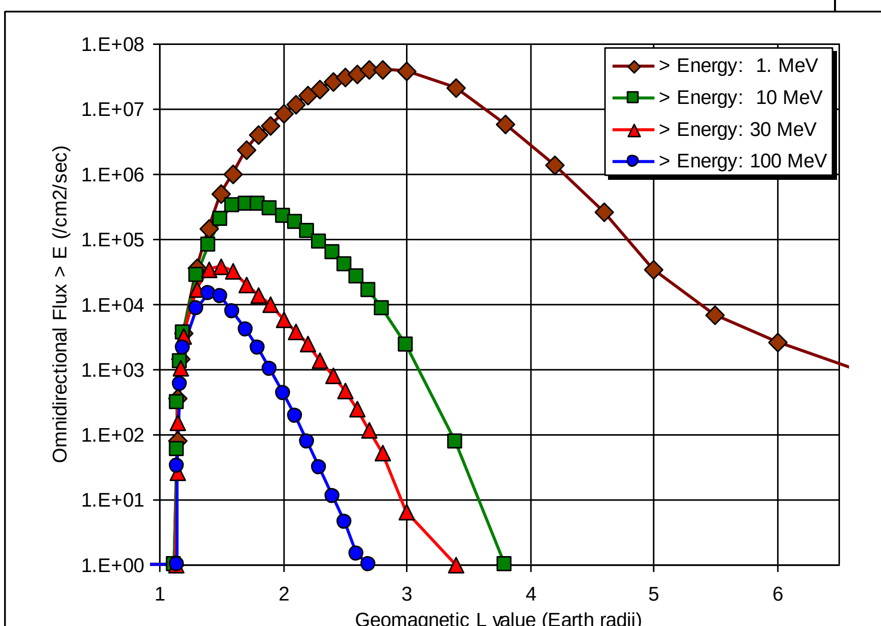
Position of magnetic North pole

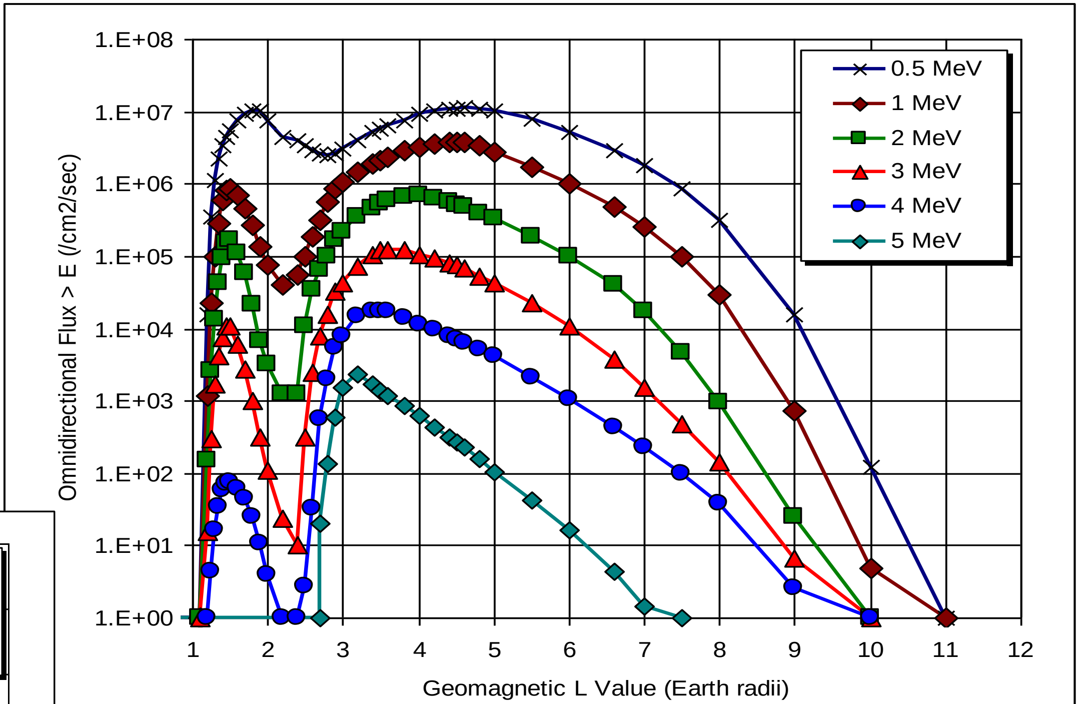


Radiation belt models

Models of radiation belts provide engineers with quantitative data

Proton fluxes

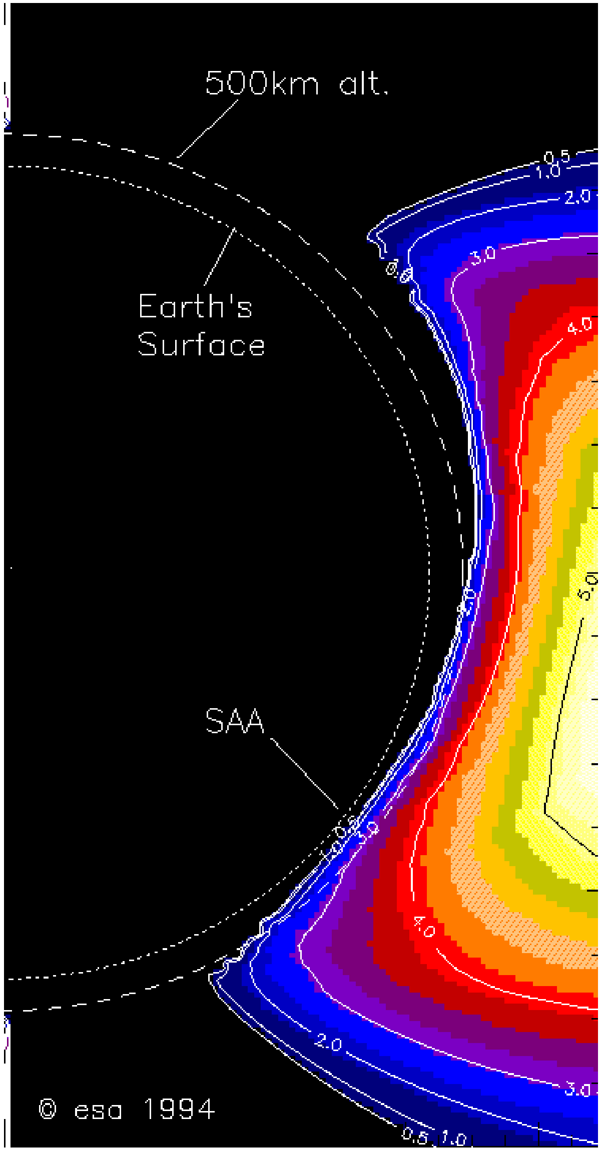




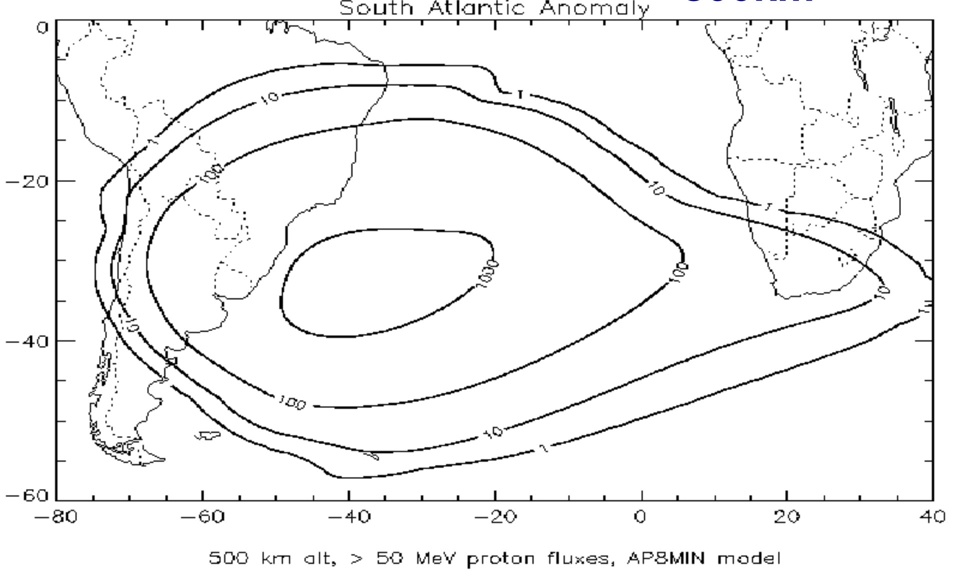
Electron fluxes

Radiation belt models have to use the correct magnetic field epoch

Radiation, SAA

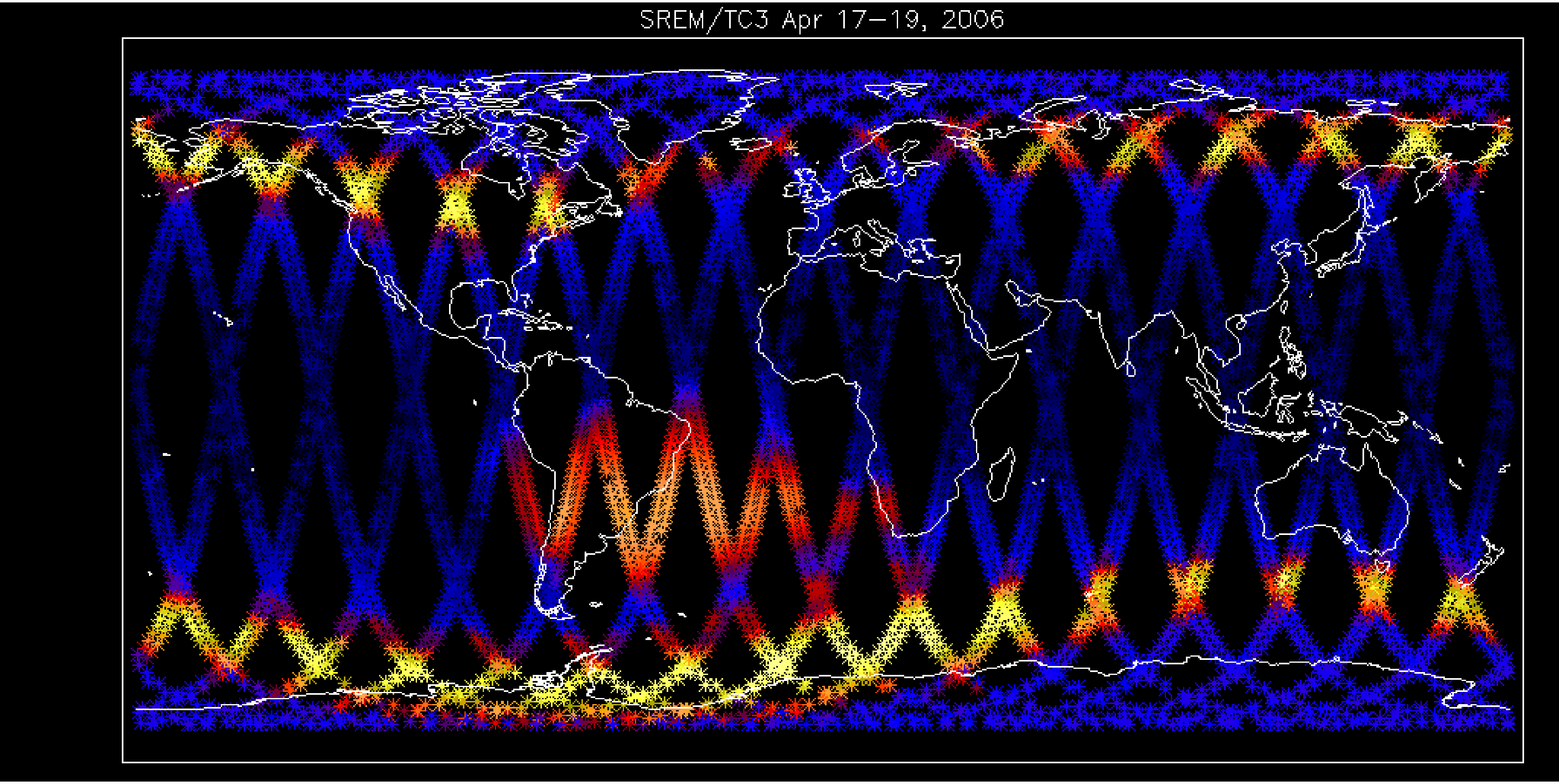


The South Atlantic Anomaly (SAA)

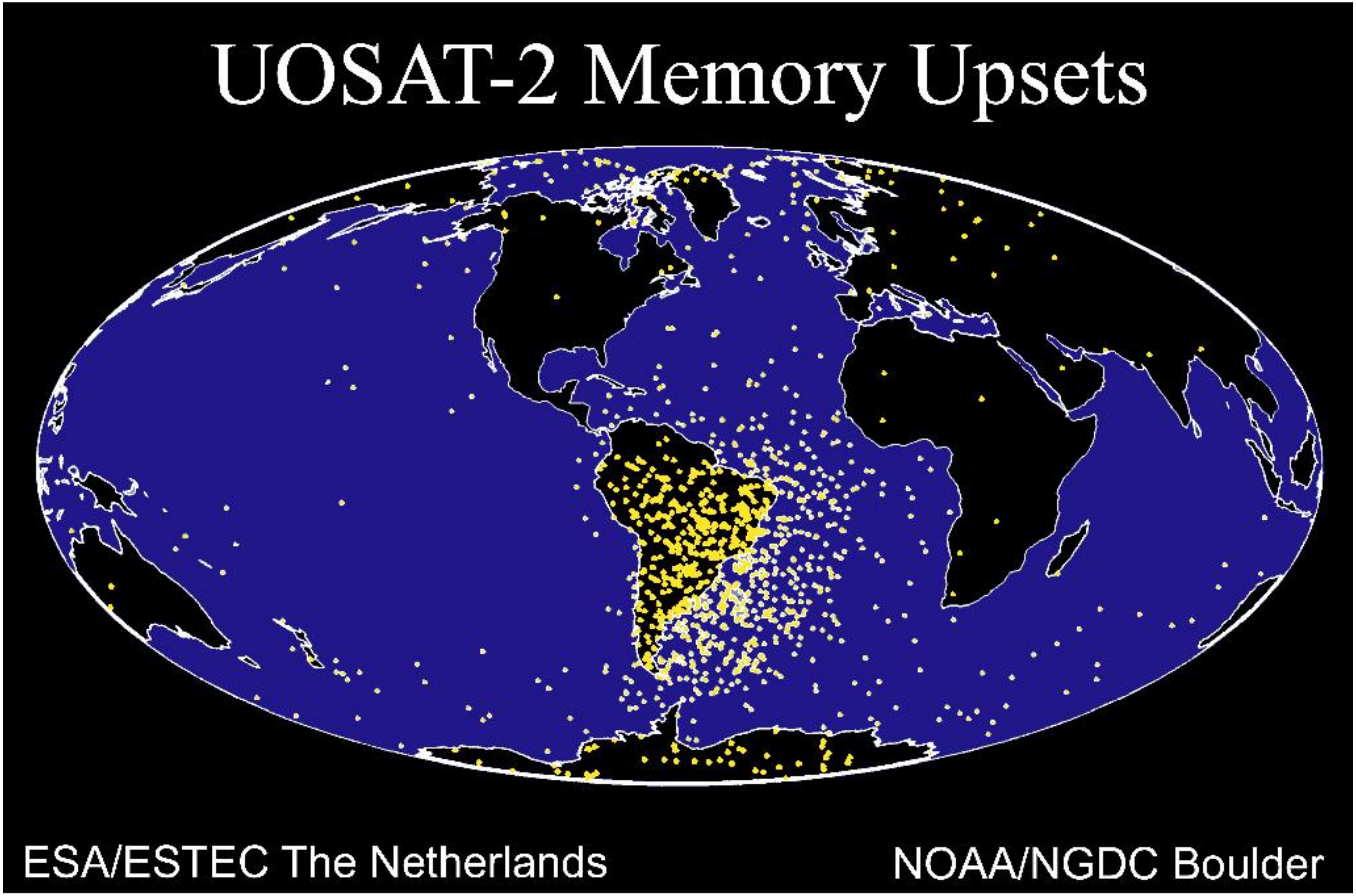


- Earth's magnetic field is an offset, tilted and distorted dipole
- Brings radiation belt down in the south Atlantic

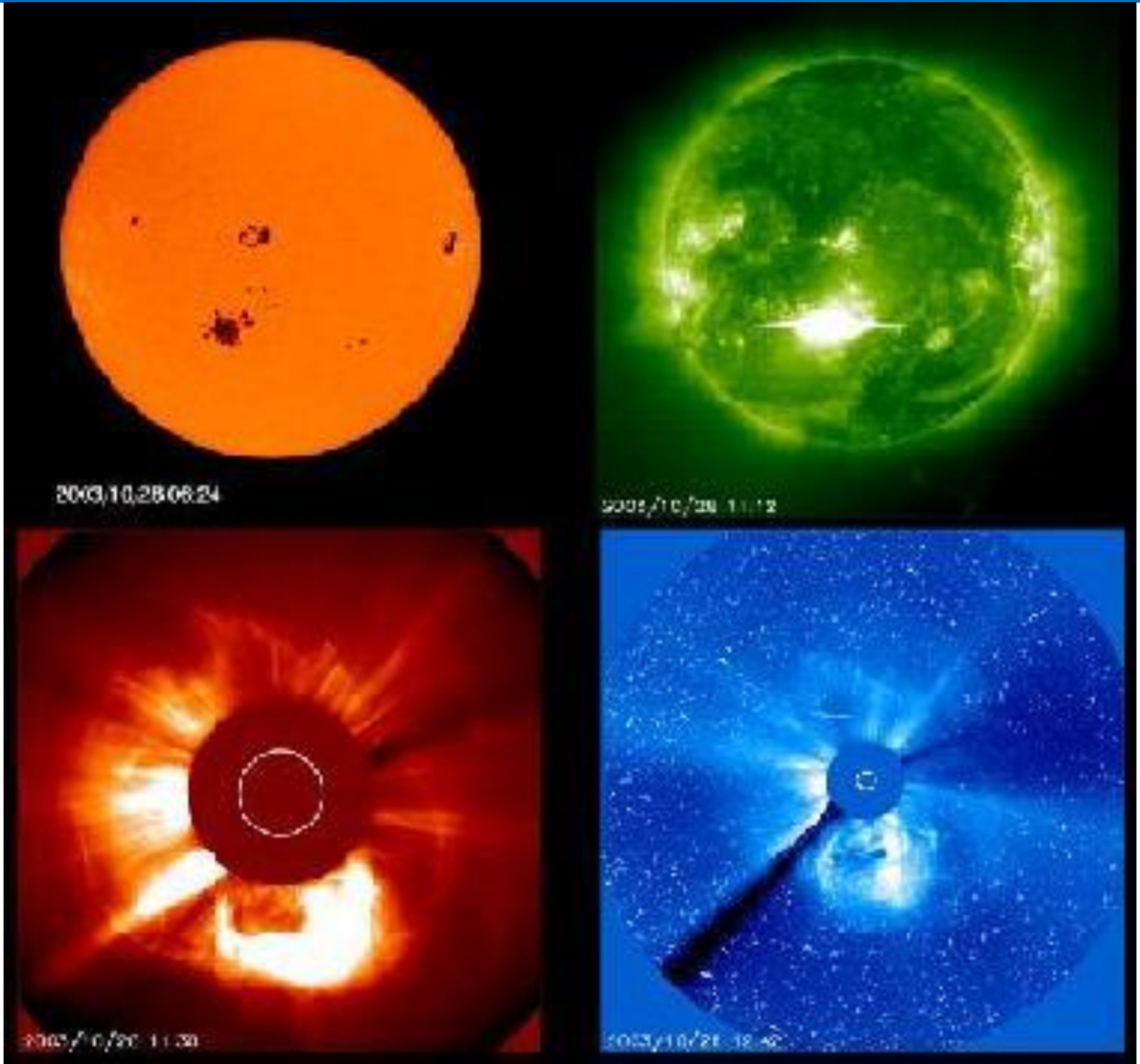
Electron fluxes on PROBA-1 satellite at ca 600 km
Source: ESA



Radiation, recorded anomalies of UOSAT-2



The solar activity



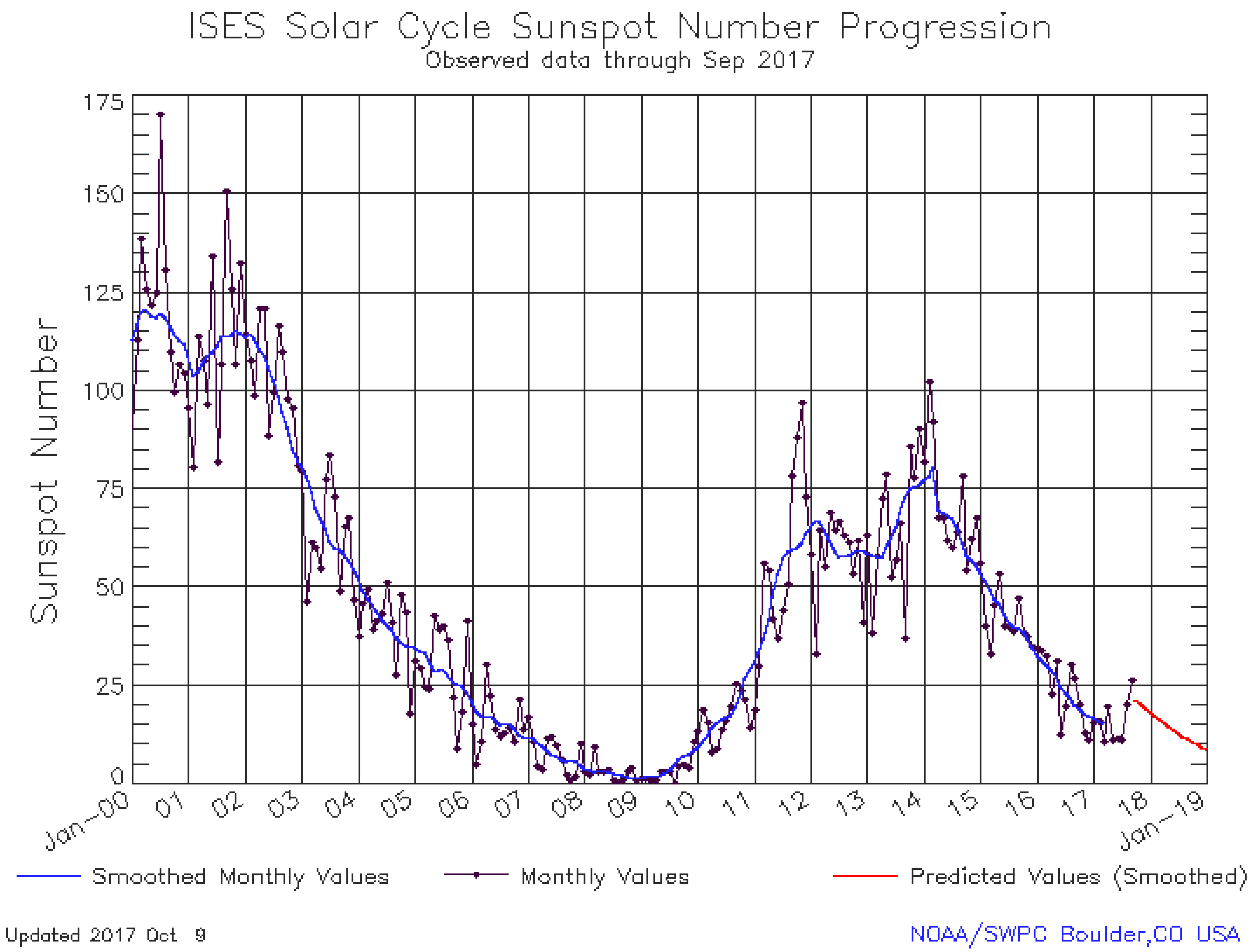
The solar activity

- **The solar activity has a cycle of about 11 years**
- **(but it varies between 8 and 16 years)**

- **The cycle is driven by the evolution of magnetic fields**
- **After each cycle the orientation of the magnetic fields is reversed**

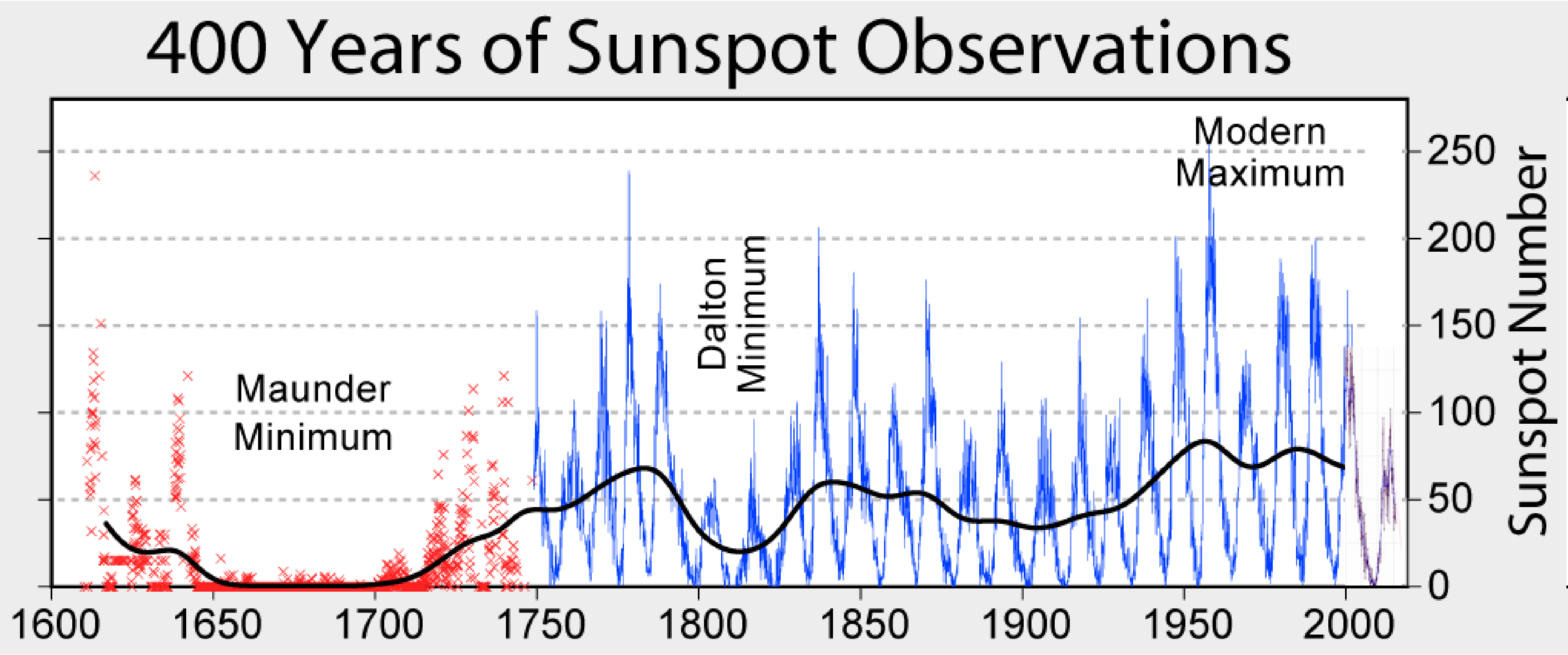
- **Systematic recording started in 1750 with the maximum of cycle 1 around 1760**
- **We are now in Solar Cycle 24**

Solar activity: solar cycles

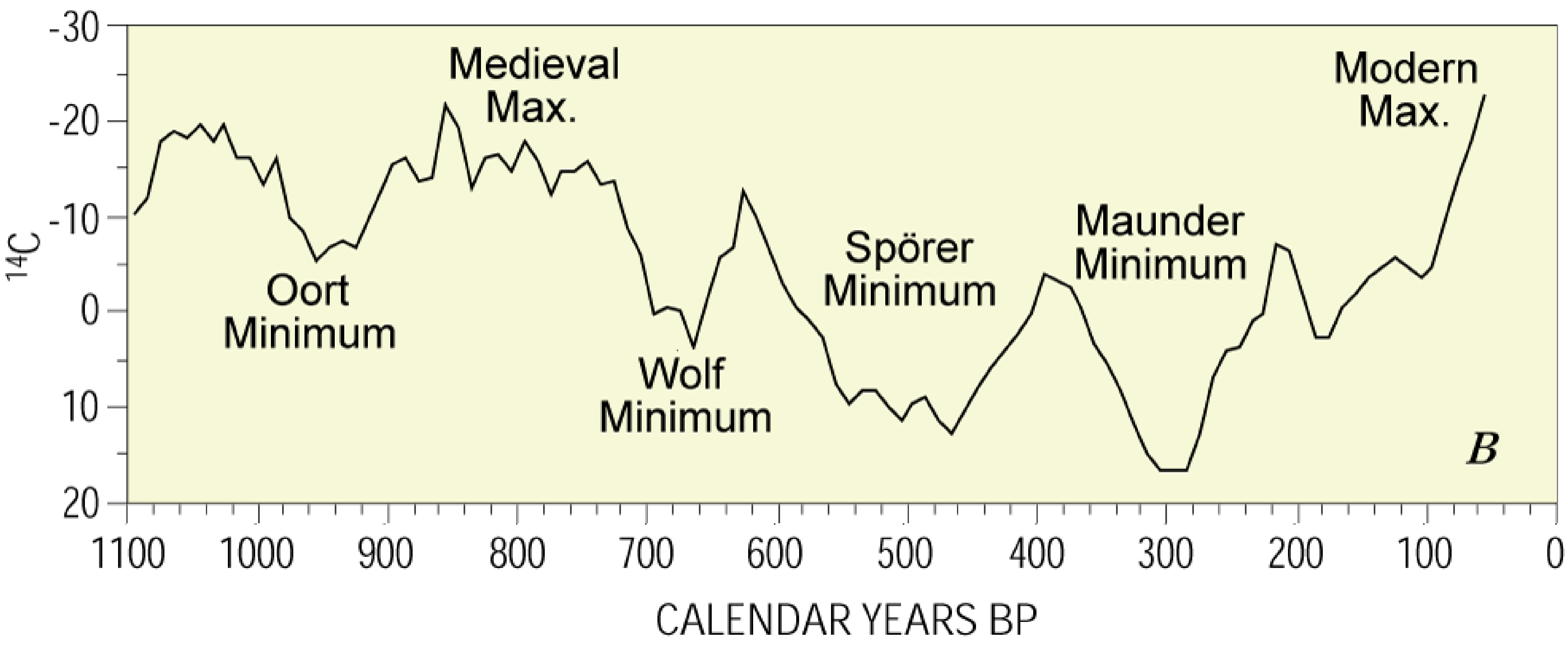


Solar activity: solar cycles

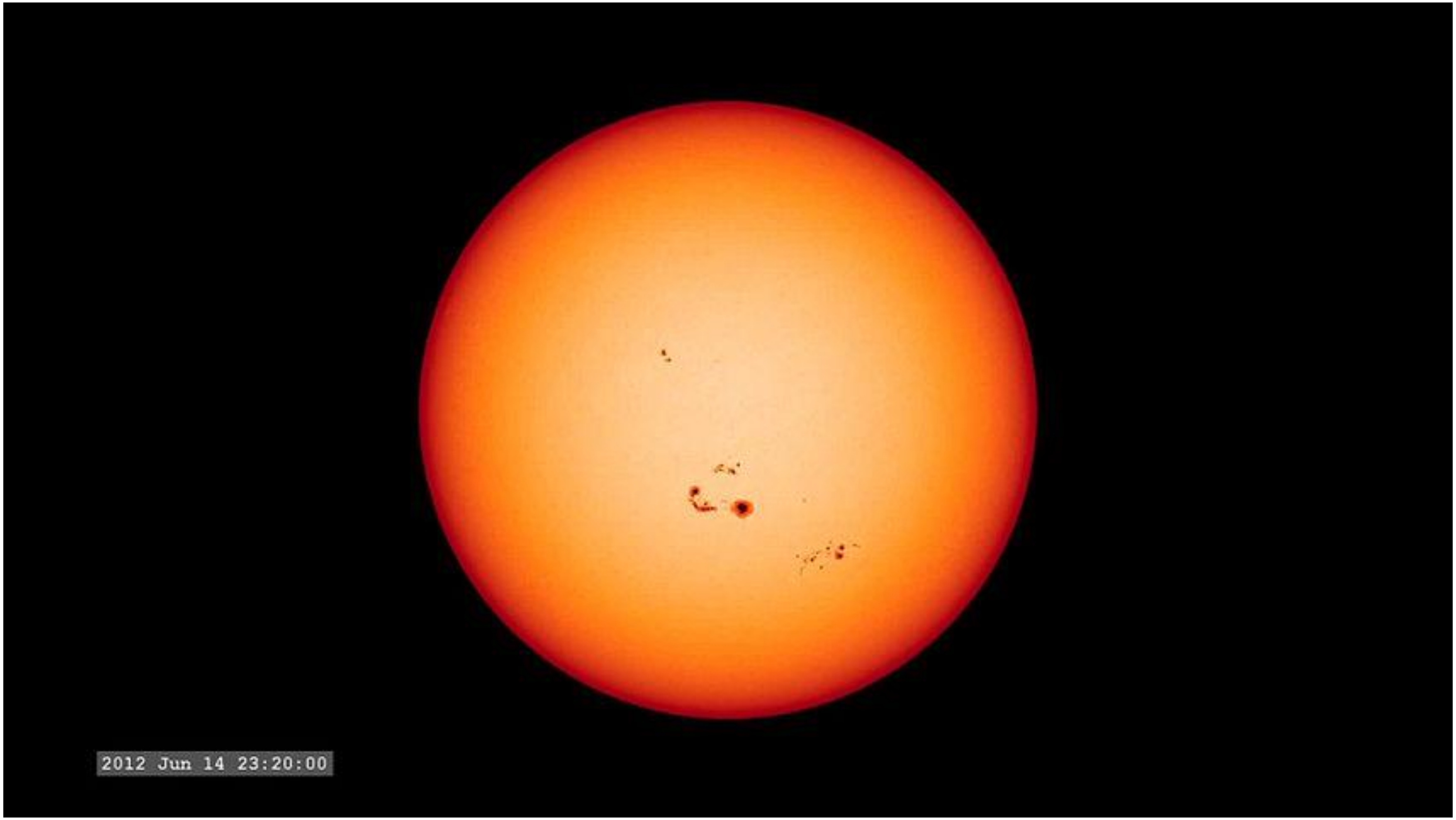
Image: NASA/MSFC



Solar activity: solar cycles
Image: US Geol. Survey



Solar activity: Sunspots



Sunspots

One marker of high solar activity are sunspots

Sunspots are darker and cooler areas on the sun.

The temperature of sunspots is typically 3000-4500K

Sunspots can be much larger than Earth

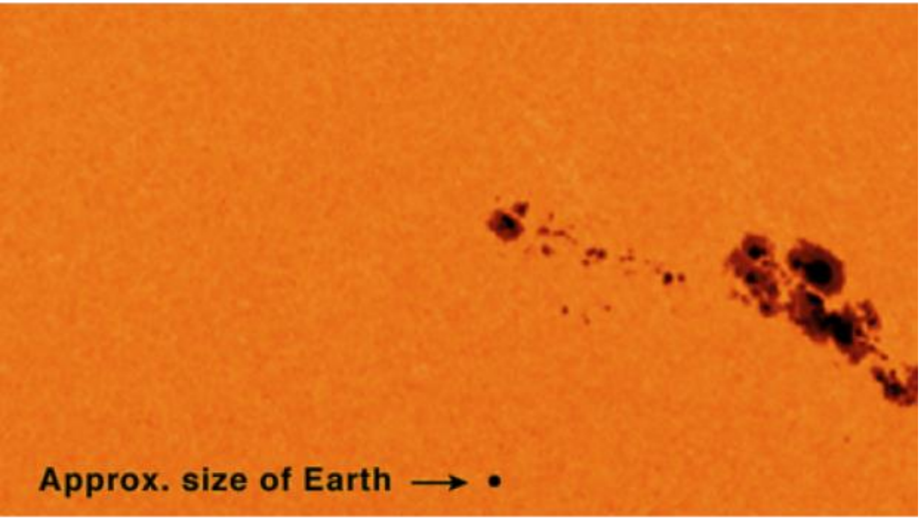
They often come in pairs and groups

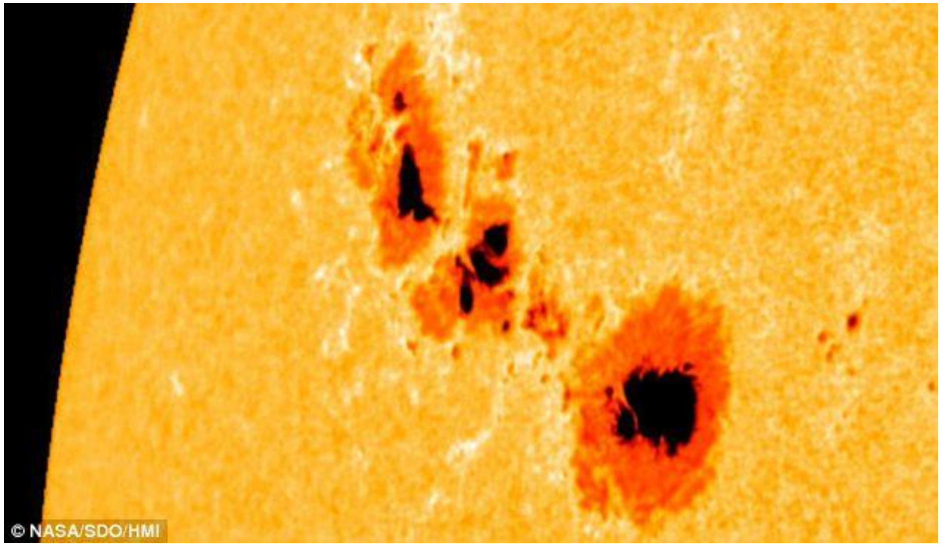
Sunspots can exist for days, weeks or months

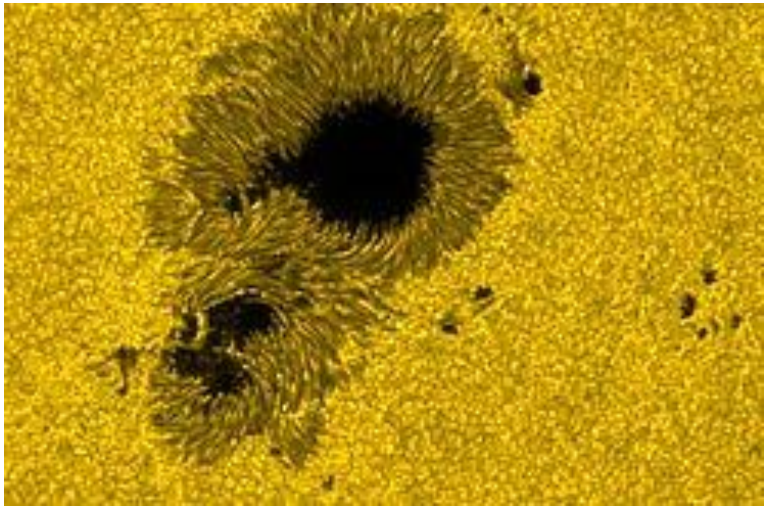
Near sunspots are hotter active areas.

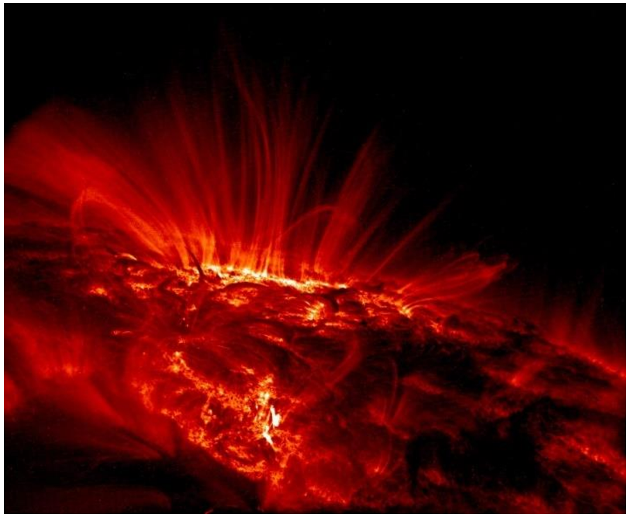
The net results is an increase of the total solar radiation by about 0.1% during solar maximum

Sun spots
Images: NASA





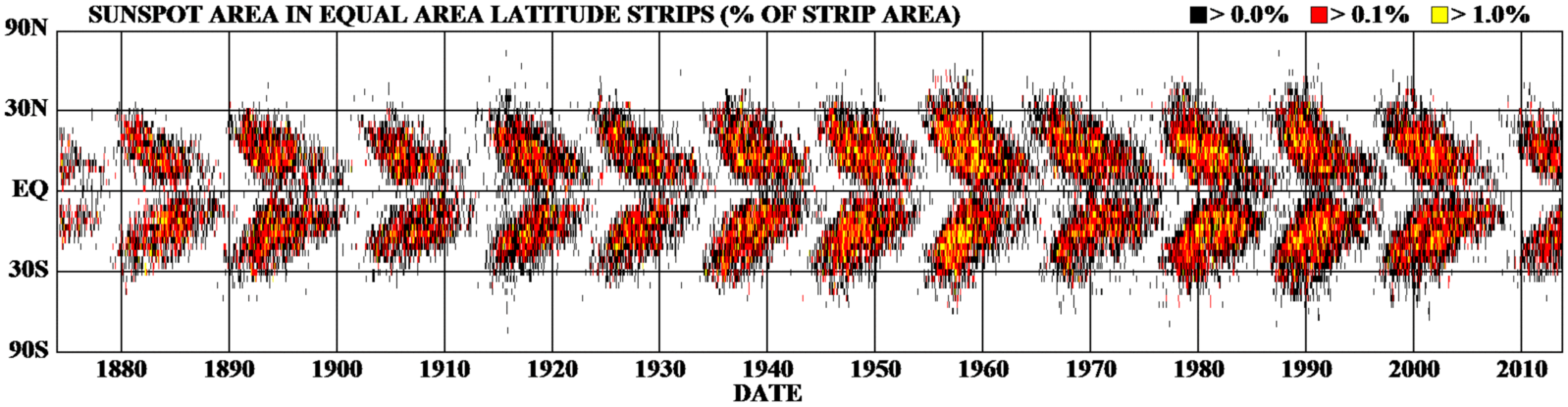




Solar activity: Sunspots
Image: NASA/GSFC

Sun spots move from higher latitudes to the Equator during one cycle.

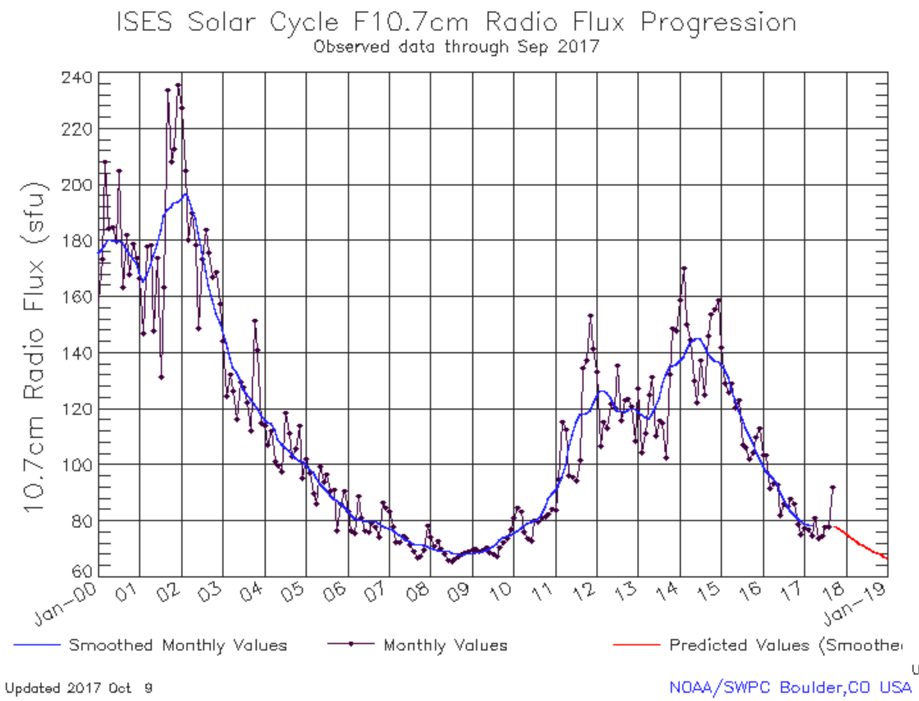
Sunspots from different cycles can be present simultaneously

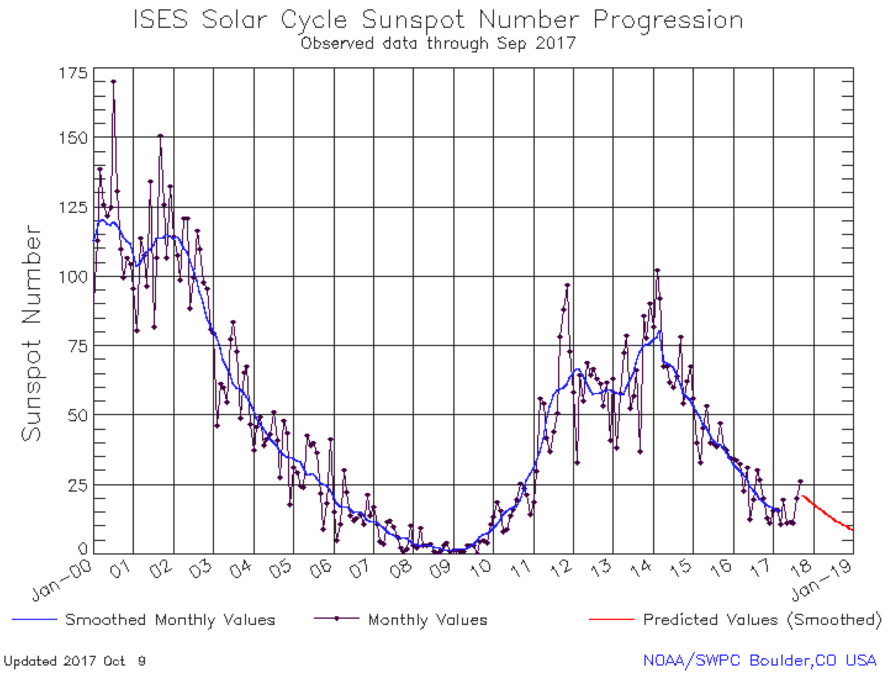


Solar activity: Sunspots and F10.7 flux

- **F10.7 flux: solar flux at a wavelenghts of 10.7 cm in units of 10^4 Jansky (one Jansky equals 10^{-26} Wm^{-2} Hz^{-1}).**
- **This unit is often called sfu (solar flux unit)**
- **Sunspot number, R:**
- **$R = k\,(10\,g + s)$**
- **were**
  - **s is the number of individual spots**
  - **g the number of sunspot groups**
  - **k is an observatory factor**
- **Empirical relation F10.7 with R (averaged over 1 month or longer):**
- **$F10.7 = 63.7 + 0.728R + 8.9\times10^{-4}R^2$**

Solar activity: Sunspots and F10.7 flux





Solar activity: Sunspots and F10.7 flux

- The F10.7 flux is a good proxy of the UV flux of the sun
- The total solar output changes only by about 0.1 % during a solar cycle
- But the UV and radio flux can change by factors 2-3 or more (being highest at high solar activity)
- The energetic UV flux is important for the Earth atmosphere
- The F10.7 flux can be measured from the ground, but the UV flux cannot.

The solar constant

The total solar radiation at 1 AU from the sun (average Earth-sun distance) is called: solar constant

It is defined as flux to a surface normal to the sun.

It´s value is:

$S=1361\ W/m^2$ (older value was $1366\ W/m^2$)

It ranges from $1321\ W/m^2$ (Jul) to $1412\ W/m^2$ (Jan)

The solar flux at the surface of Earth (without clouds) varies from ca:

$700\ W/m^2 – 900\ W/m^2$

Radiation, variability

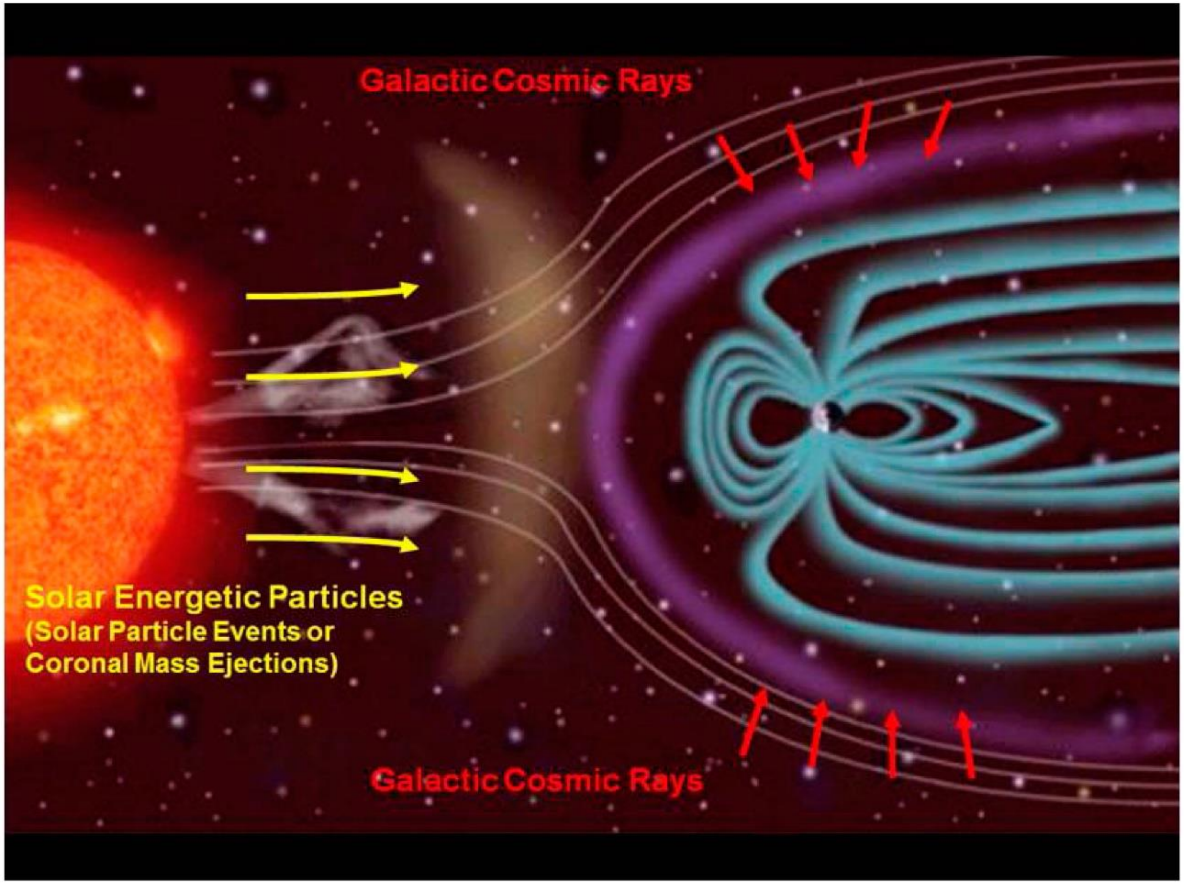
- **Trapped radiation levels are always present**
  - **At lower altitudes proton fluxes can be lower during solar maximum**
  - **Electron fluxes are usually higher at solar maximum**
- **Cosmic ray fluxes are lowest during solar maximum**
- **Energetic particle events from the sun (mainly high energy protons) can lead to high radiation levels for several hours**
- **The magnetosphere shields Earth from cosmic rays and energetic solar protons (cut-off rigidity, it depends on magnetic latitude, poles are ´open´)**
- **Extremely energetic cosmic rays can reach the ground from all directions and at all times**

Short term variations of the radiation environment in space

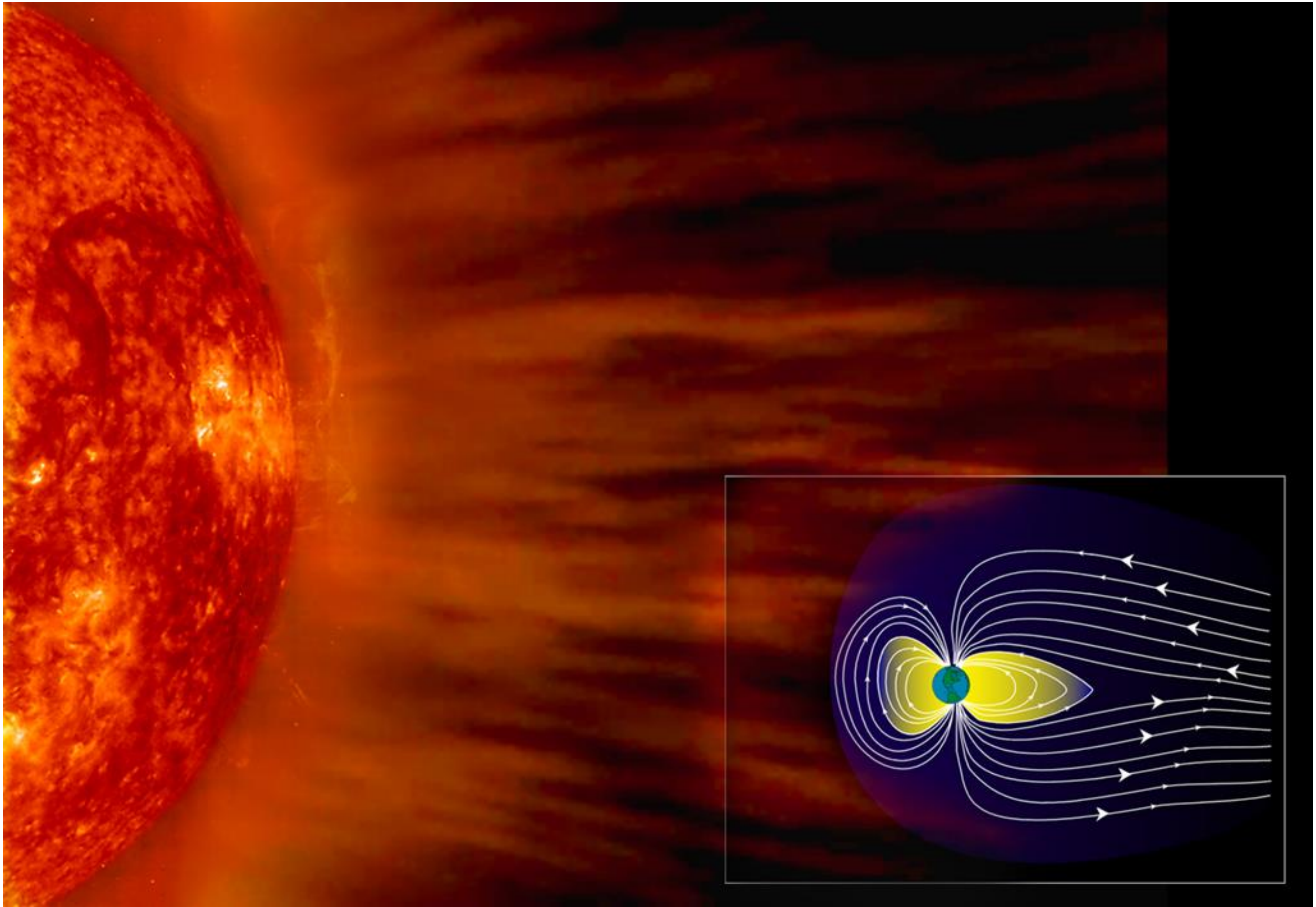
- Brief introduction to space weather
- Solar particle events

Solar particle events
image source: NASA

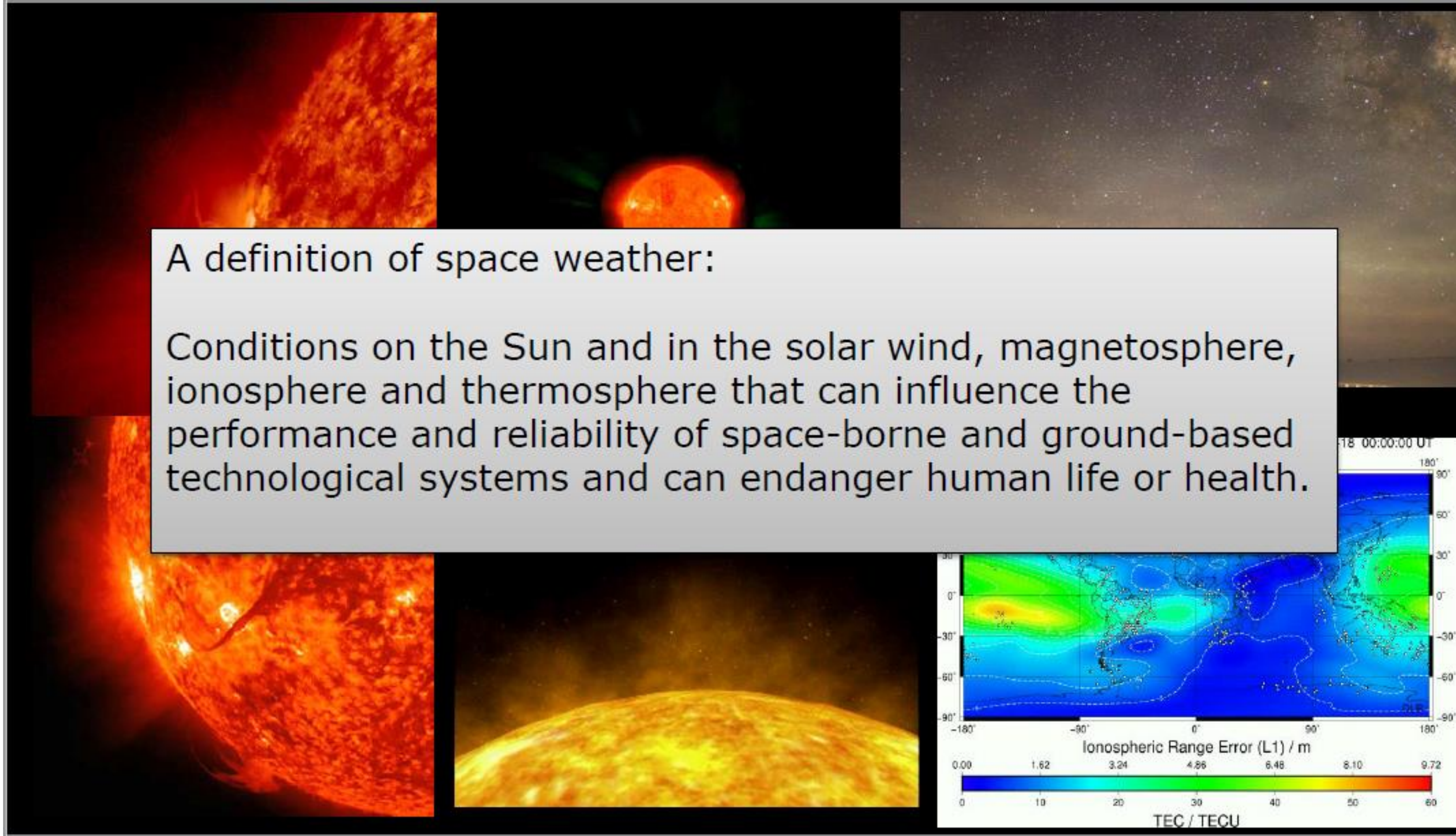
- Energetic particle events from the sun (mainly protons) occur at random intervals
- They can reach Earth within hours



Space Weather



Solar events



A definition of space weather:

Conditions on the Sun and in the solar wind, magnetosphere, ionosphere and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health.

Solar-terrestrial interaction

The magnetosphere is highly dynamic

The interaction with charged particles from the sun and their magnetic field leads to:

- **Disturbance of the magnetic field**
- **Injection of particles into magnetosphere**
- **Aurora at lower latitudes**
- **High energy plasma**
- **New (temporary) radiation belts**

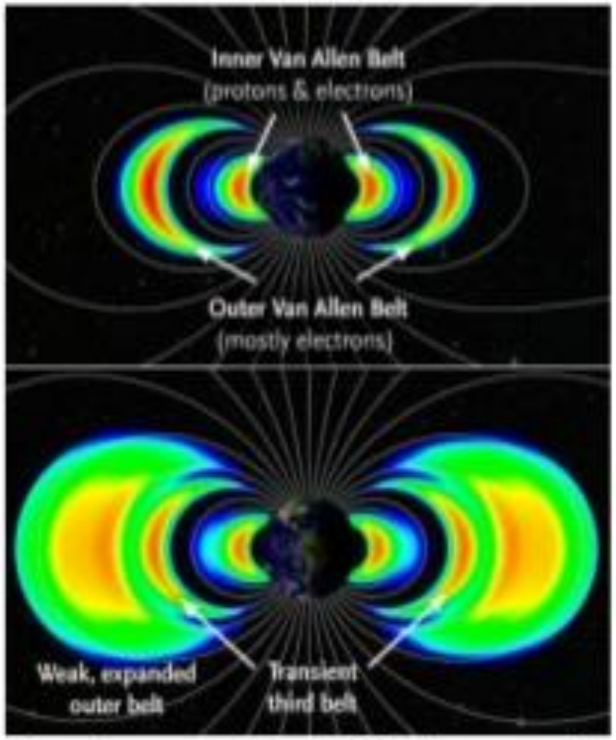
Visibility of Aurora Borealis

Visibility of Aurora Borealis

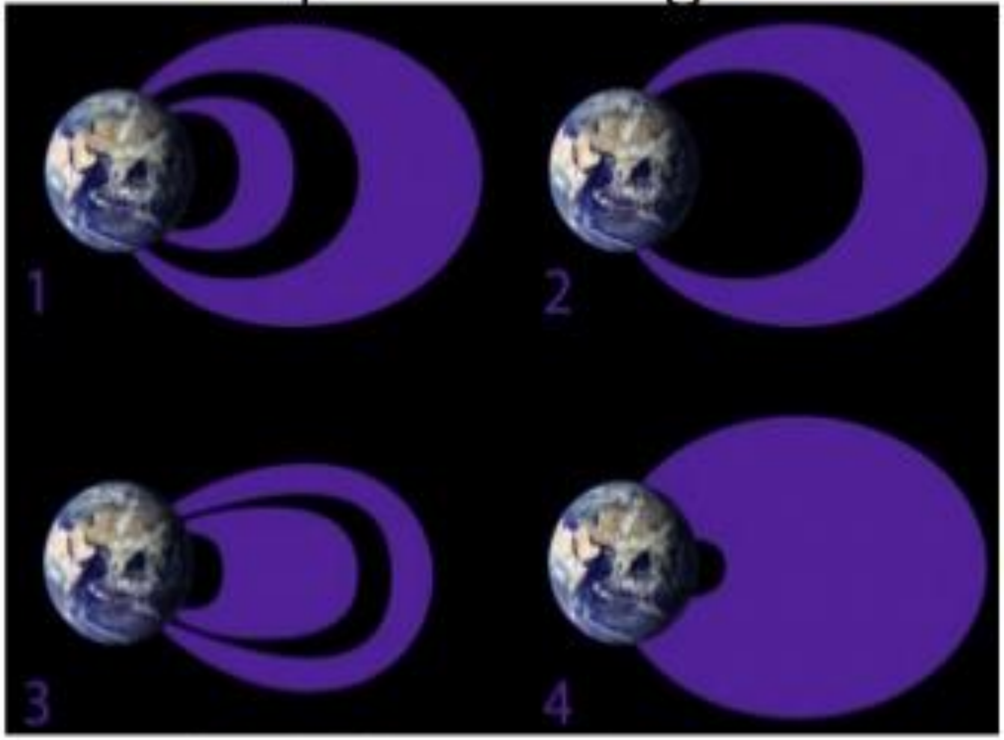
Kp: geomagnetic index

Radiation belts, variability

Radiation Environment: Earth Orbit
Van Allen Belts – drastic temporal changes

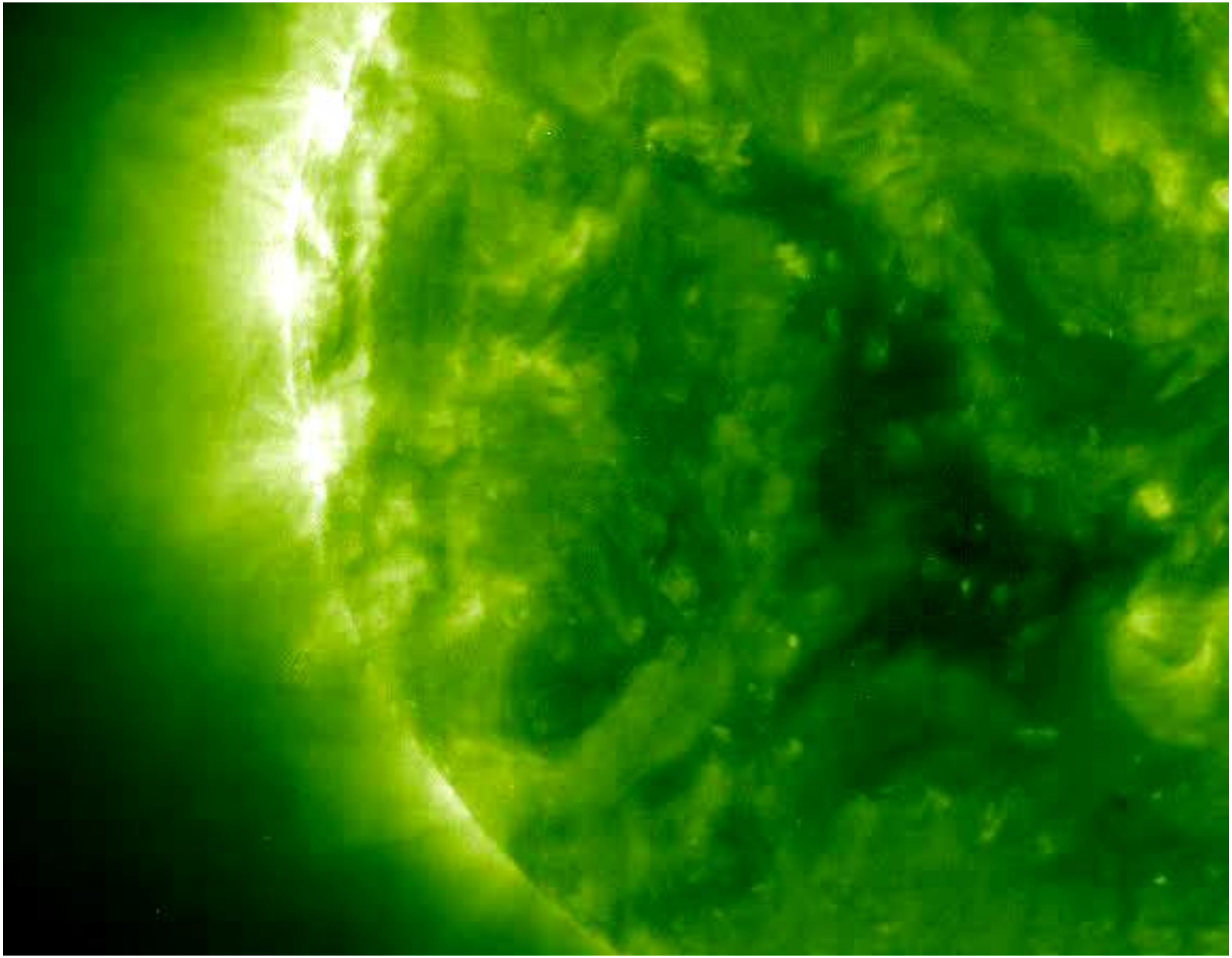


Transient event Sept. 2012; Image credit: NASA / JHU-APL / Univ. of Colorado

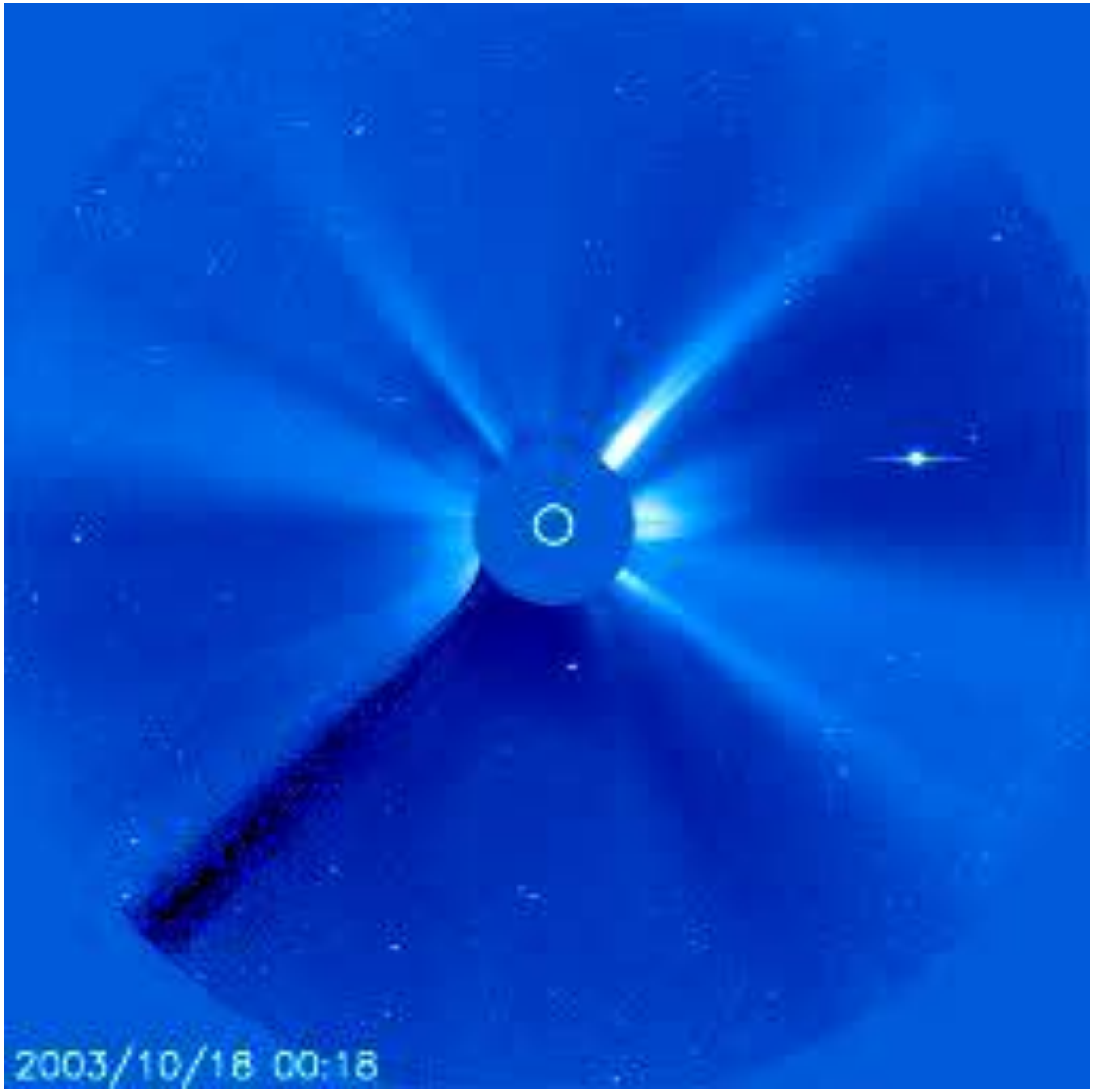


Dynamics of Van Allen belts; Image credit: NASA Goddard/Duberstein; DOI: 10.1002/2015JA021569

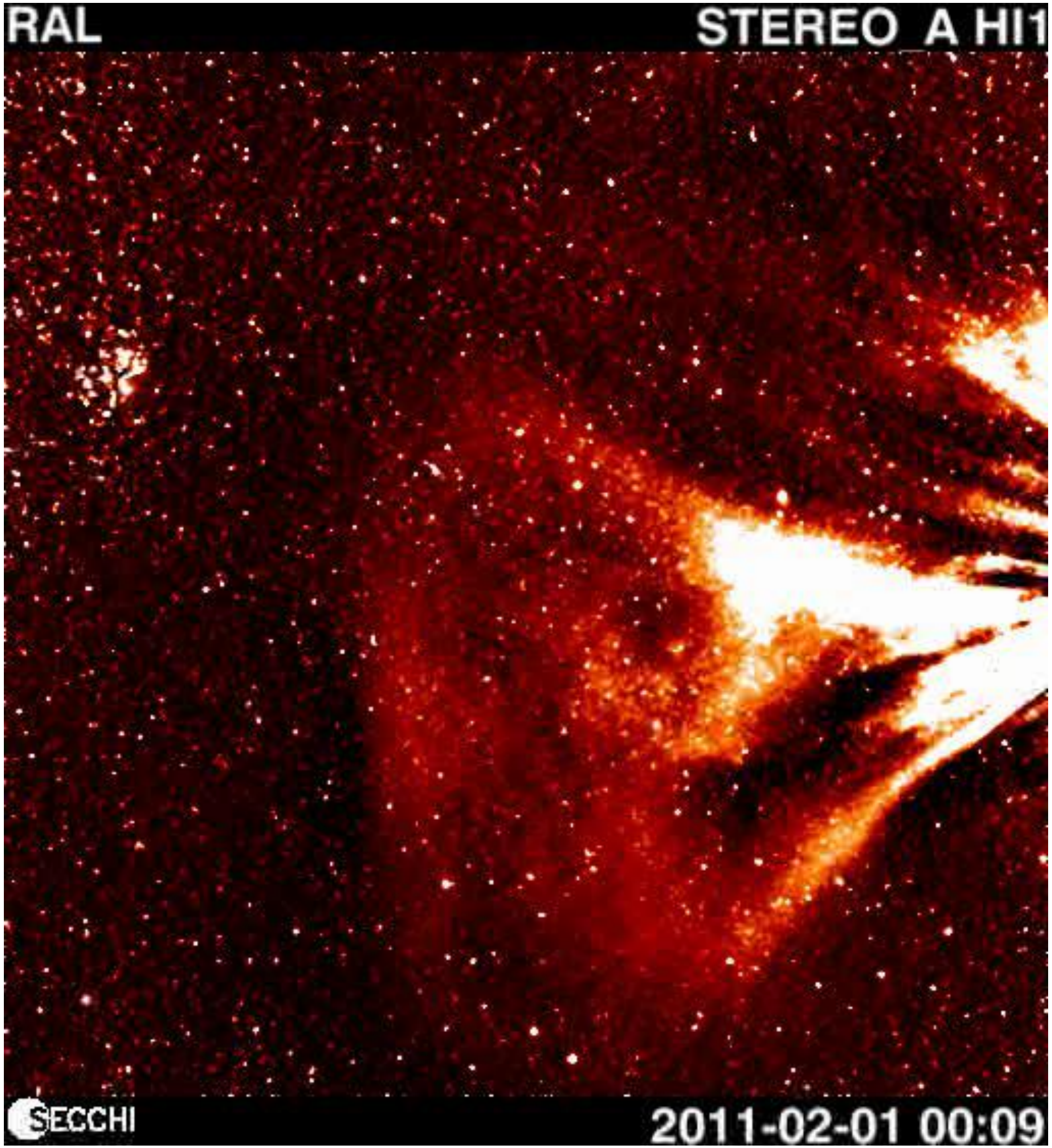
Solar electromagnetic (x-ray) flares
Image: SOHO, ESA/NASA



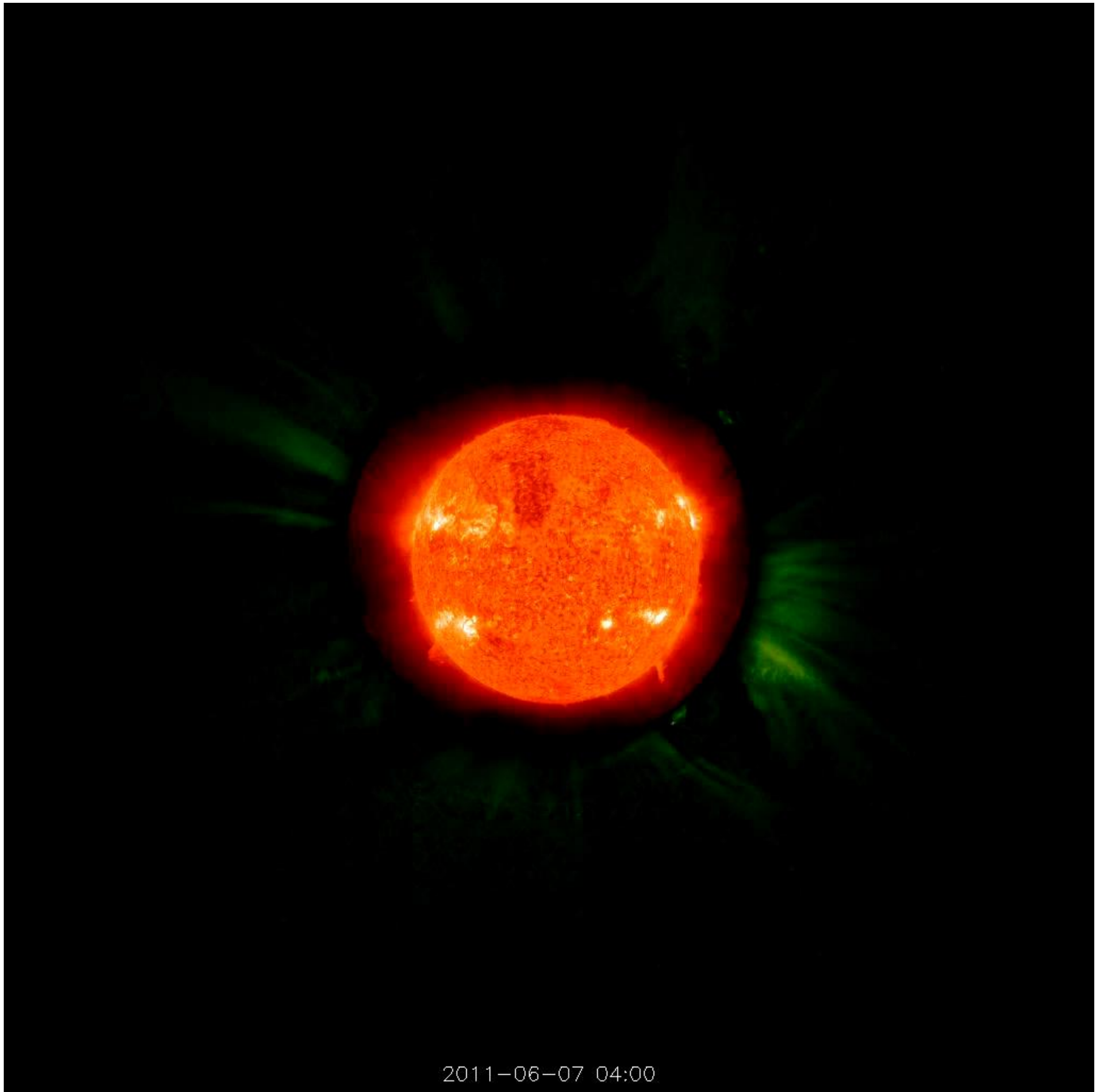
Solar Particle Events (SPE)



Coronal Mass Ejection (CME)



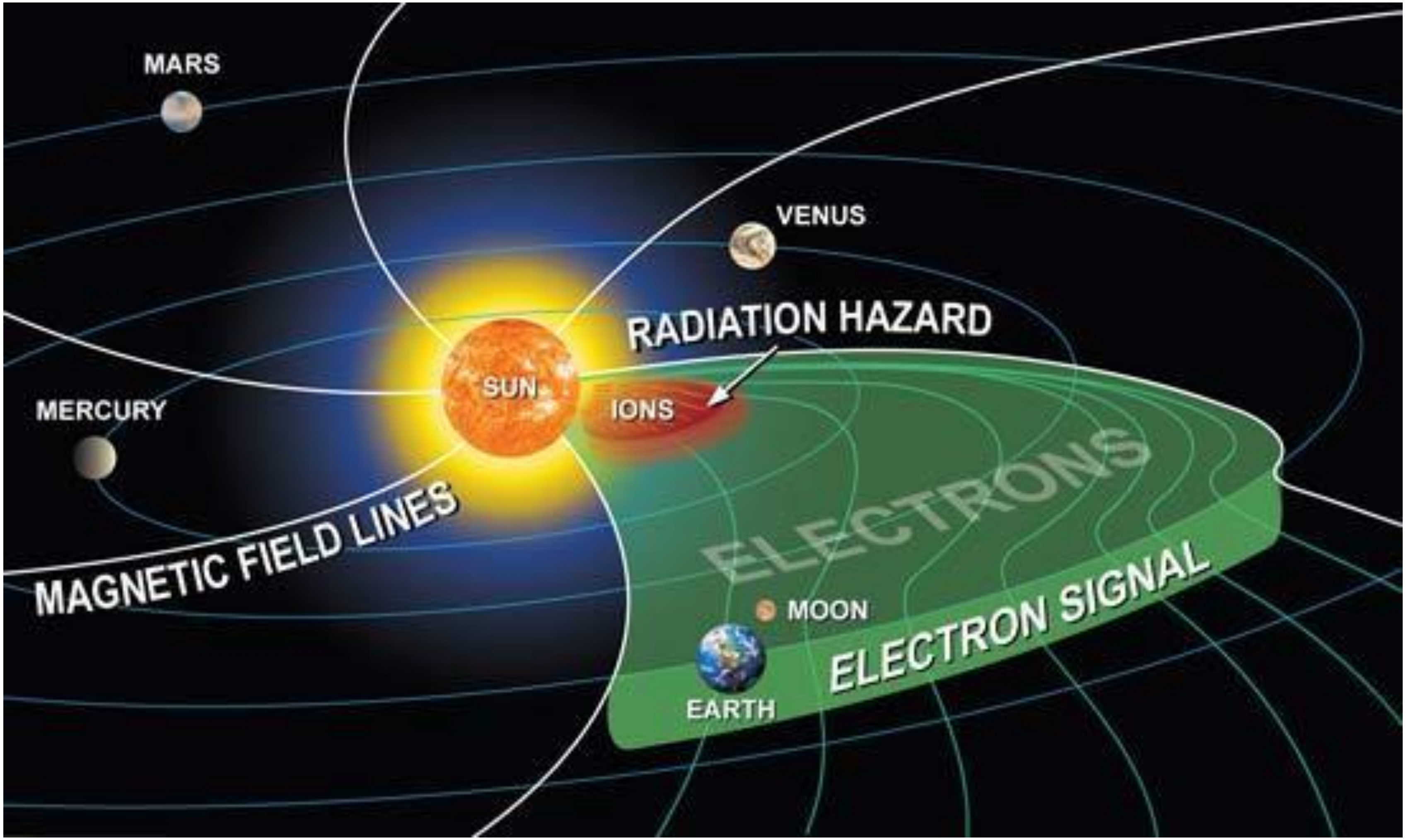
Coronal Mass Ejections



Solar events, movement in space

- Electrons, protons and ions travel along magnetic field lines
- The solar magnetic field is not a dipole
- The interplanetary magnetic field is carried by the solar wind
- The magnetic field lines are not straight but curved
- The ´connection´ of the emitting region of the sun to Earth via the magnetic field lines decides on effects on Earth
- Events initiated behind the sun can reach Earth

Particles in interplanetary magnetic field
Image source: NASA?



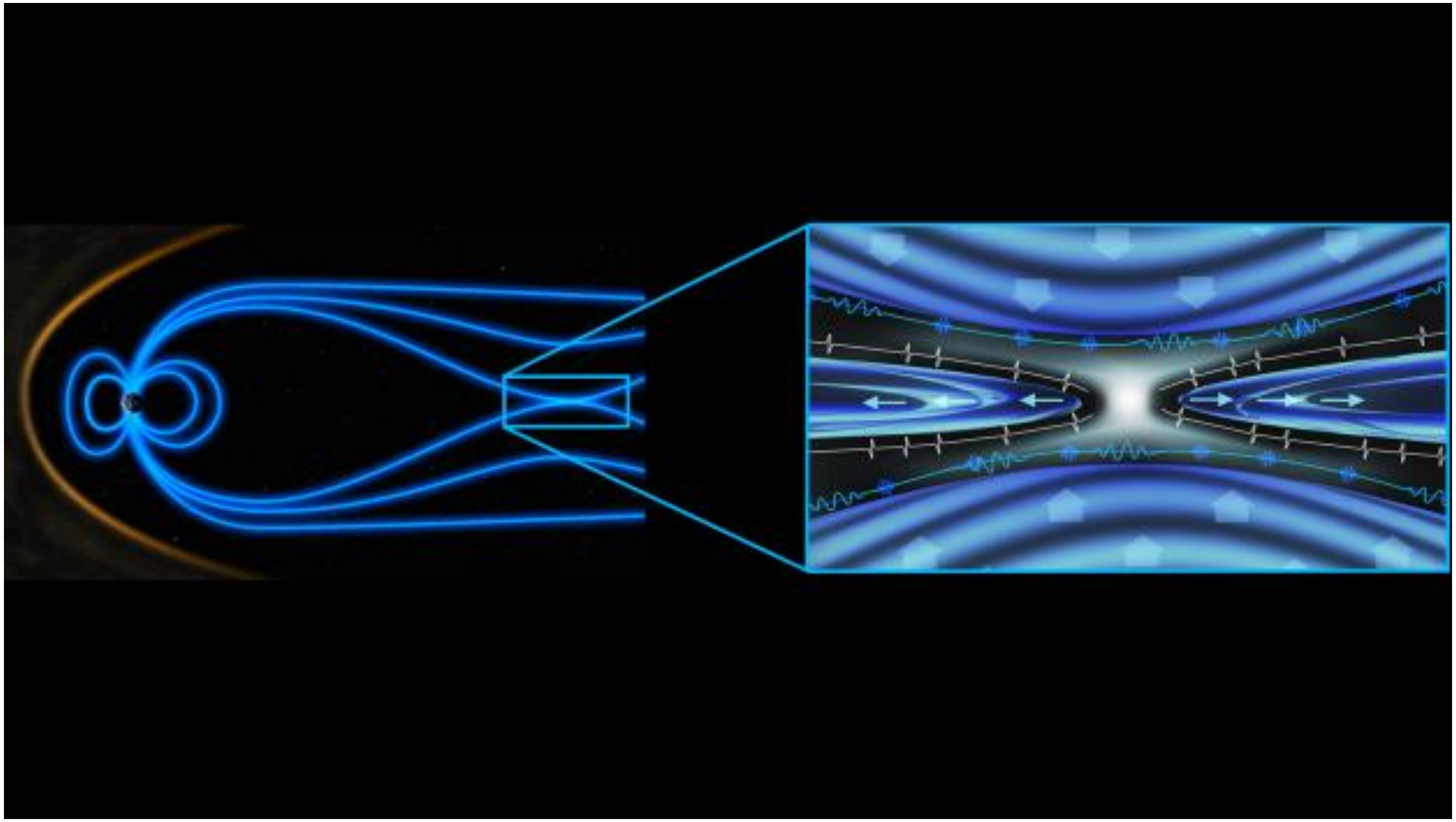
Solar events

Time it takes to reach Earth

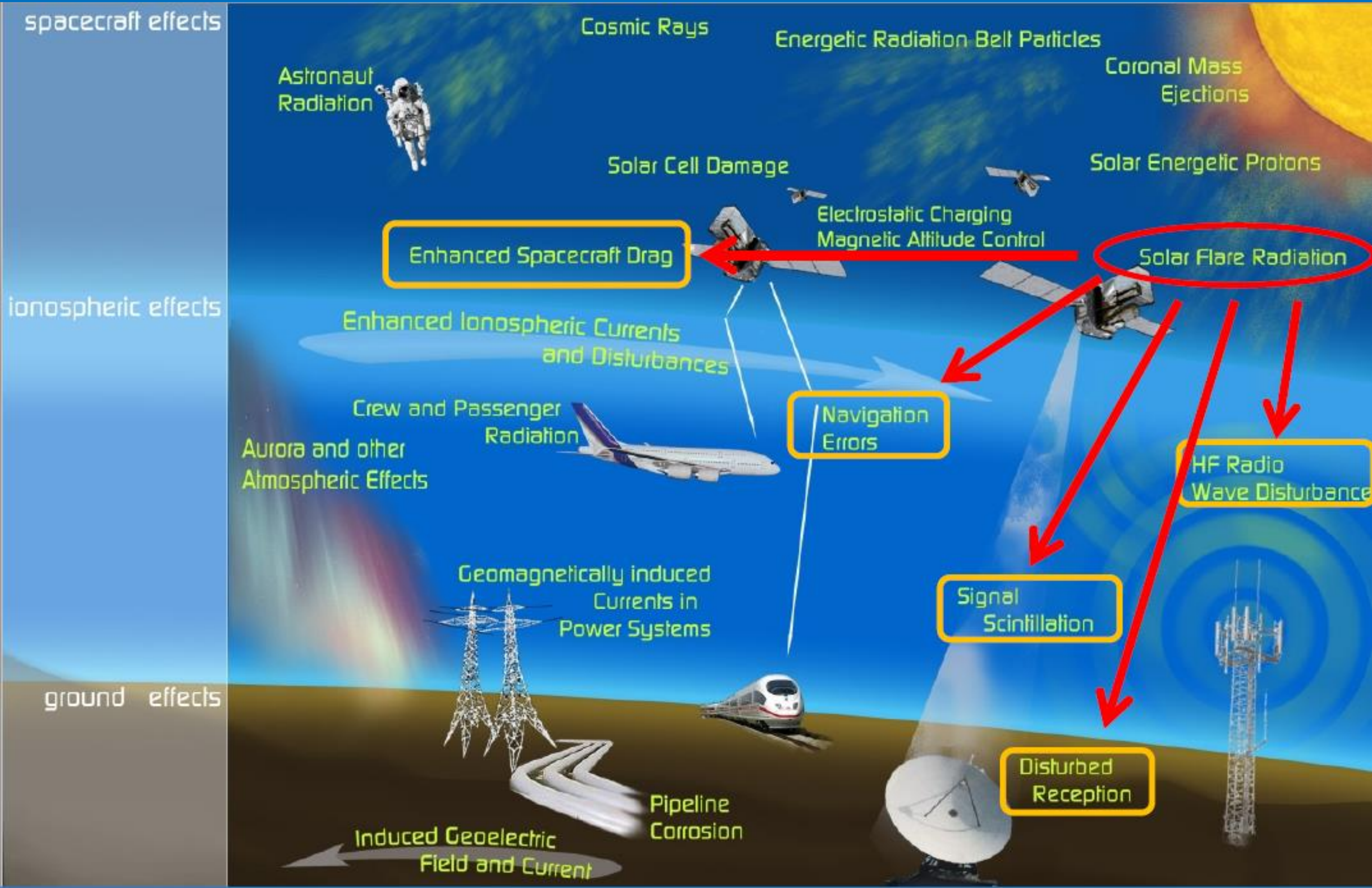
- X-ray flares: 500 s (speed of light)
- Most energetic particles: a few hours
- Energetic particle radiation: several hours to 1 day
- Plasma from CMEs: several days

Magnetic reconnection
Illustration: ESA

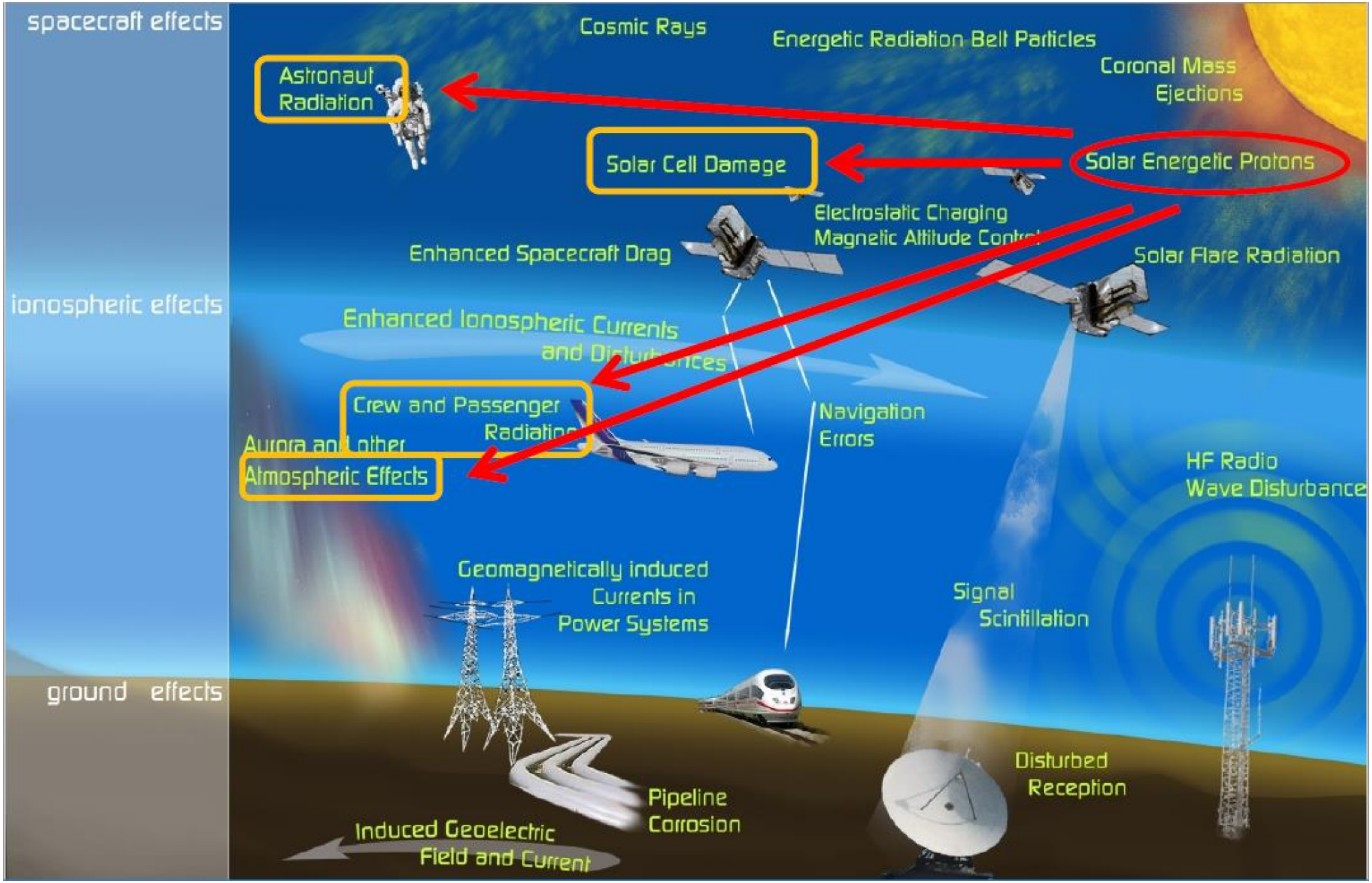
Magnetic reconnection is seen as a major mechanism to accelerate particles in the magnetosphere and also above the sun surface.



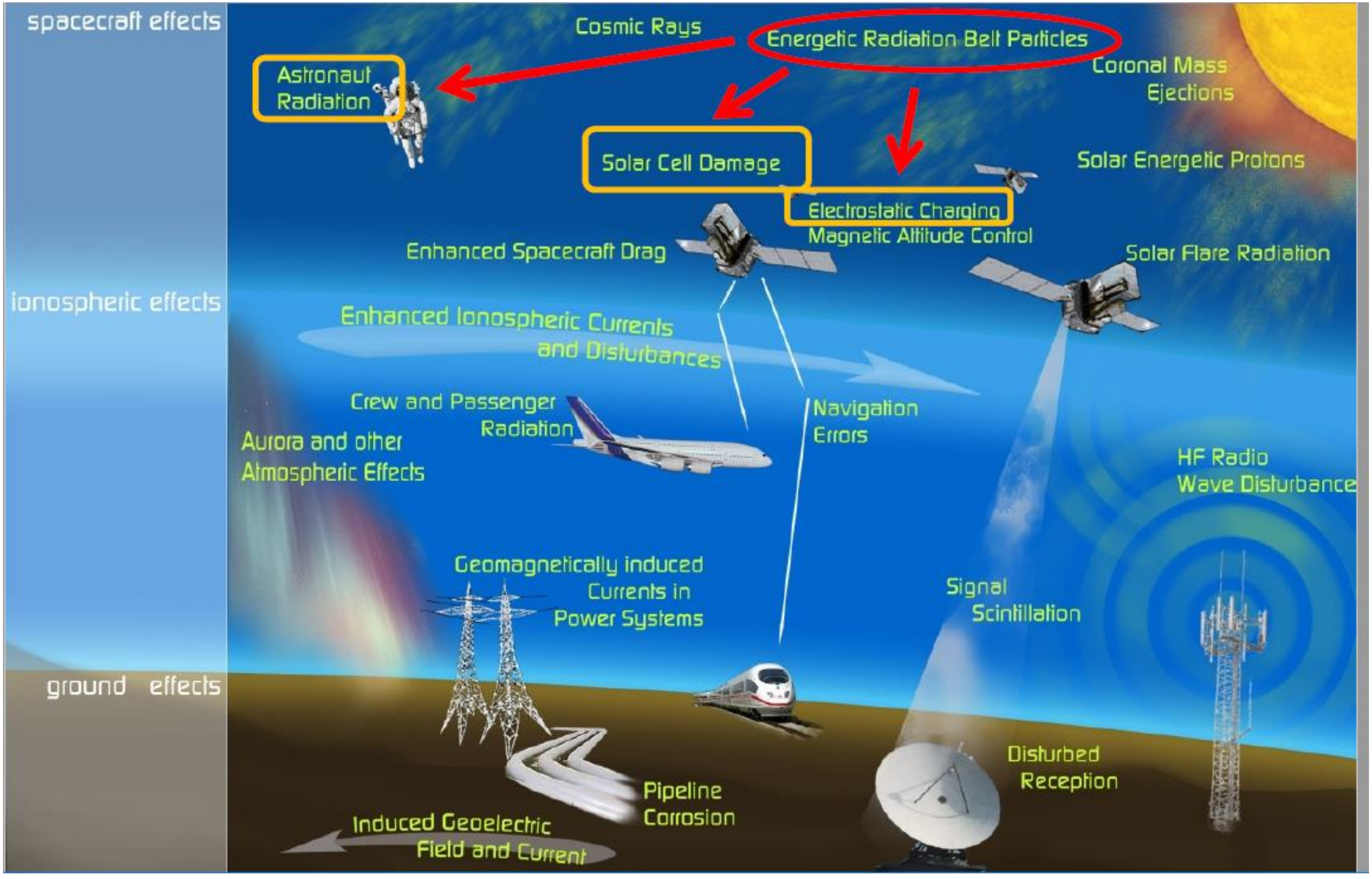
Effects of Solar Events



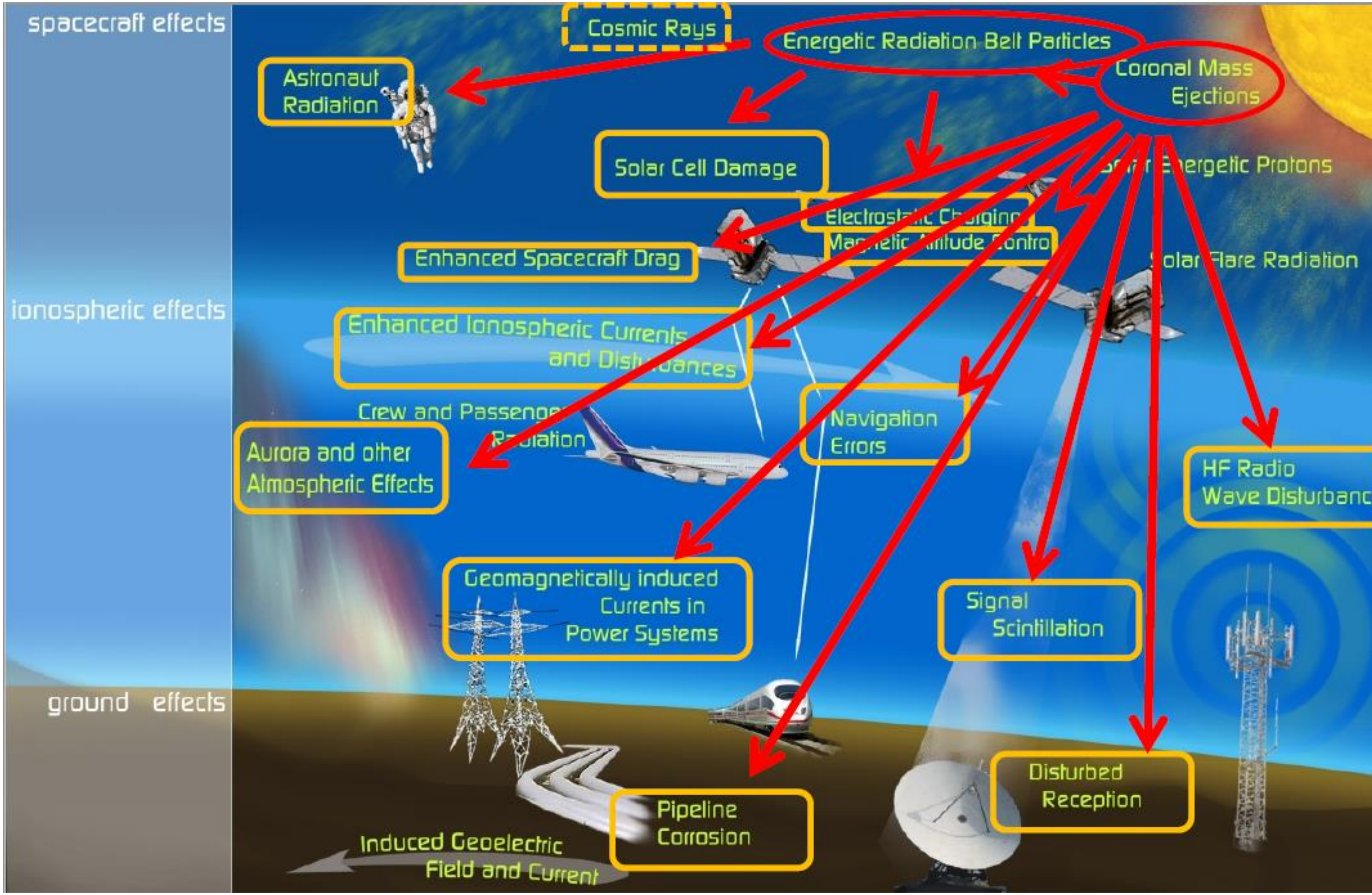
Effects of SPEs



Effects of enhanced radiation belts



Effects of CMEs



Hazards of Space Weather

A major storm could:

Disable temporarily a large number of satellites,
$\Rightarrow$ **recovery would take days to weeks and cost millions**

Damage permanently 10s of satellites
$\Rightarrow$ **recovery would take years and cost billions**

Lead to severe disturbance of dependent ground systems

Space Weather hazards

Solar flares and geomagnetic storms cause ionisation of the upper atmosphere.
Potential impacts:

- **Disturbances in satellite telecommunication and radio data links**
- **Fading and disturbance in VHF/UHF communication including effects on aviation in polar regions**
- **Increased navigation errors or loss of signal in satellite navigation**

Solar flares and CMEs expand the upper layers of the atmosphere increasing atmospheric drag

- **Impact on most orbits below 600 km**
- **Earlier than expected re-entry for low orbits**

Space Weather hazards

- **Very strong solar events can increase the solar radiation dose at aircraft flight altitudes up to 300-fold.**
- **Impacts are mostly in the polar region**

- **Note: solar radiation will never cause immediate health risk for aviation but the annual dose limit for crew could be reached sooner.**

- **An electronic device can suffer Single Event Effects (SEE) due to an energetic particle impact in the semicinductor material**

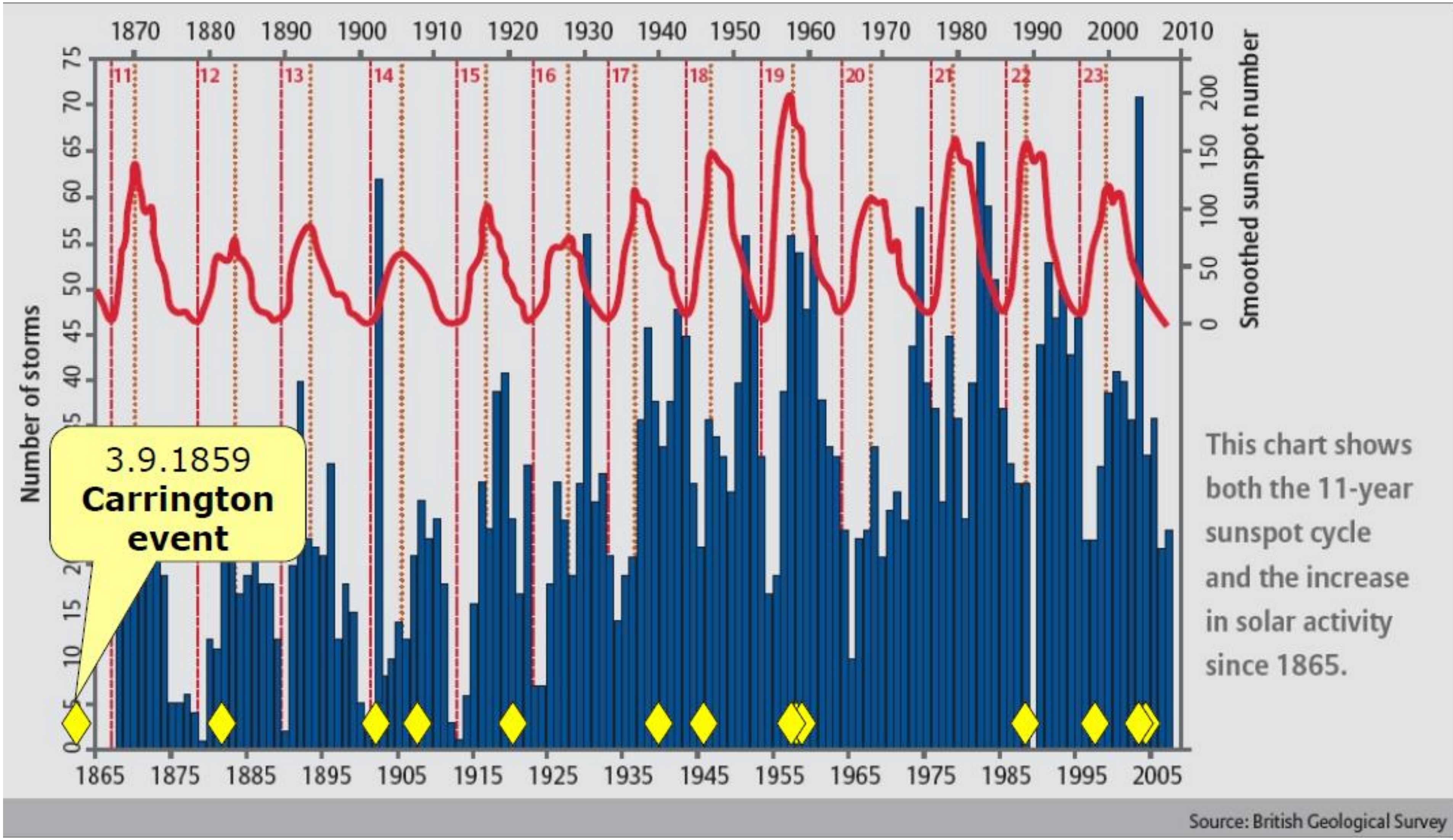
Space Weather hazards

Potentially destructive current induced into long, conducting structures like power grids, wired communication links, railway lines and gas pipelines

Potential impacts:

- **Disturbances in power grids,**
- **Tripping of relays, in extreme cases transformer damages causing blackout.**
- **False signals in railway control systems**
- **Increased corrosion of gas pipelines**

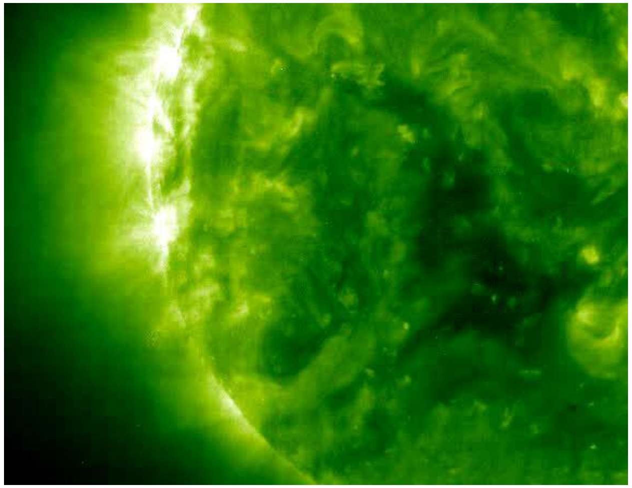
Solar particle events



Solar events

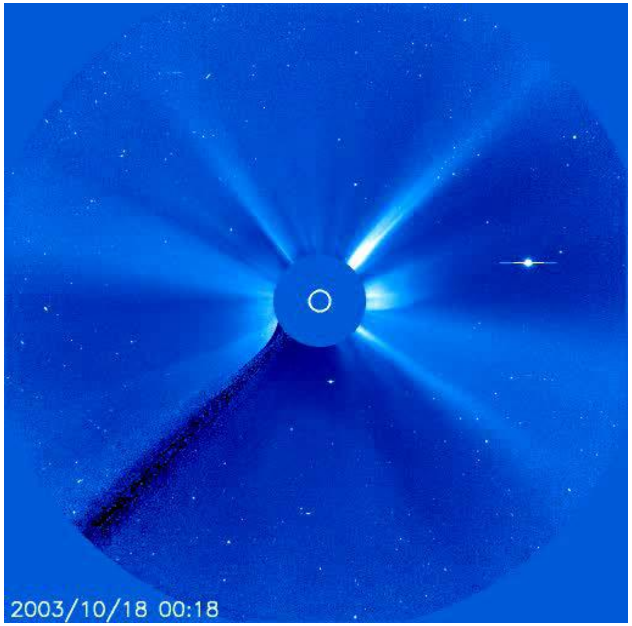
Halloween storms 19 Oct – 5 Nov 2003 were a major recent solar events

- **Not just a storm, but a series of events 18 X-ray events: M5.0 – X28.0**
- **18 radio blackout events: R1 – R5**
- **5 CMEs with geoimpacts: Kp 6 – 9**
- **5 > 10 MeV proton events**



Continuing disturbances cause accumulated damage e.g.

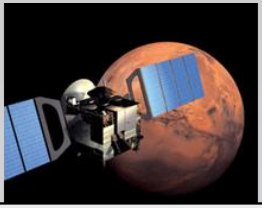
- **on solar arrays**
- **increasing risk of permanent radiation damage**
- **complications in the satellite recovery**
- **service outages in satellite dependant ground systems**



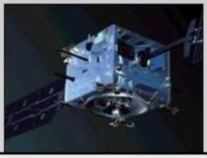
Space Weather events

Effects on space missions during the Halloween storm (Oct – Nov 2003)

Mars Odyssey mission: Safe mode during radiation storm. Memory error and loss of MARIE instrument



Mars Express star trackers blinded by particle radiation

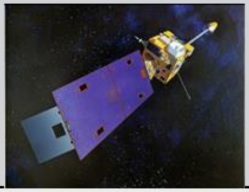


Smart-1 spacecraft solar panels damaged

DMSP F16: SSIES sensor lost data twice, microware sounder damaged

ADEOS-2 Spacecraft lost

ACE: EPAM instrument permanently damaged

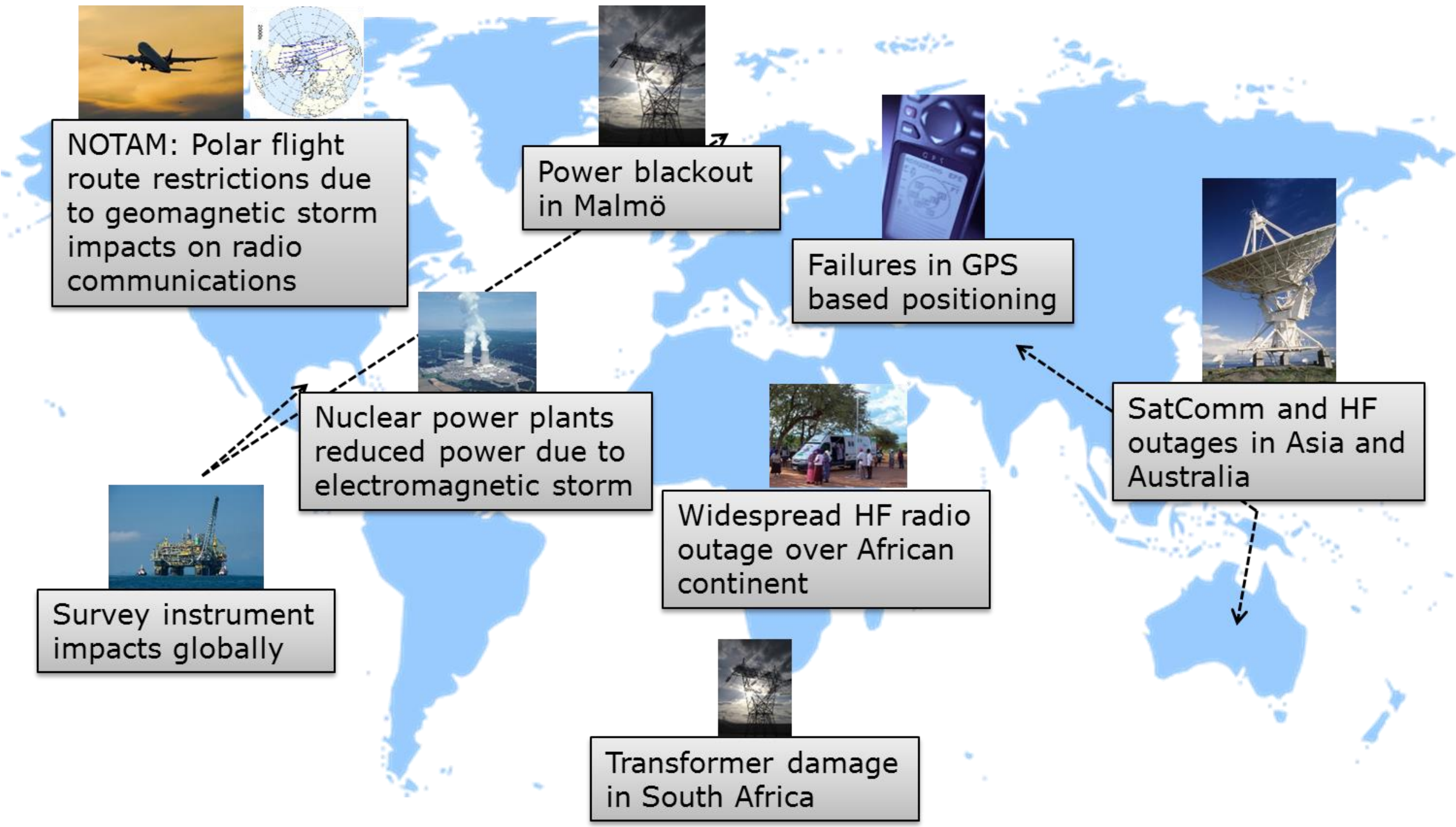


GOES-9, 10 and 12: High bit error rates (9,10), magnetic torguers disabled (12)

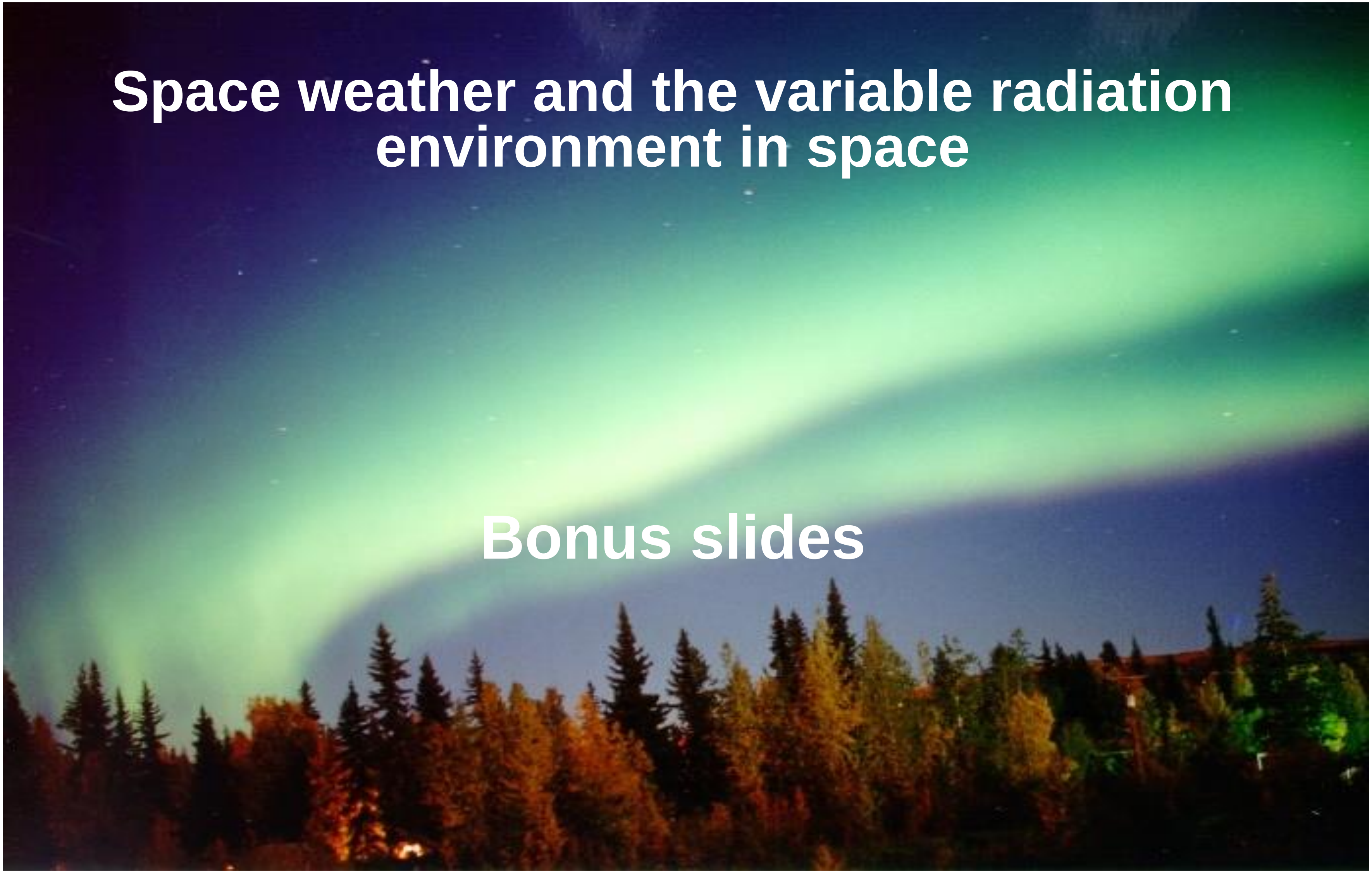
Multiple anomalies in GEO TV and Pay Radio satellites: Momentum wheels, CPU, service outages, …

Space Weather events

Ground Effects of Space Weather during Halloween storm (Oct – Nov 2003)



Space weather and the variable radiation environment in space



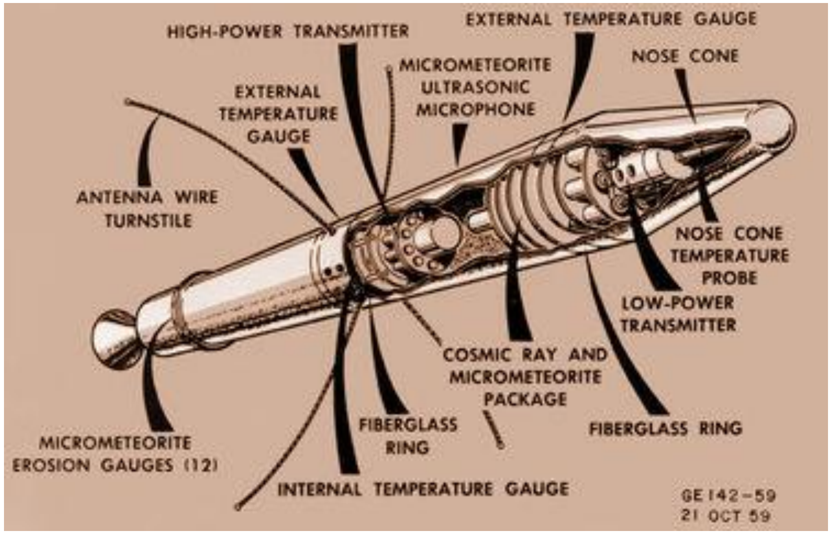
Bonus slides

RADSAGA

The Space Environment
Radiation belts

Two belts:

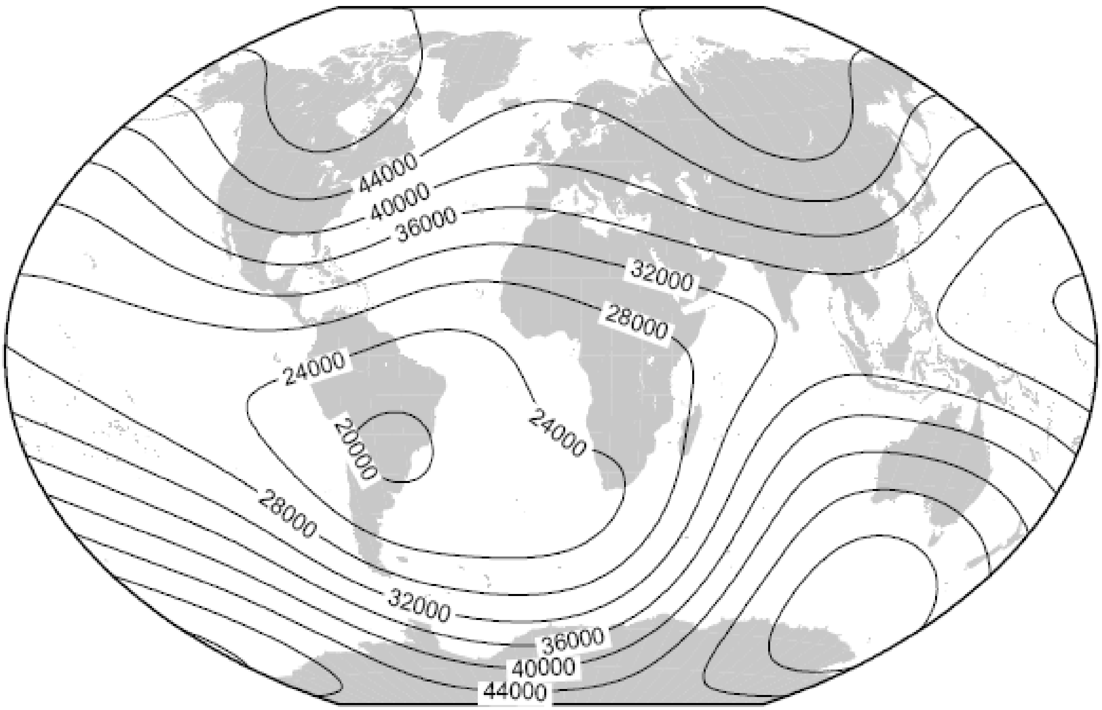
- **Inner belt** – dominated by protons
  - CRAND= Cosmic Ray Albedo Neutron Decay
  - ~static
- **Outer belt** – dominated by electrons
  - Storm driven
  - Very dynamic
- the "***first scientific discovery of the space age***" by James Van Allen et al., Explorer I (Jan. 1958) & Explorer III (Mar. 1958)



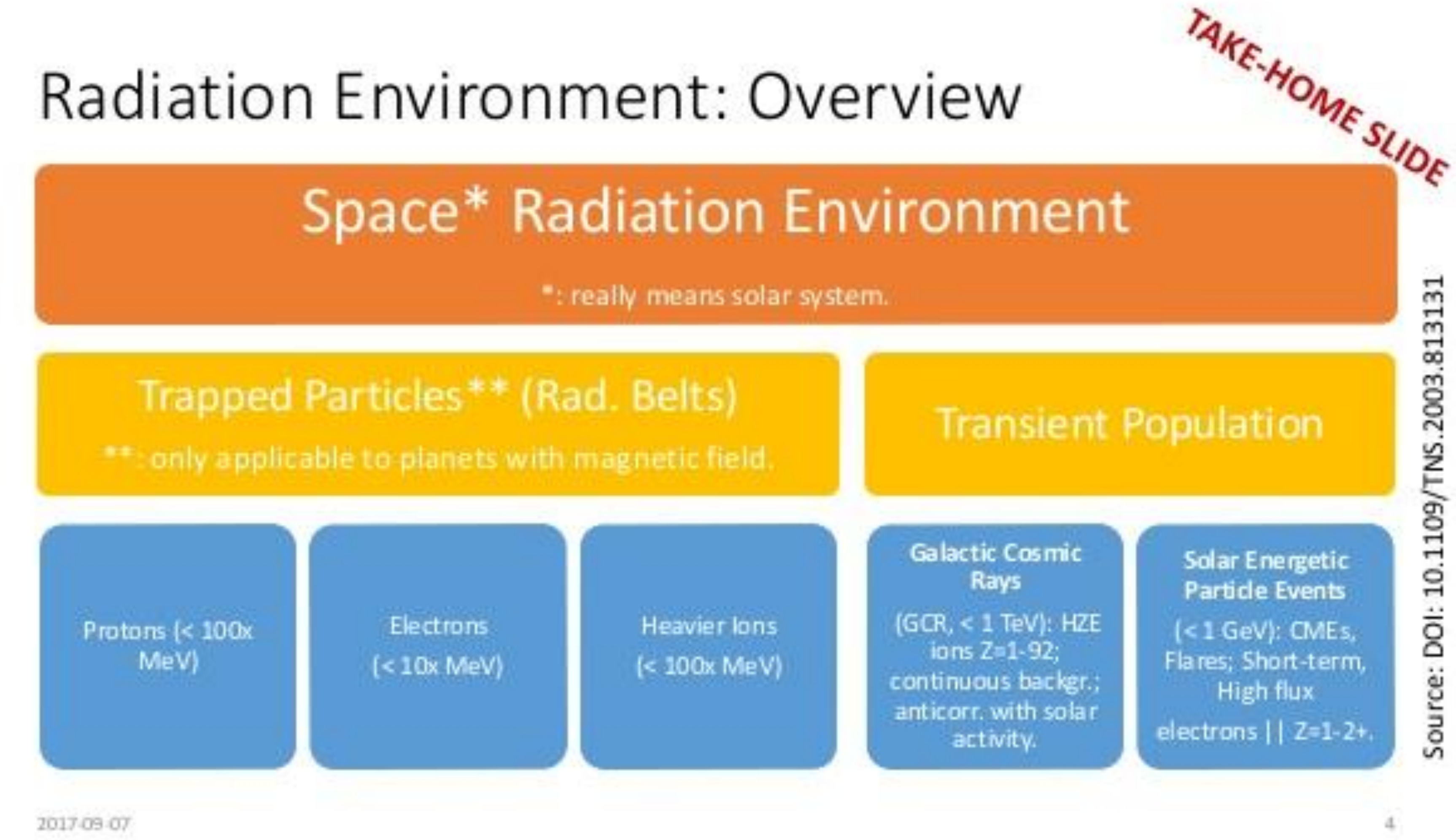
The Earth magnetic field

The magnetic field is weaker over the South Atlantic (South Atlantic Anomaly, SAA) and stronger South of Australia

Total intensity (nT) at 400km altitude at 2005.0



The Space Environment
Space Radiation Environment



Solar events