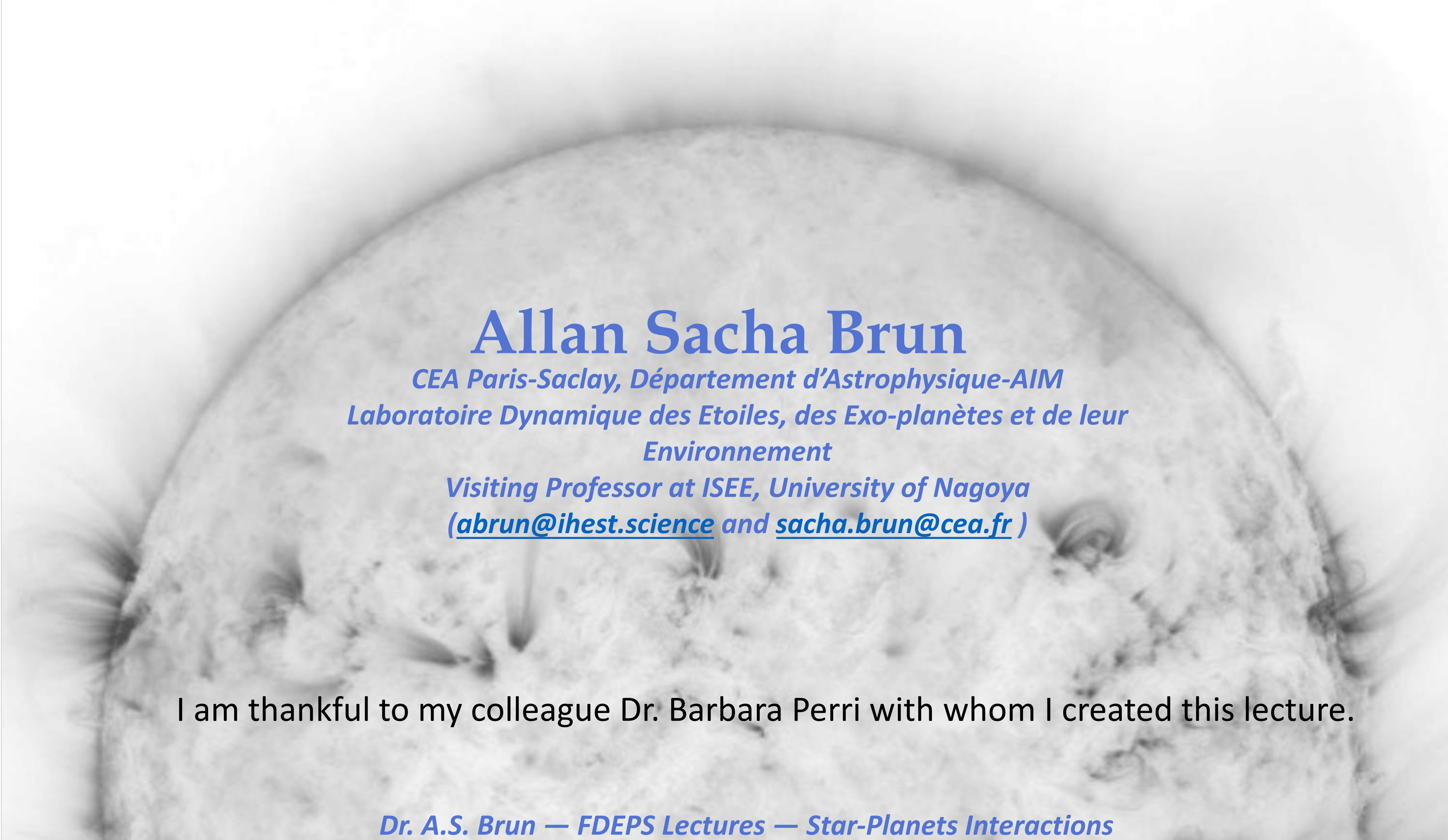
Star-Planets Interactions
Space Weather



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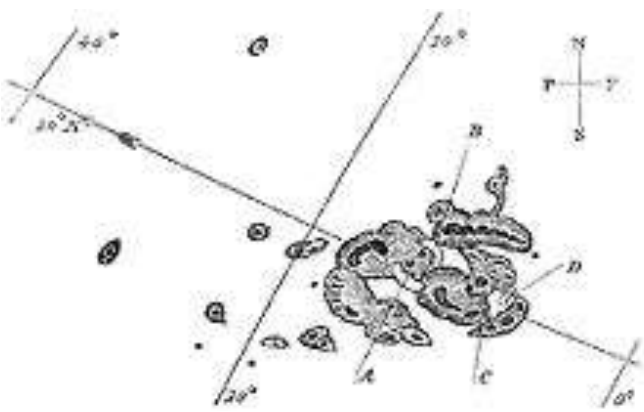
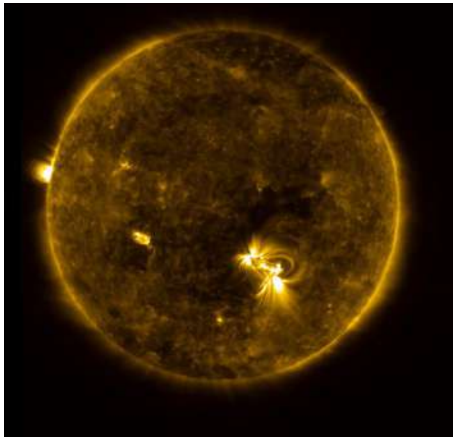
I am thankful to my colleague Dr. Barbara Perri with whom I created this lecture.

The birth of space weather

On September 1st 1859, Carrington notices a very spectacular solar eruption
17 hours later, spectacular auroras around the world and major damages to telegraphs
→ **The Carrington event**



[Carrington 1859]



[NOAA]

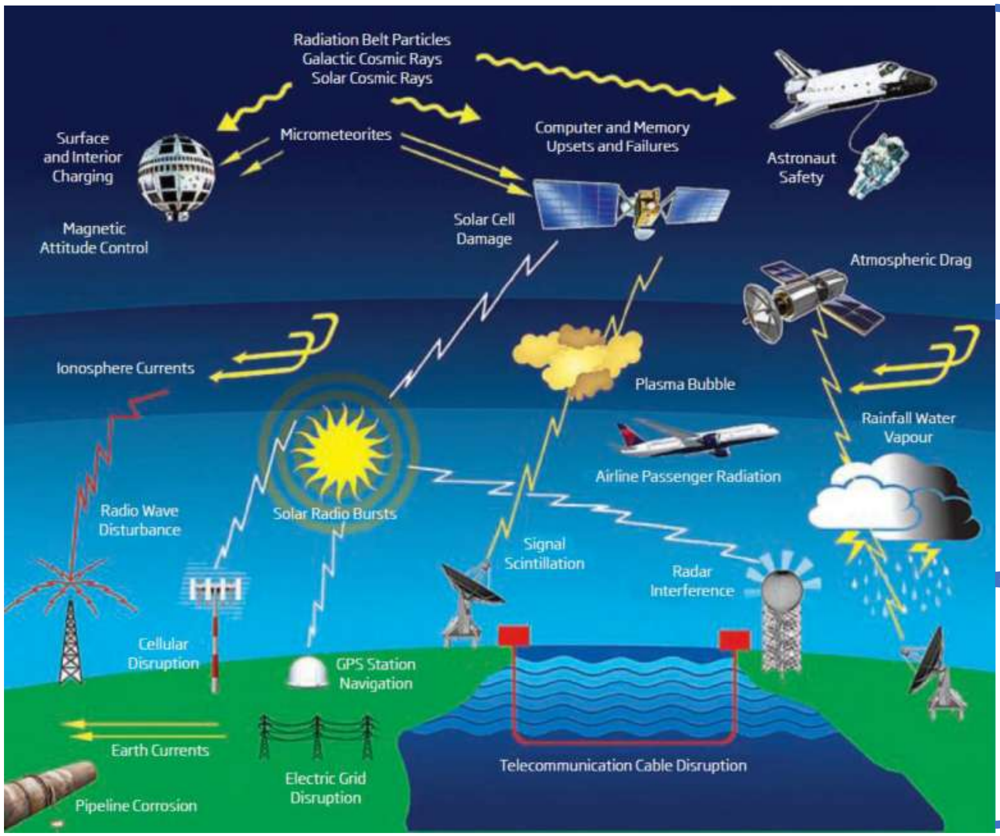
For the first time, a link between the Sun and the Earth is suspected

Key question:
Can we **understand** and **anticipate** these events?

A technological society

Space weather is the study of the energetic events of the Sun and how they **impact the Earth**

[Bell Laboratories]



Impact on **space** (satellites, astronauts)

Impact on **atmosphere** (communications, flights)

Impact on **ground** (electrical installations)

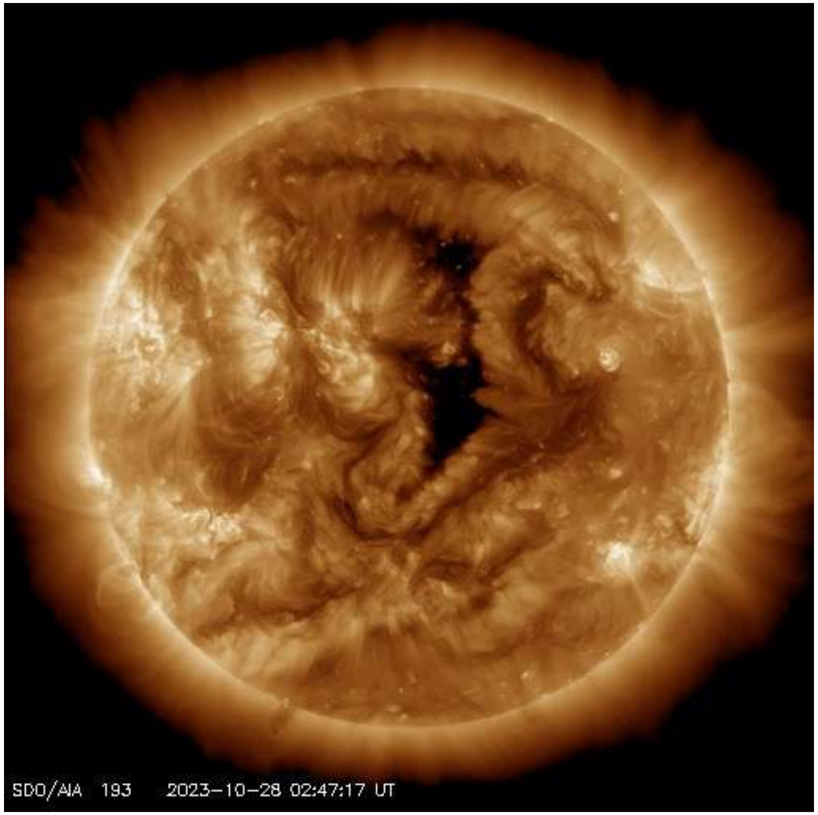
[Schrijver+2015]

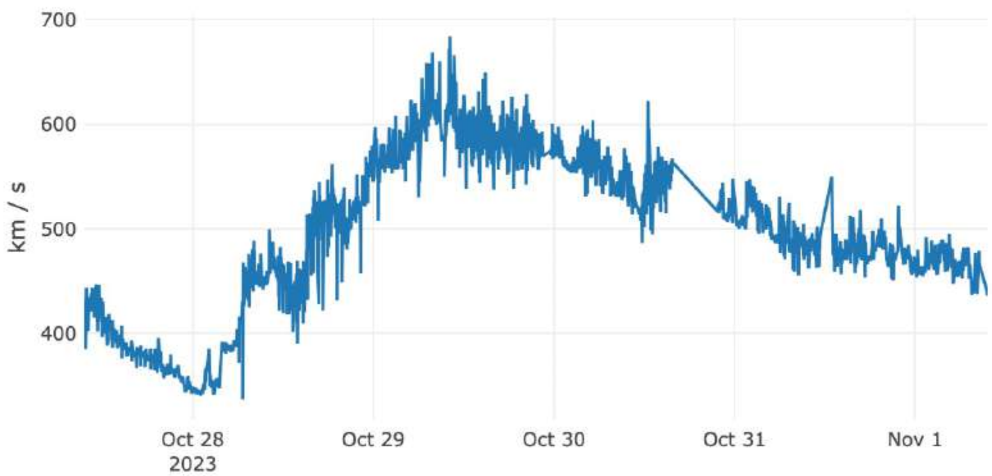
→ If a Carrington event happened today, the damages would be of billions of dollars

Solar events of space weather

High-Speed Streams (HSSs): Origin

The opening of a coronal hole near the equator can trigger a stream of fast solar wind
→ A high-speed stream can reach 700-800 km/s at Earth with sharp increase!

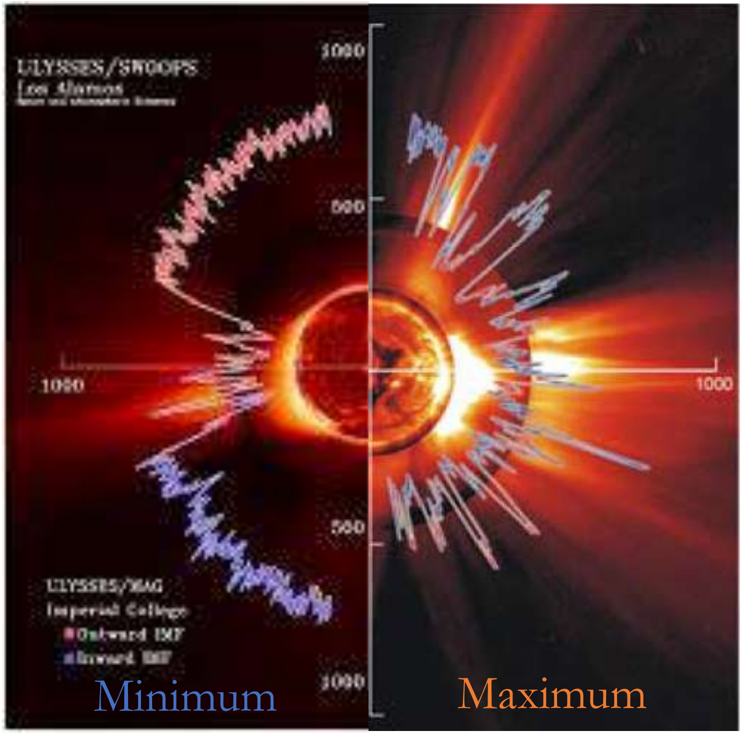




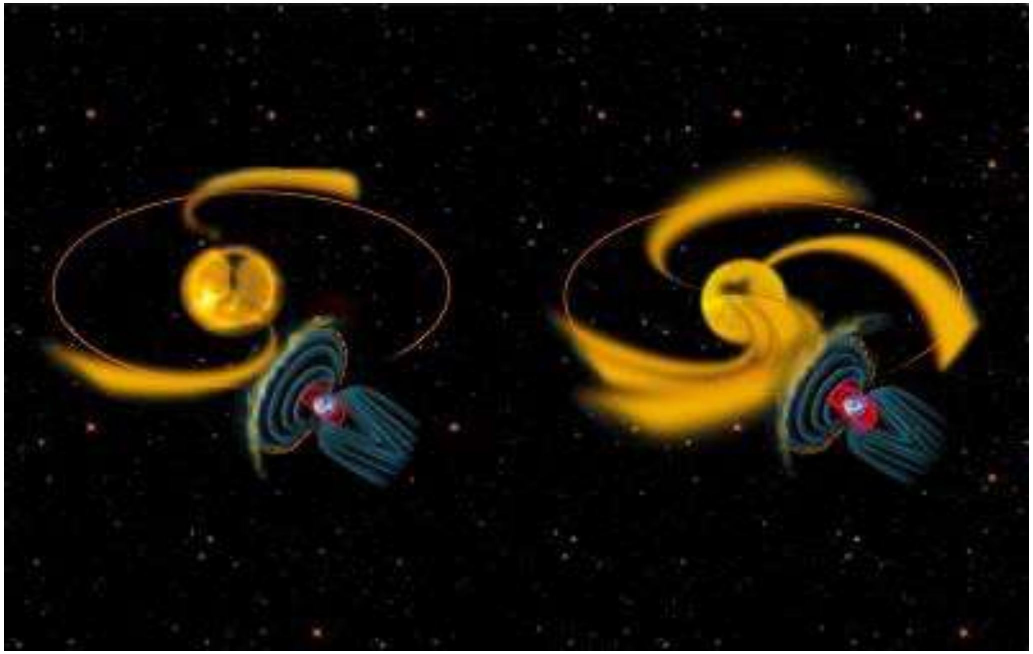
High-Speed Streams (HSSs): Impact

At minimum of activity, fast solar wind is usually located at high latitudes BUT at maximum, it can reach more often the ecliptic plane

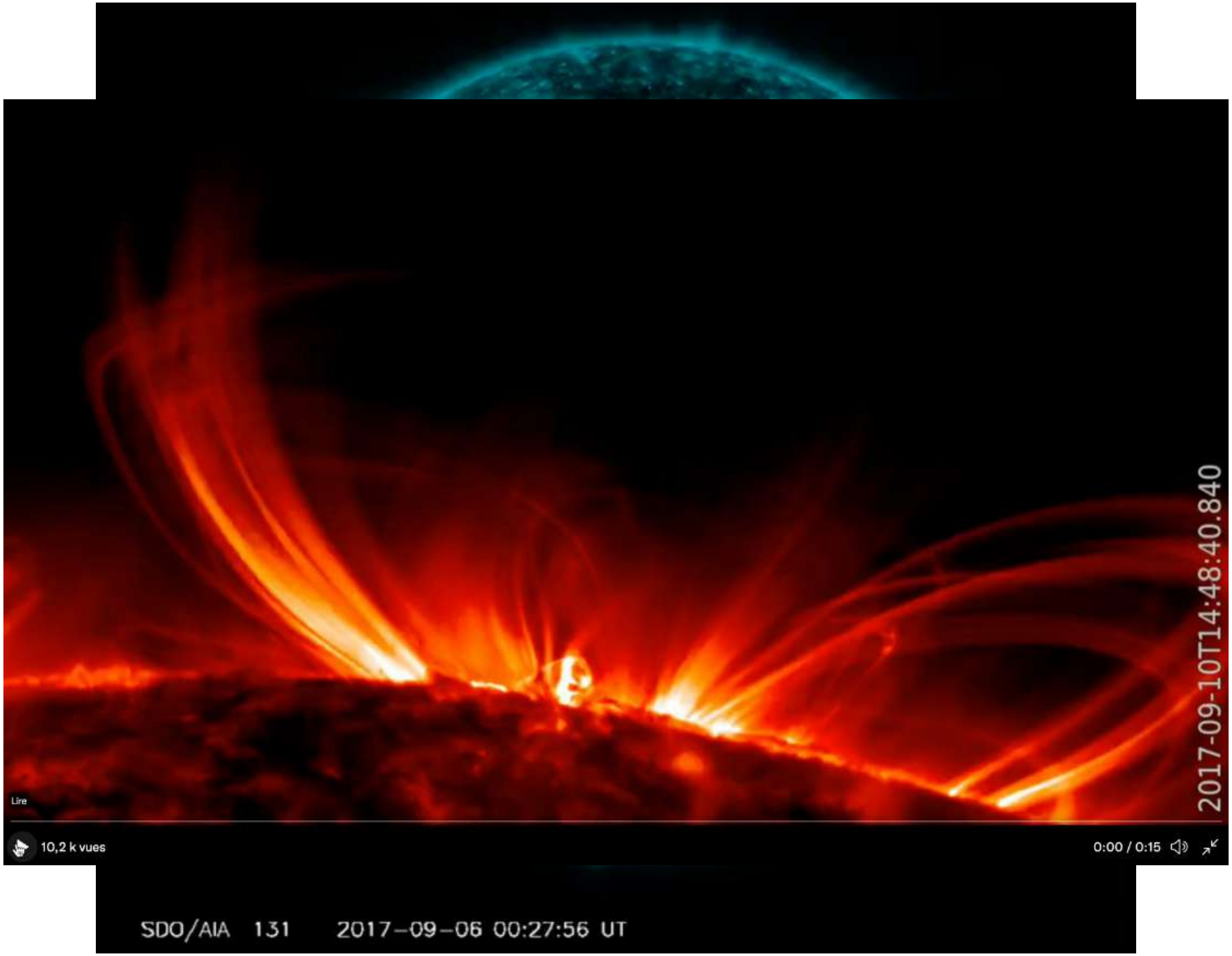
→ Fast solar wind will disturb the magnetosphere, compressing it and injecting large amount of particles



[McComas+2003]



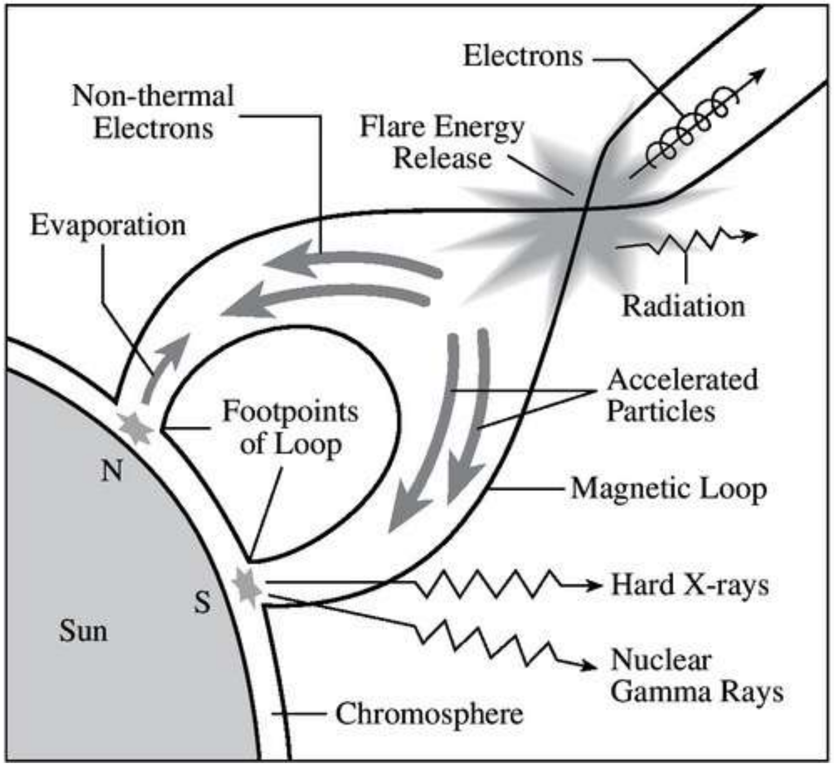
Solar flares: Observations



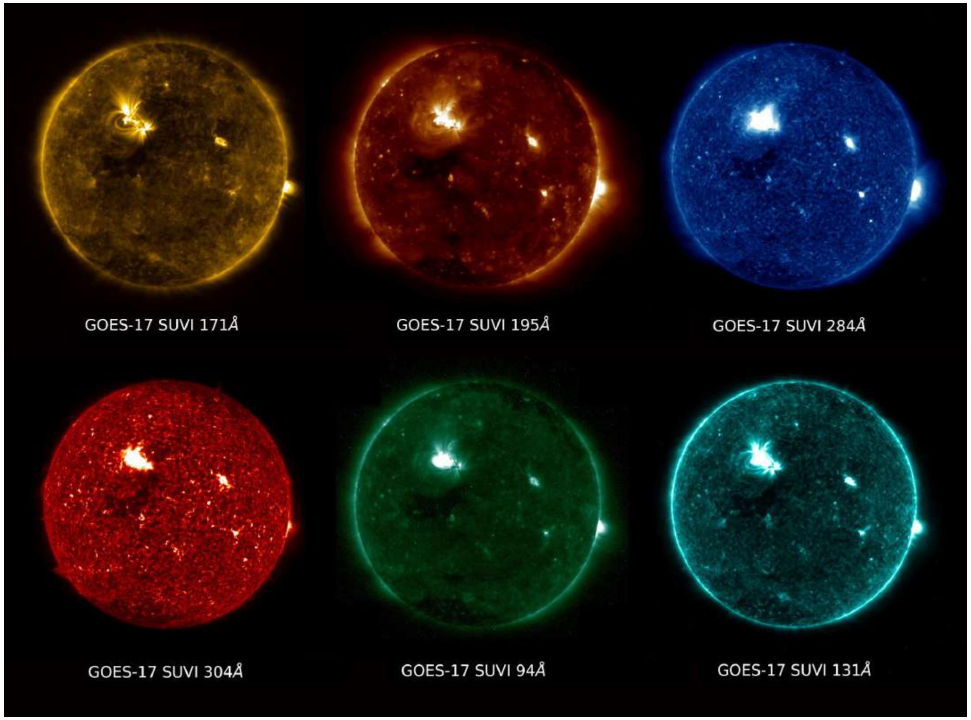
Solar flares: Definition

When the magnetic field at the surface of the Sun becomes too complex, it can reconfigure through magnetic reconnection

[NASA]

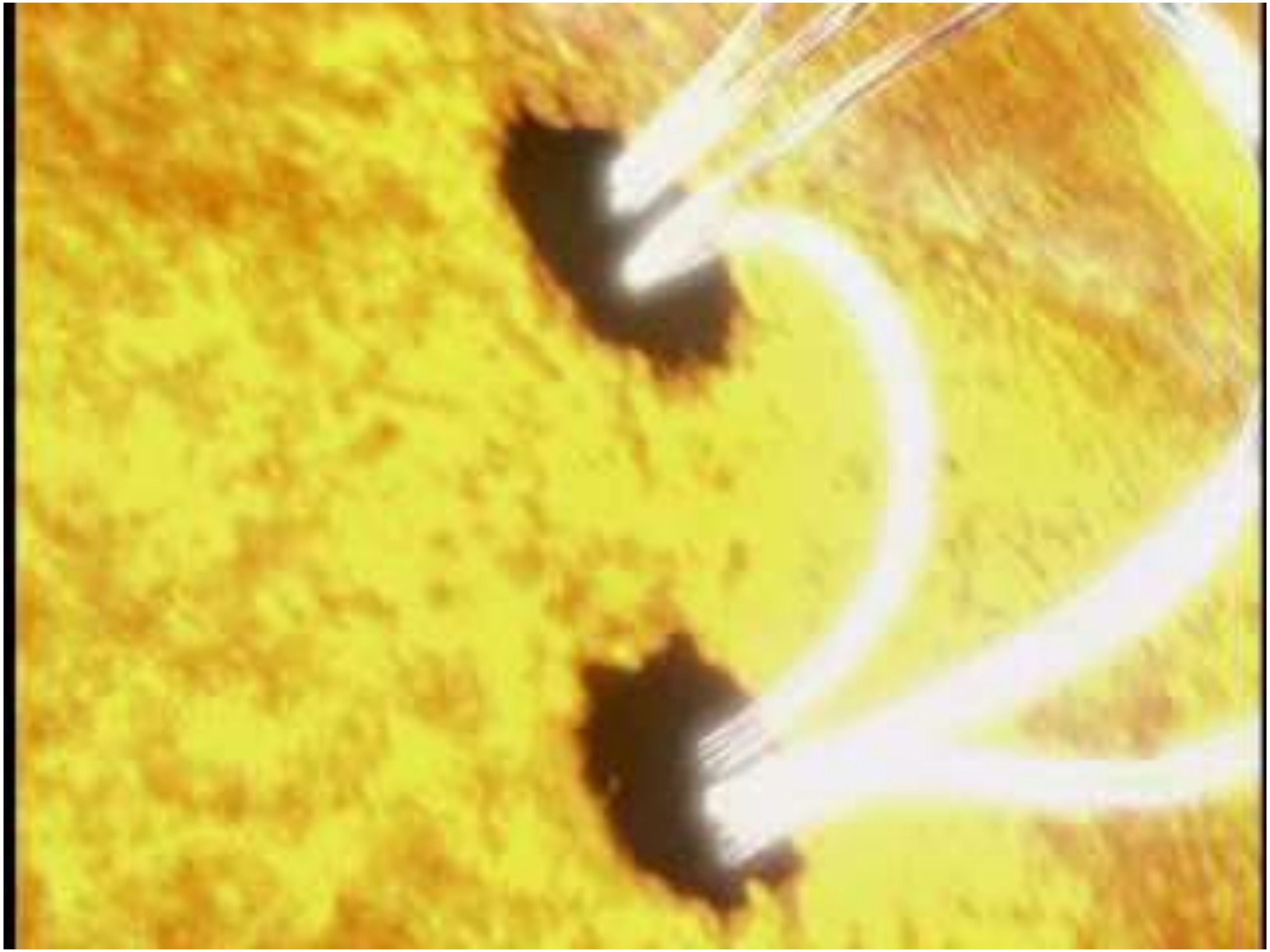


[NOAA]



→ This releases energy into a bright flash in all wavelengths + particle acceleration

Solar flares: Origin



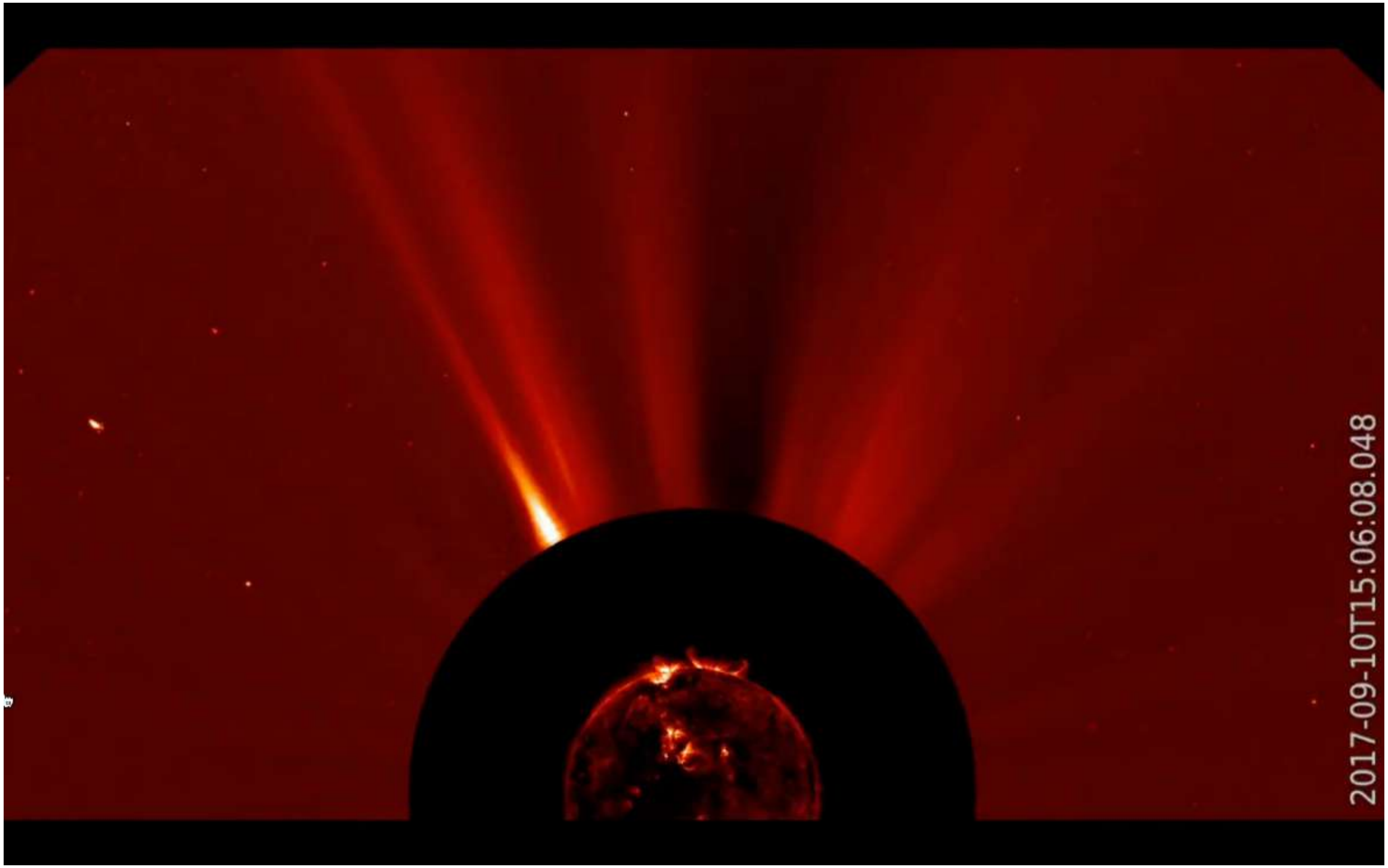
Solar flares: Classification

There is an official classification of the solar flares intensity, based on the X-ray flux intensity measured at Earth

Class	Flux peak betwen 100 and 800 pm (W/m^2)
A	$< 10^{-7}$
B	$10^{-7} - 10^{-6}$
C	$10^{-6} - 10^{-5}$
M	$10^{-5} - 10^{-4}$
X	$> 10^{-4}$

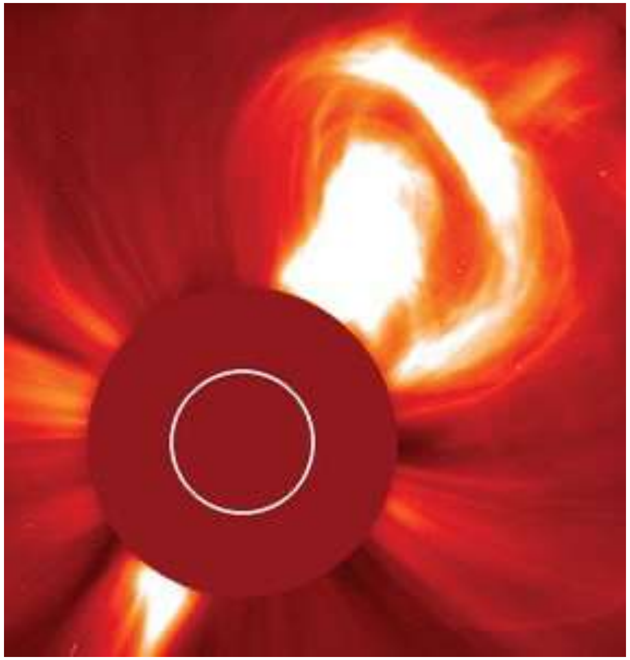
→ M and X-class flares only occur close to maximum of activity (X-class flares only a couple of times per cycle)

Coronal Mass Ejections (CMEs): Observations

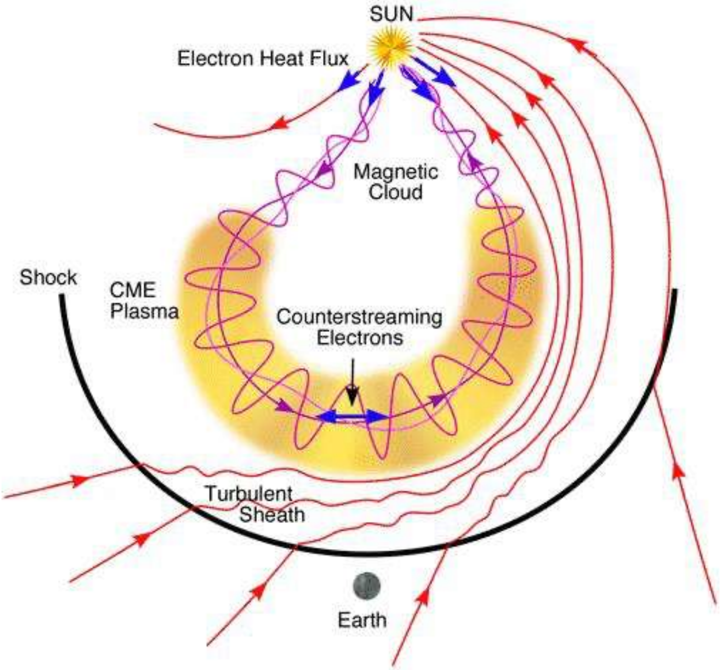


CMEs: Definition

Following (or not!) the flare reconnection, matter can be ejected and accelerated
→ this is what is called a CME



[SOHO]



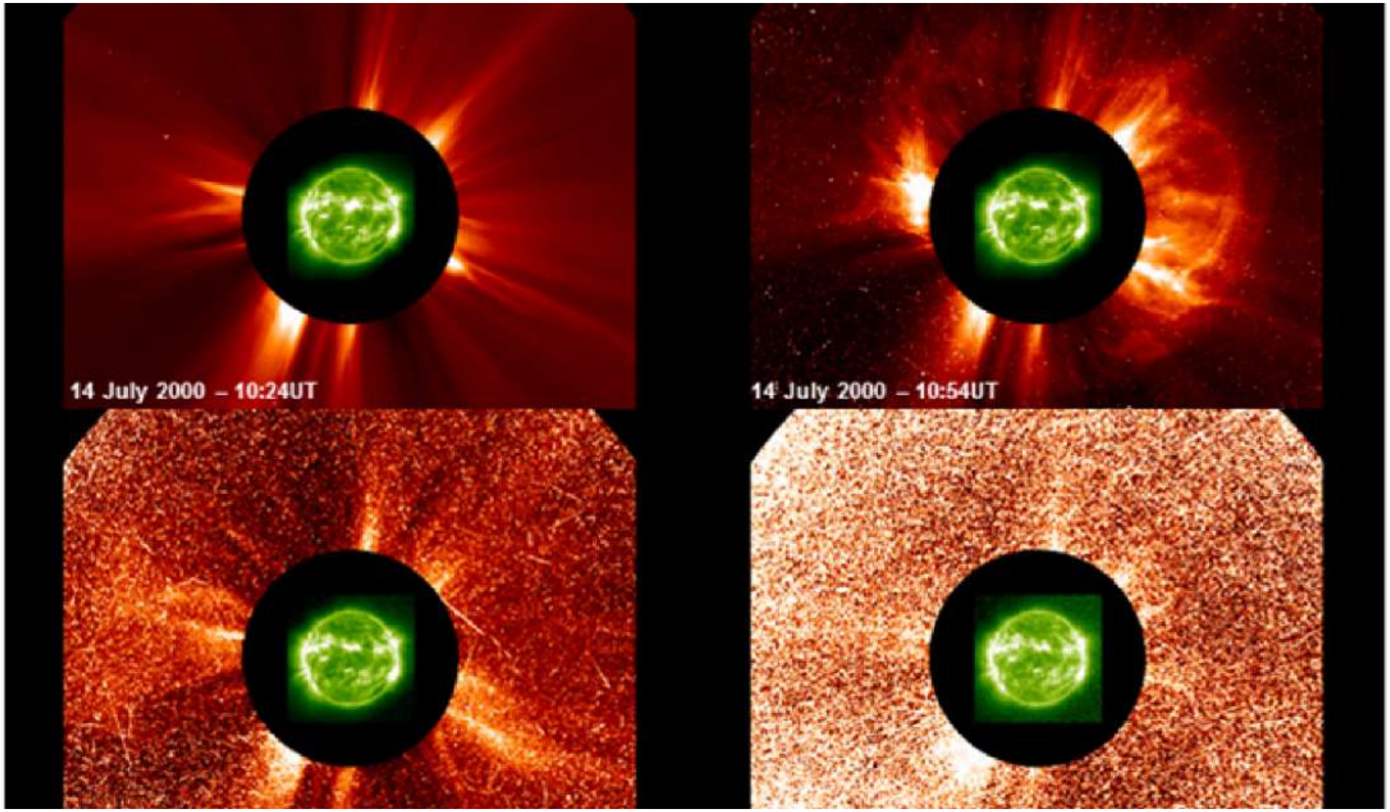
[Zurbuchen & Richardson 2006]

→ Near the Sun, they are characterized by a shock, a cavity and a core
→ Near Earth, they are ICMEs (Interplanetary), with a shock, a sheath and an ejecta

Solar Energetic Particles (SEPs)

The Sun's accelerated particles can reach almost the speed of light

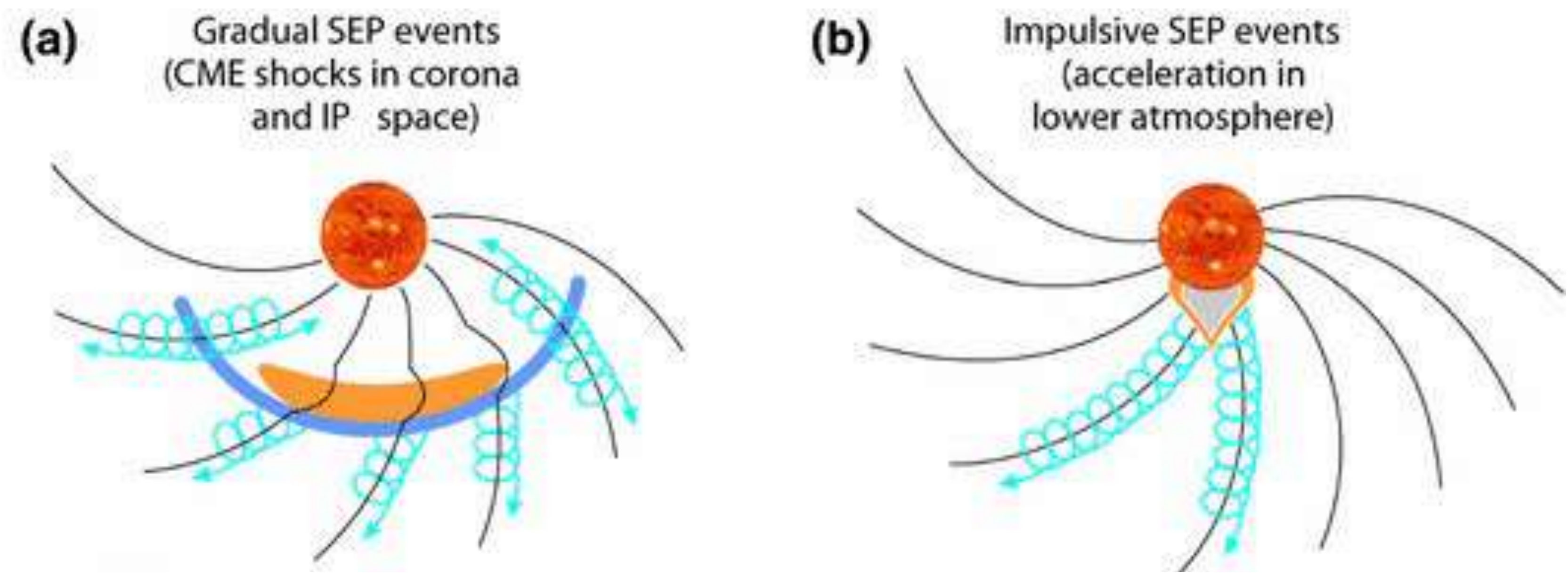
→ They accumulate energy and become dangerous



→ SEPs can reach Earth in around 10 minutes!

Types of SEPs

There are 2 different kinds of SEPs:

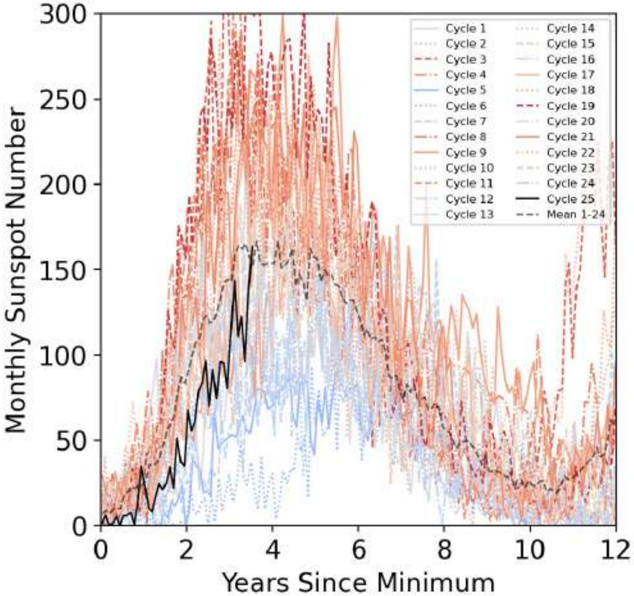


[Desai & Giacalone 2016]

Graduel SEPs:
- last longer
- created by shocks (CMEs)

Impulsive SEPs:
- short but much stronger
- created by flares

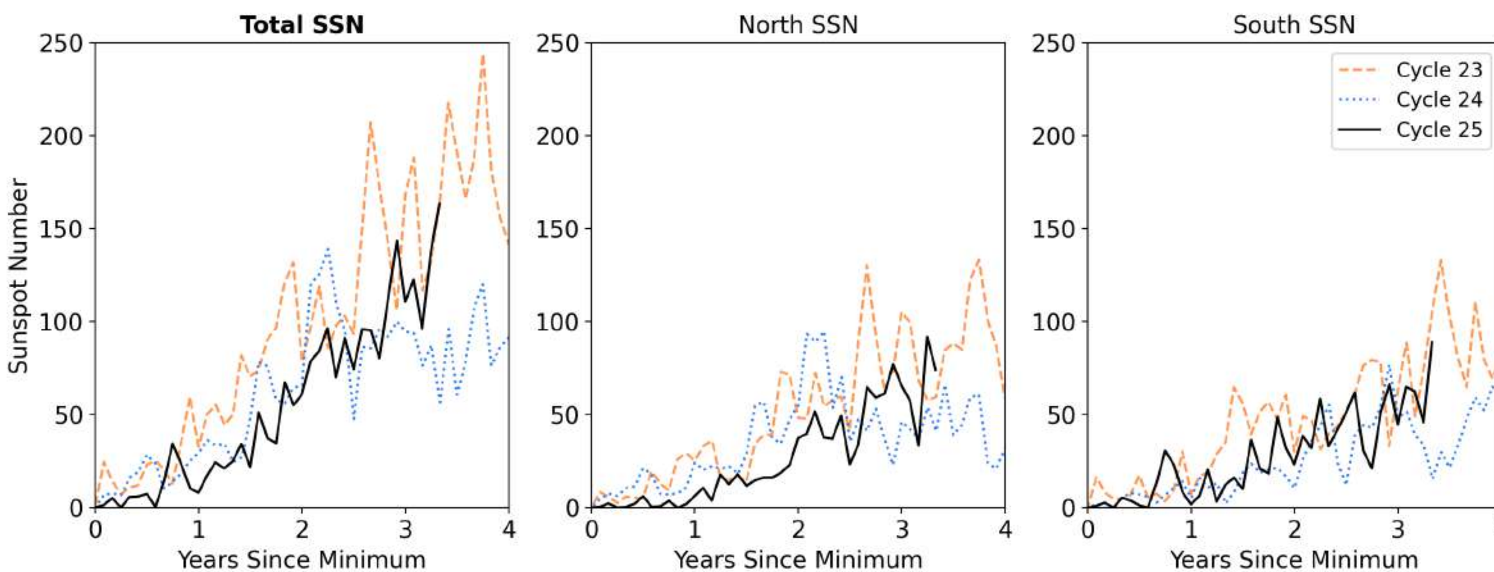
The solar activity



As we saw before, the solar cycle takes around 11 years, and has an amplitude modulated by the 100-year Gleissberg cycle

→ We are currently in cycle 25, which appears to be stronger than cycle 24, but weaker than cycle 23

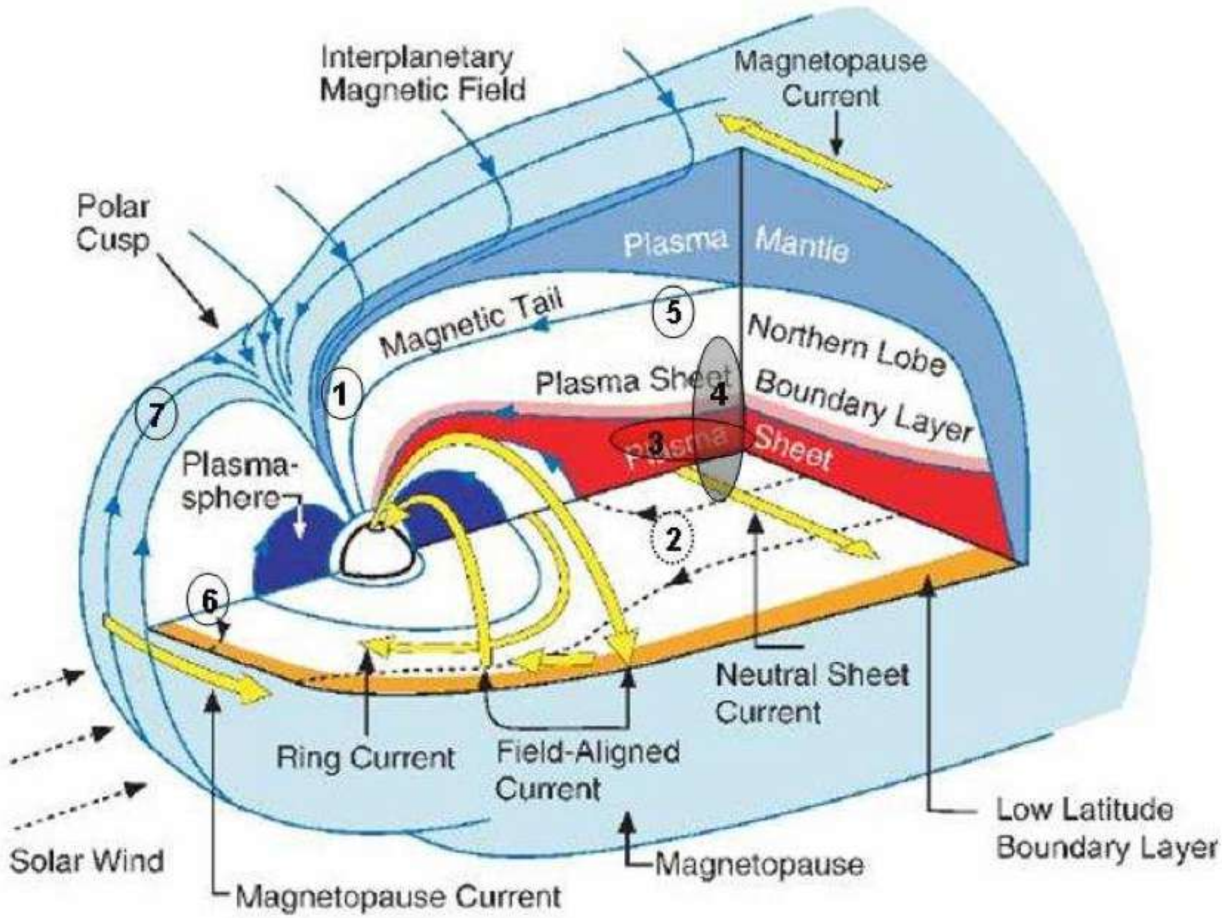
→ Being able to anticipate the phase of the solar cycle is crucial, as it gives you the probability of events



Technological impacts

Geomagnetic storms

Geomagnetic storms are created by magnetic reconnection in the day-side magnetosphere which generates currents

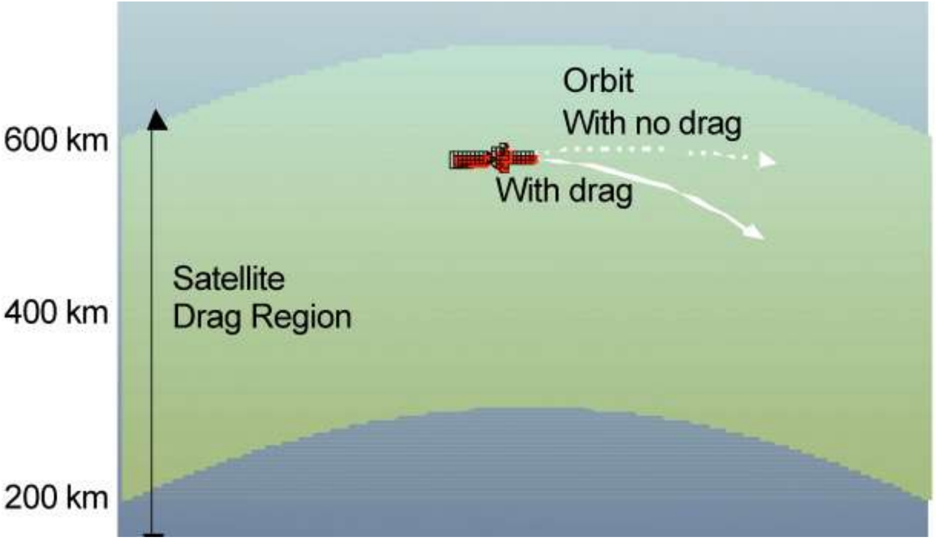


[R. Lopez]

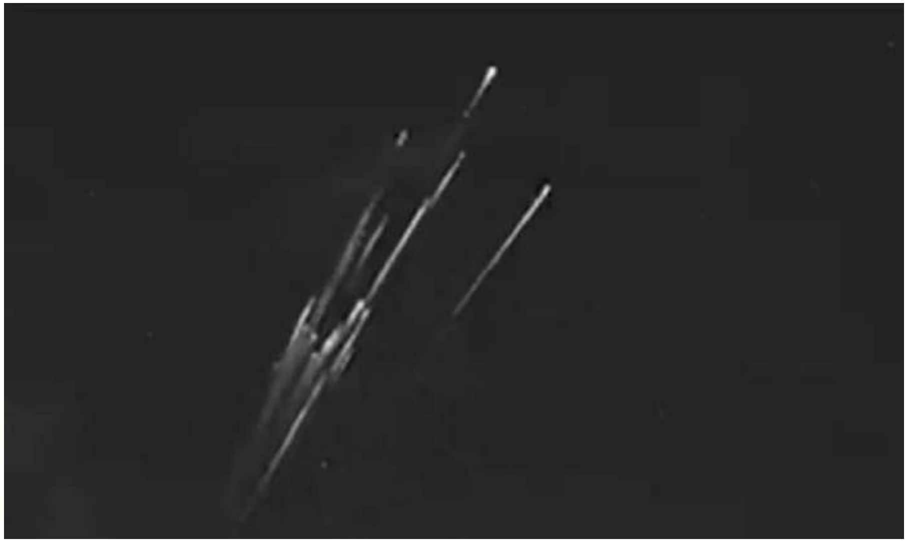
→ The global magnetic field of the Earth is then disturbed, which has many consequences

Geomagnetic storms and atmosphere

The currents in the ionosphere heat up the atmosphere and cause it to expand
→ This can create satellite drag for low-orbit satellites, which leads to satellite orbital decay



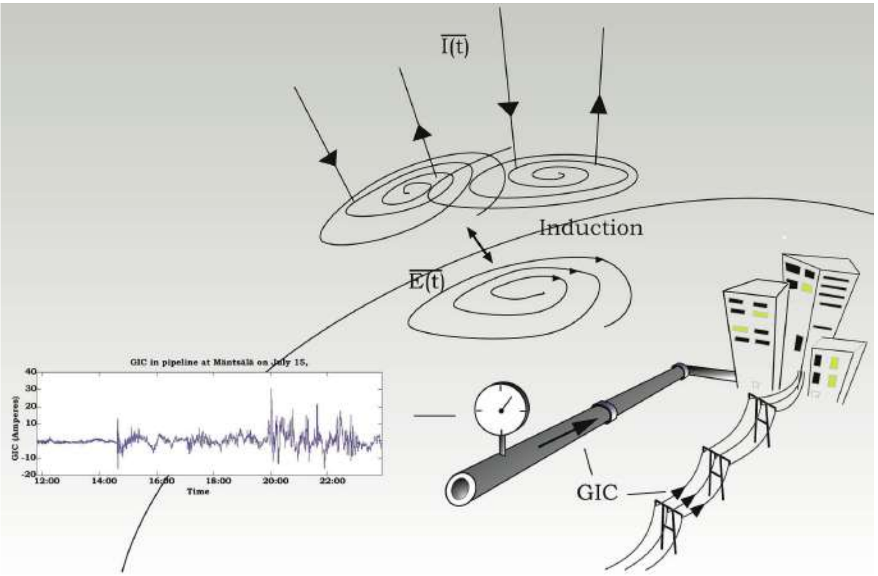
[NOAA]



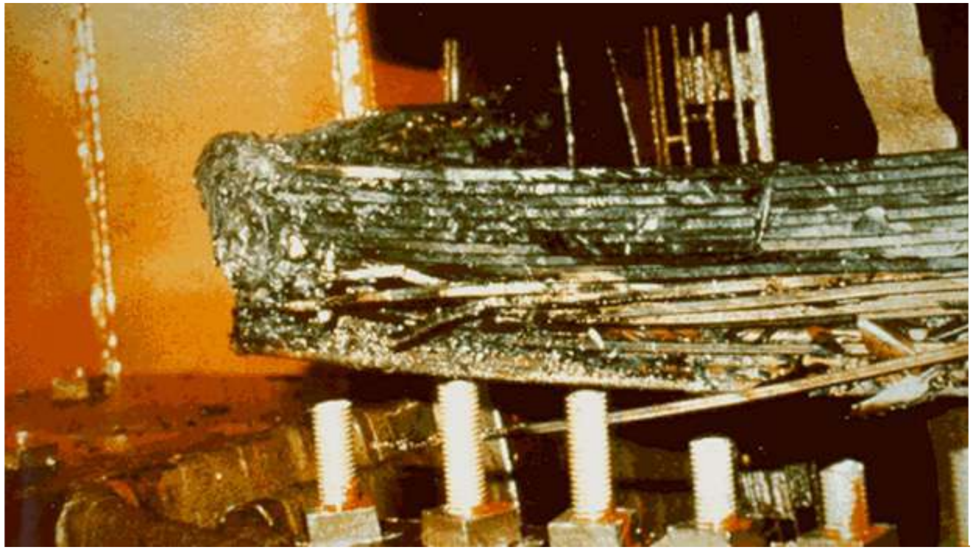
→ This is what happened to StarLink satellites in February 2022 (42 satellites lost)

Geomagnetic storms and ground effects

By induction, the currents in the ionosphere create currents in Earth crust
→ They are called Ground-Induced Currents (GICs)



[Wikipedia]



→ GICs cause electrical overloads, especially in large installations (pipelines, etc.)

Summary of geomagnetic storms effects

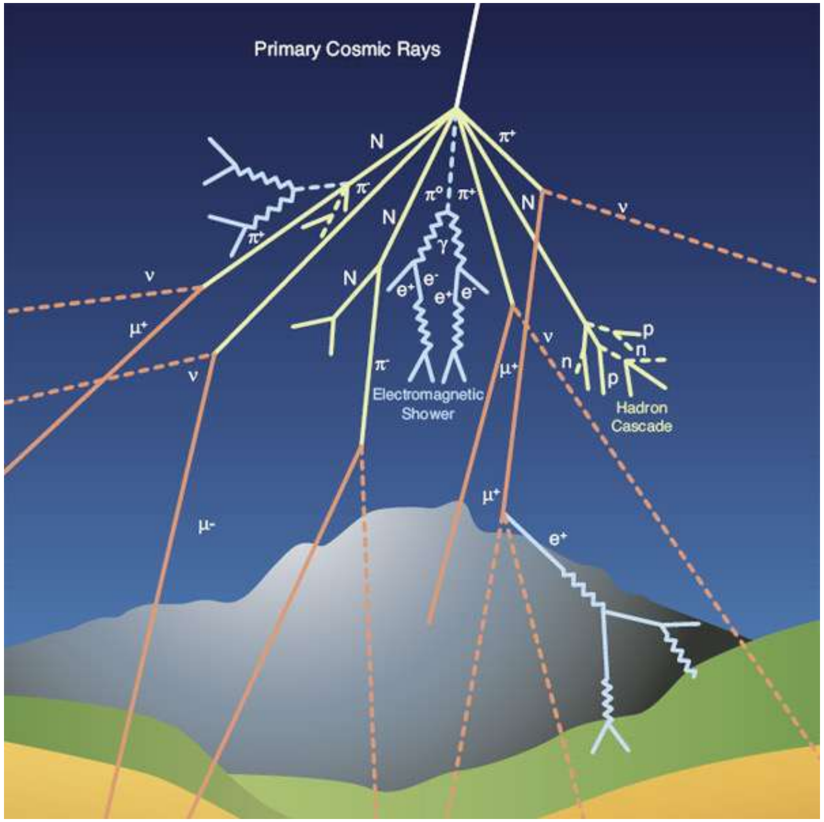
NOAA Space Weather Scales

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.).**	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.).**	Kp=8	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.).**	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).**	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).**	Kp=5	1700 per cycle (900 days per cycle)

* Based on this measure, but other physical measures are also considered.
** For specific locations around the globe, use geomagnetic latitude to determine likely sightings (see www.swpc.noaa.gov/Aurora)

Solar radiation storms

When SEPs penetrate the atmosphere, they interact with the particles there and generate a particle shower reaction

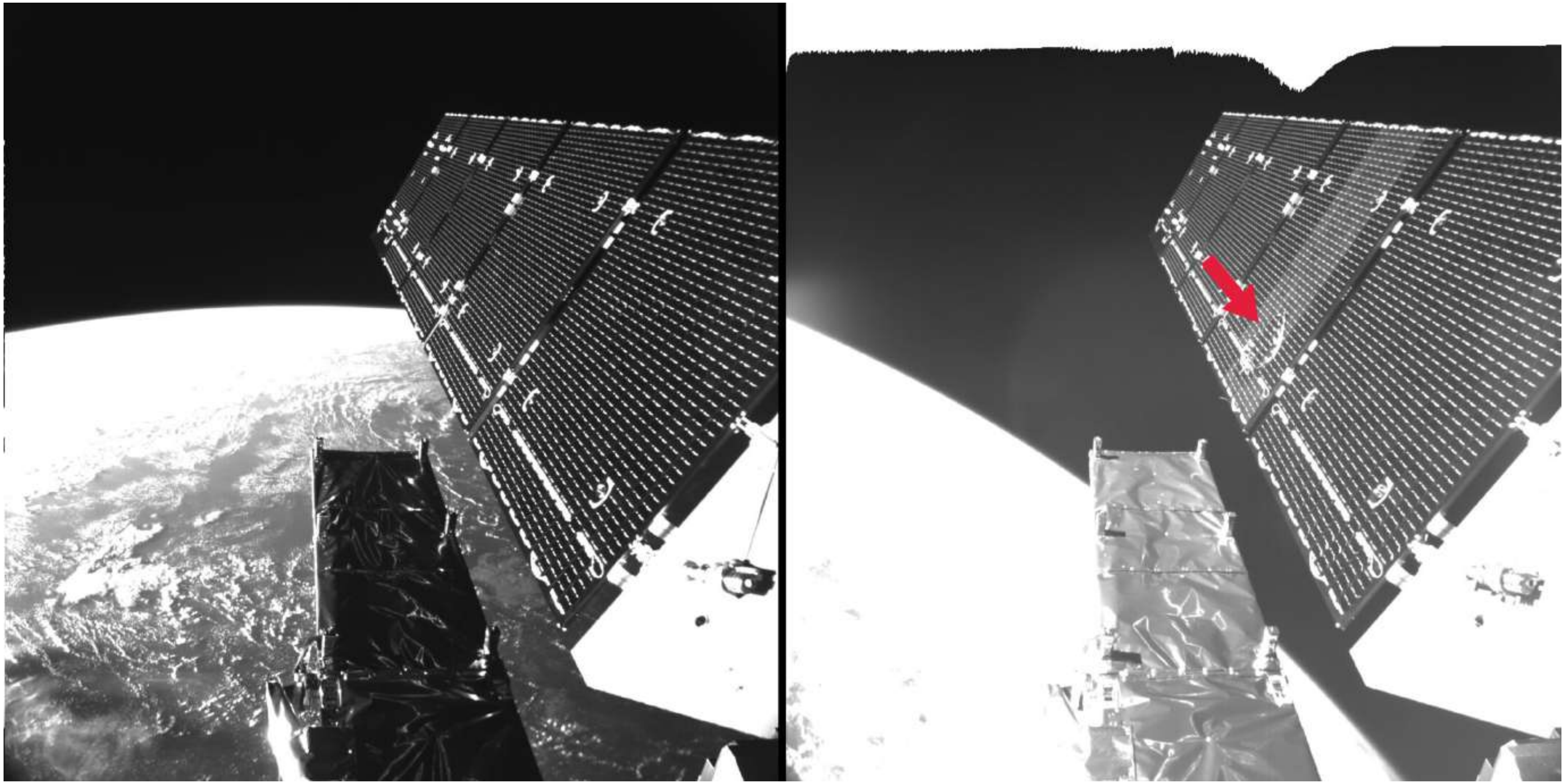


[CERN]

→ This will modify the properties of the atmosphere, and especially create radiations

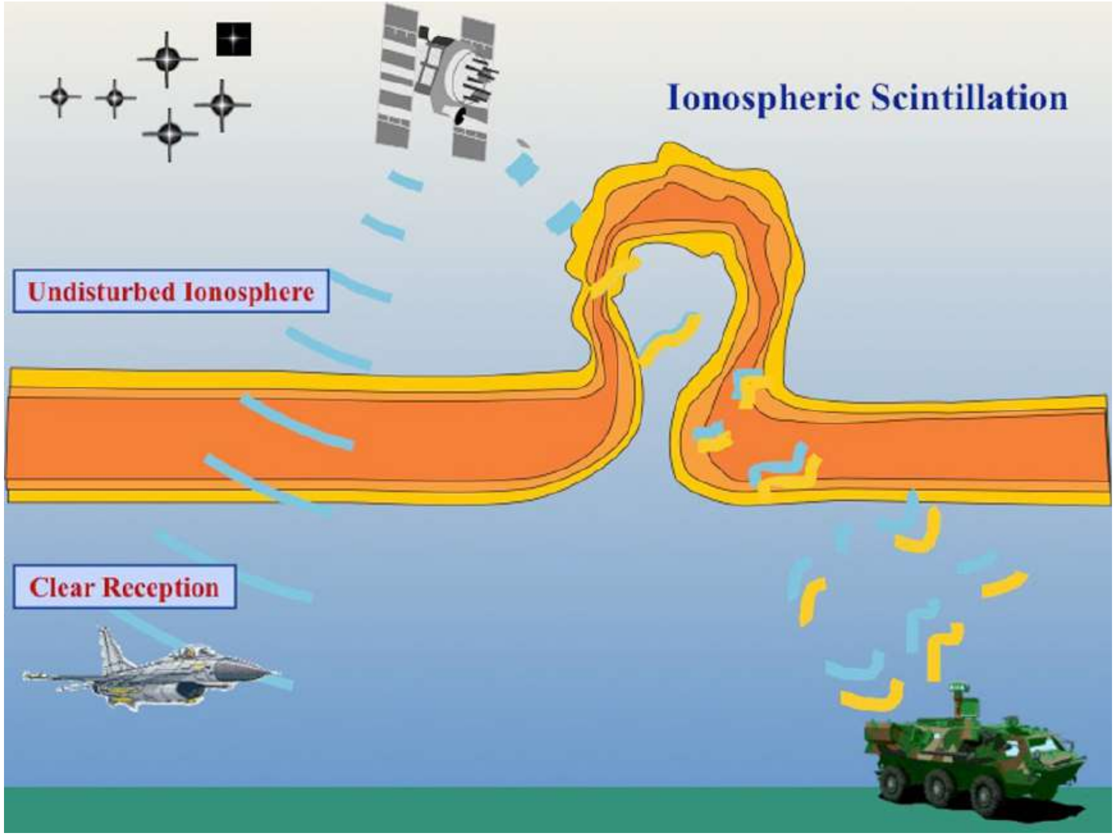
Radiations storms and satellites

Particles responsible for radiation storms are dangerous for satellites
→ Impacts can damage electronics, especially the solar panels



Radiation storms and communications

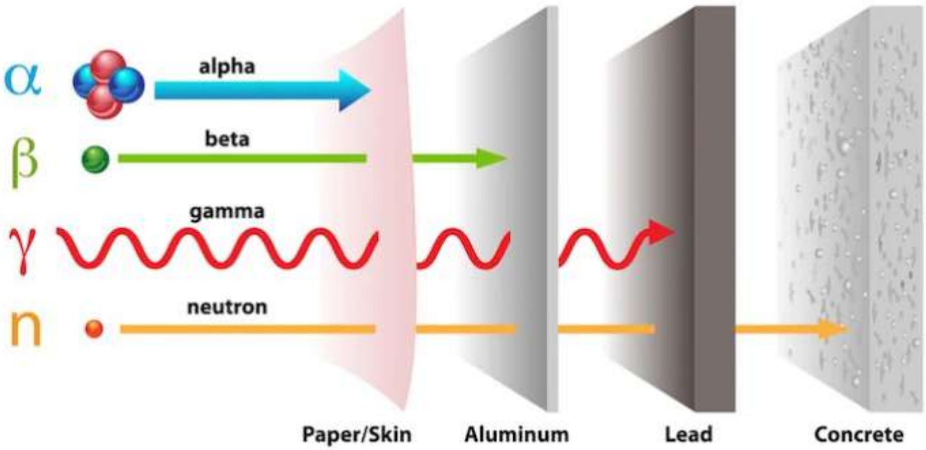
The disturbed ionosphere generates ionospheric scintillations



→ These scientillations get in the way of satellite communication (GPS, etc.)

Radiation storms and human health

Radiations and particles are both dangerous for astronauts in space



Radiations are also dangerous for air crew (not so much for passengers)

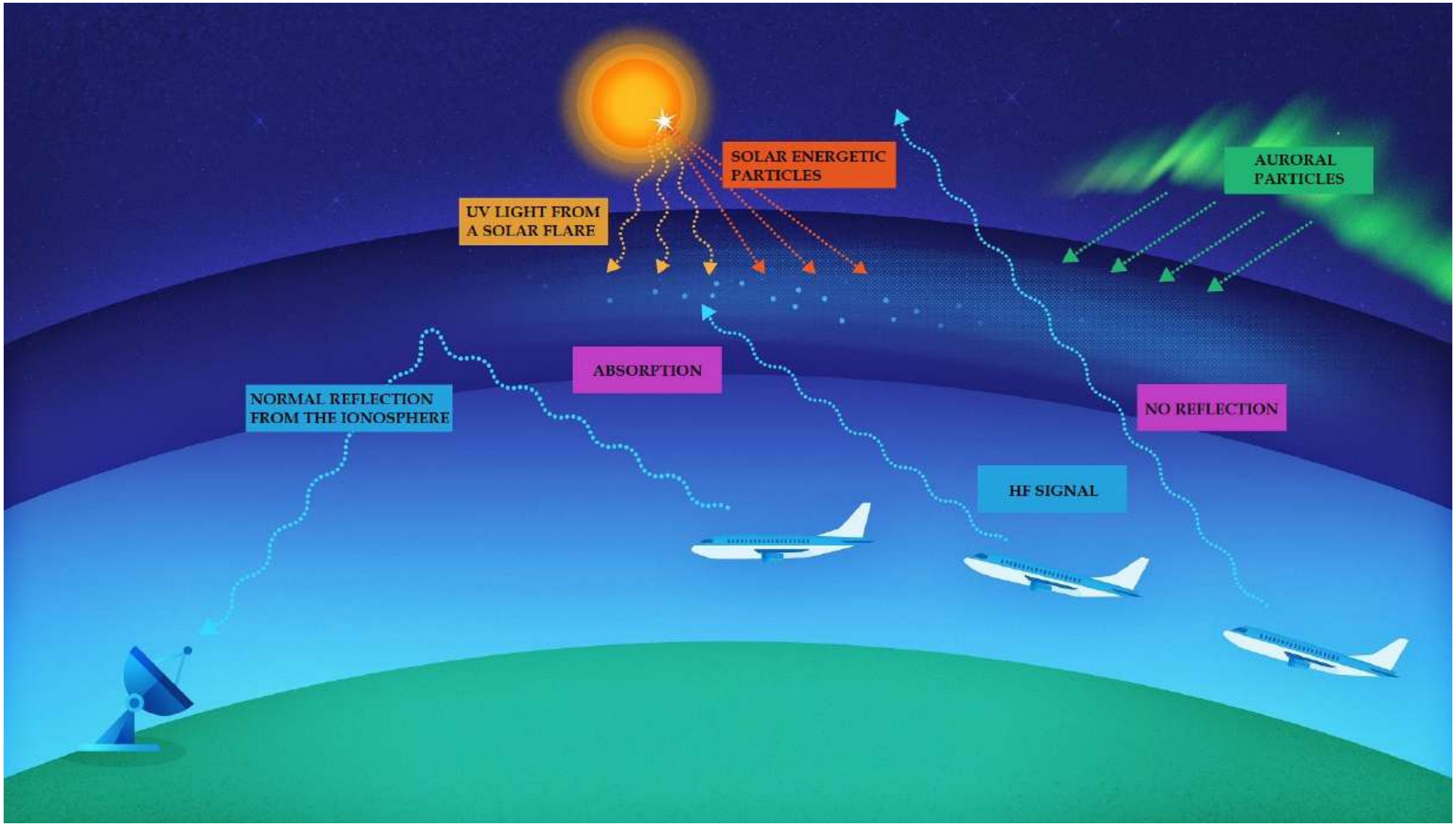
Summary of radiation storms effects

Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Satellite operations: infrequent single-event upsets possible. Other systems: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S1	Minor	Biological: none. Satellite operations: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·$ster^{-1}$·cm^{-2} Based on this measure, but other physical measures are also considered.
** These events can last more than one day.
*** High energy particle (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

Radio blackouts

The combination of light and particles from the Sun changes the properties of the ionosphere, especially its cut-off frequency



→ This results in delays or even local suppression of radio waves communications

Summary of radio blackouts effects

Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	HF Radio: Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. Navigation: Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 ($2x10^{-3}$)	Fewer than 1 per cycle
R 4	Severe	HF Radio: HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	HF Radio: Limited blackout of HF radio communication on sunlit side of the Earth, loss of radio contact for tens of minutes. Navigation: Degradation of low-frequency navigation signals for tens of minutes.	M5 ($5x10^{-5}$)	350 per cycle (300 days per cycle)
R 1	Minor	HF Radio: Weak or minor degradation of HF radio communication on sunlit side of the Earth, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Flux, measured in the 0.1-0.8 nm range, in $W \cdot m^{-2}$. Based on this measure, but other physical measures are also considered.

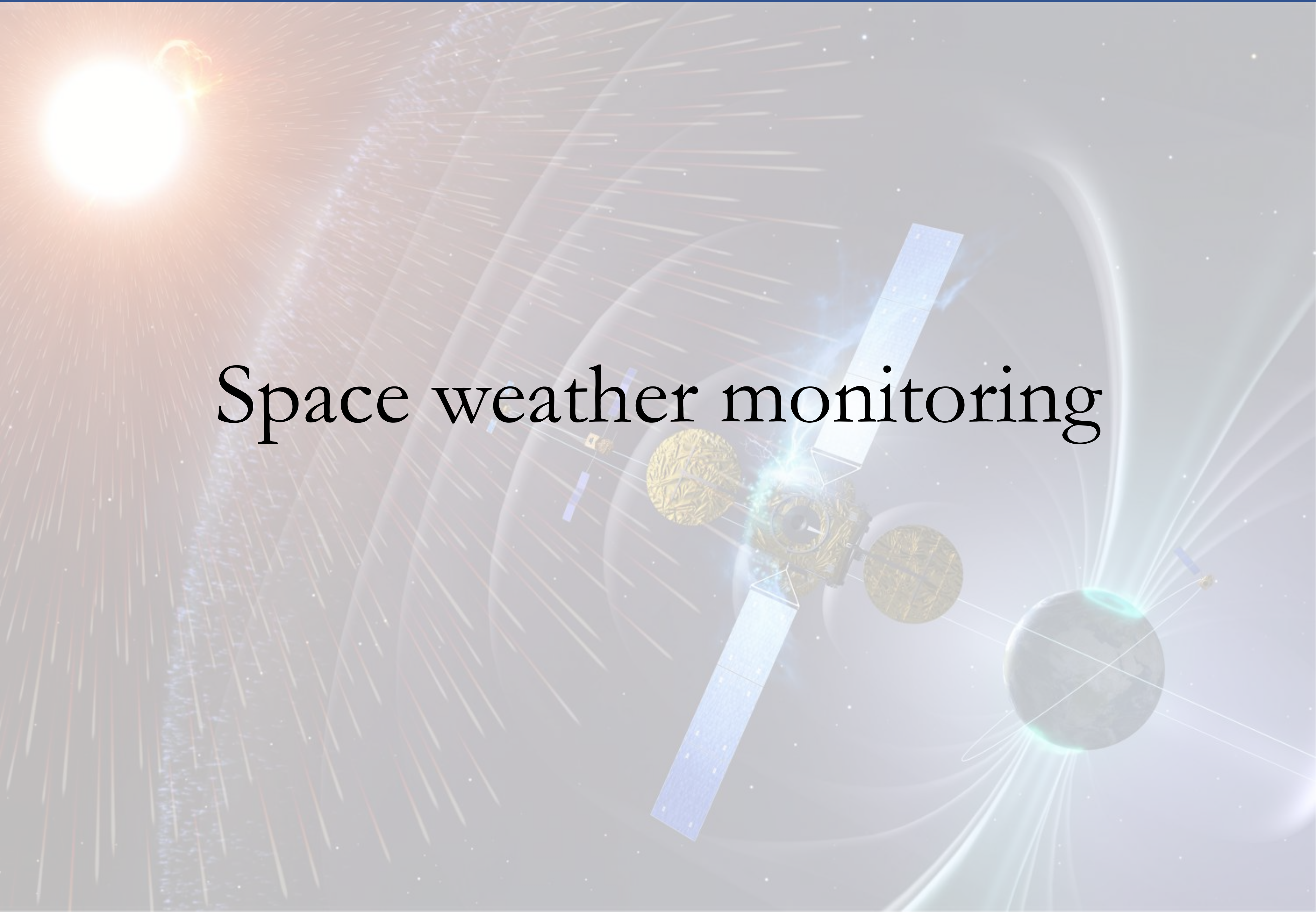
** Other frequencies may also be affected by these conditions.

URL: *www.swpc.noaa.gov/NOAAscales*

April 7, 2011

Recent examples of space weather events

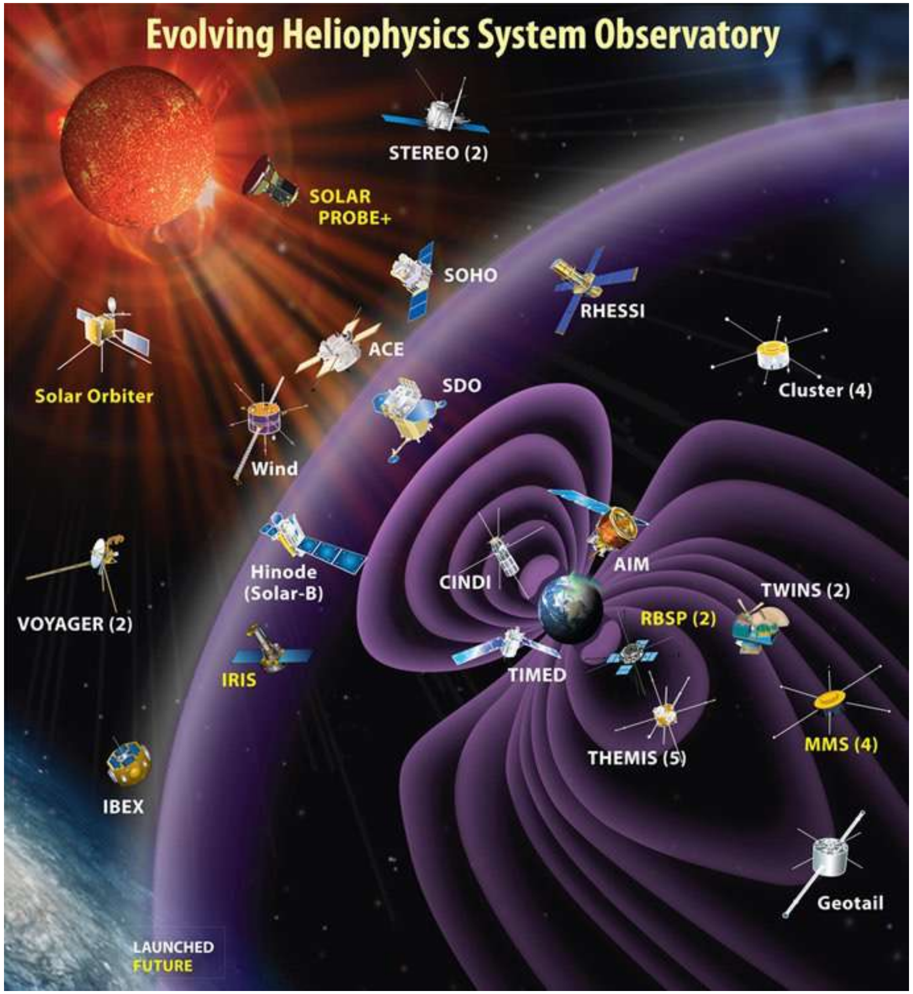
Date	Type of event	Intensity	Consequences
May 1921	CME	Kp>9 (G5)	Damages to telegraphs + New York Railroad on fire
August 1972	Flare + CME	X20 (R5, S5) + Kp>9 (G5)	Severe damages to satellites + detonation of sea mines + nearly endangered Apollo missions
March 1989	Flare + 2 CMEs	X15 (S5) + Kp>9 (G5)	Hydro-Quebec down for a day + loss of communications for UN in Namibia
January 1994	HSS	Kp=8 (G4)	Loss of 2 satellites
July 2000	Flare + CME	X5 (S3) + Kp>9 (G5)	Damages to power transformers and satellites
October 2003	Flare	X45 (R5, S5)	Power outage in Sweden
November 2015	Flare	X2 (R5)	Closure of swedish airspace



Space weather monitoring

Monitoring the Sun and the Earth

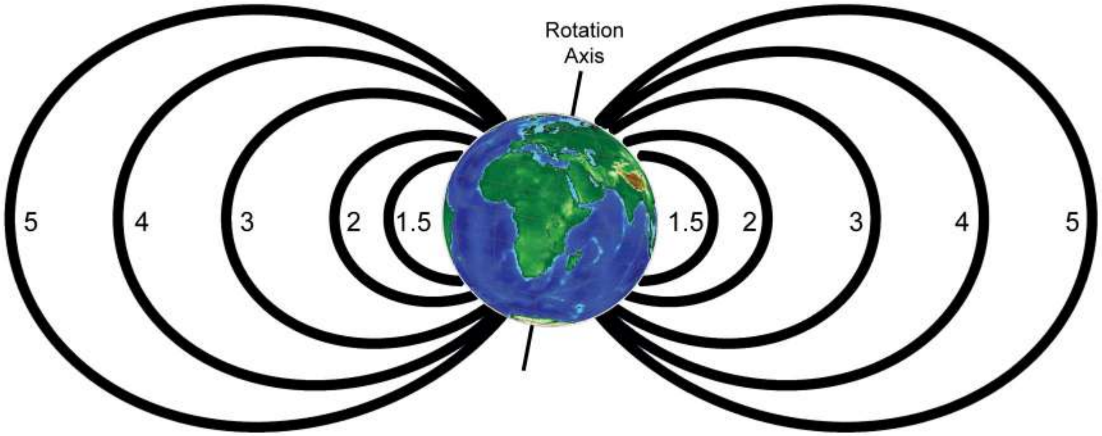
Large number of satellites between the Sun and the Earth for monitoring
→ BUT is it still enough?



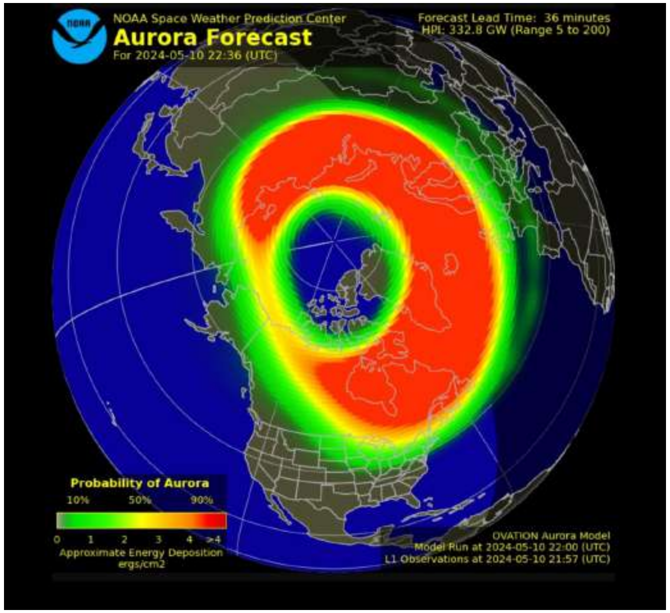
[NASA]

Ovale auroral

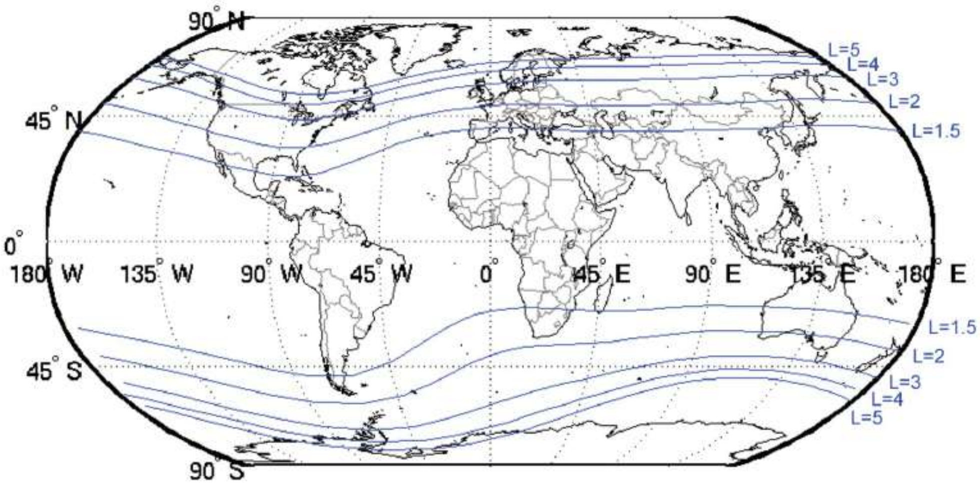
L shells

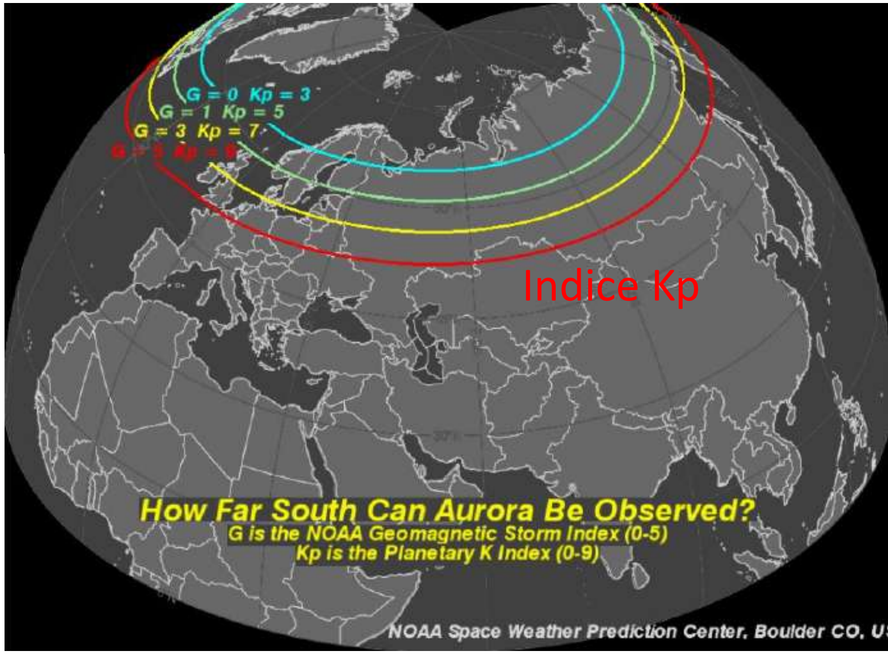


L-shells are magnetic field lines that are located at a given multiple of R_T



Plus la tempête est puissante plus elle compresse et modifie les lignes magnétiques profondes, déplaçant l'ovale auroral vers les plus basses latitudes.





L-shells and particles rigidity

L-shells are directly linked to the energy necessary for particles to reach them

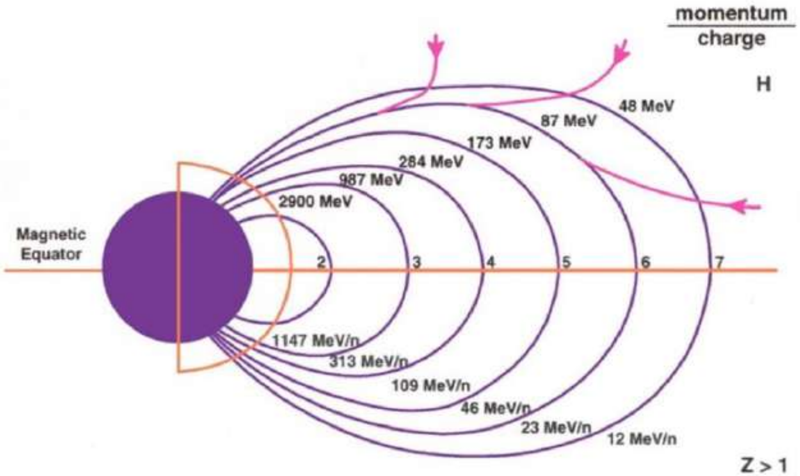
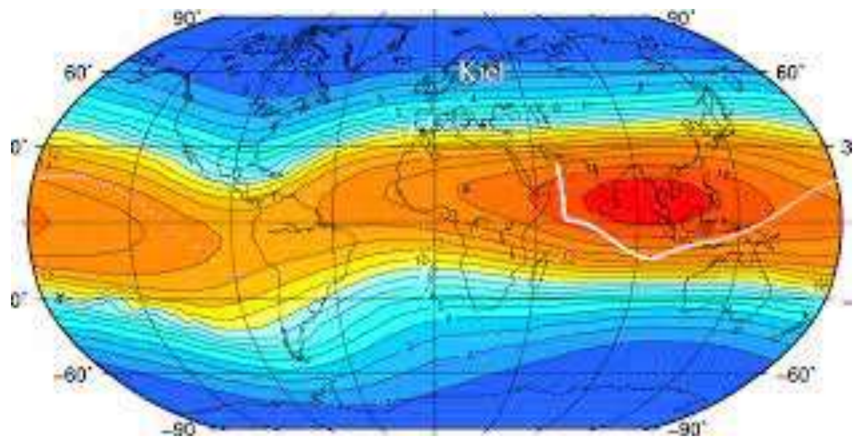


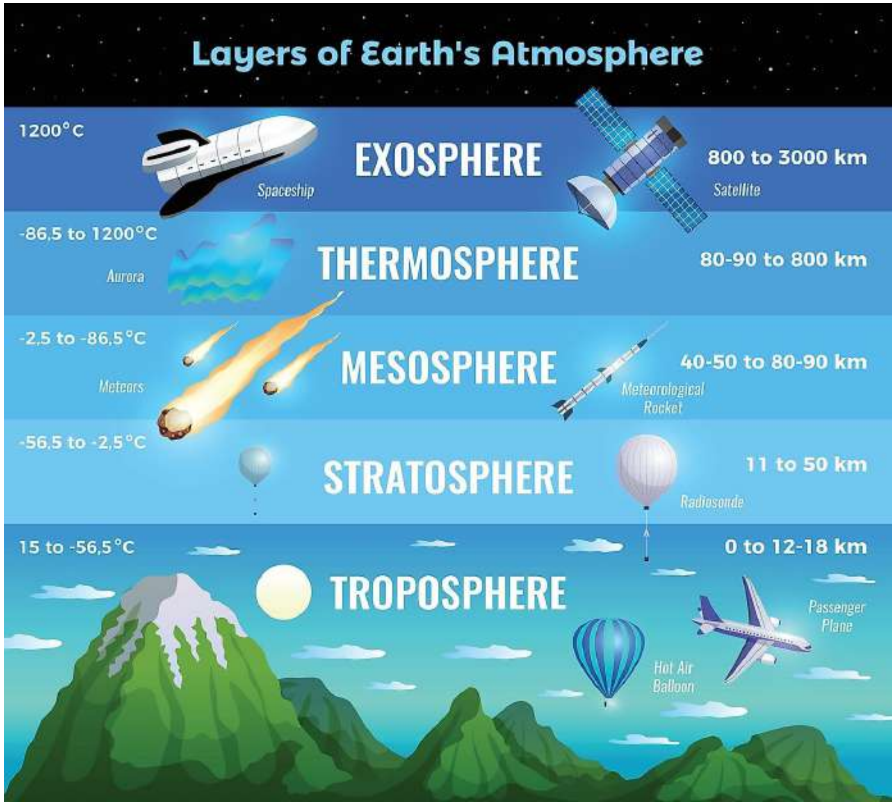
Figure 66: L-shell contours with rigidity imposed energy penetration limits.

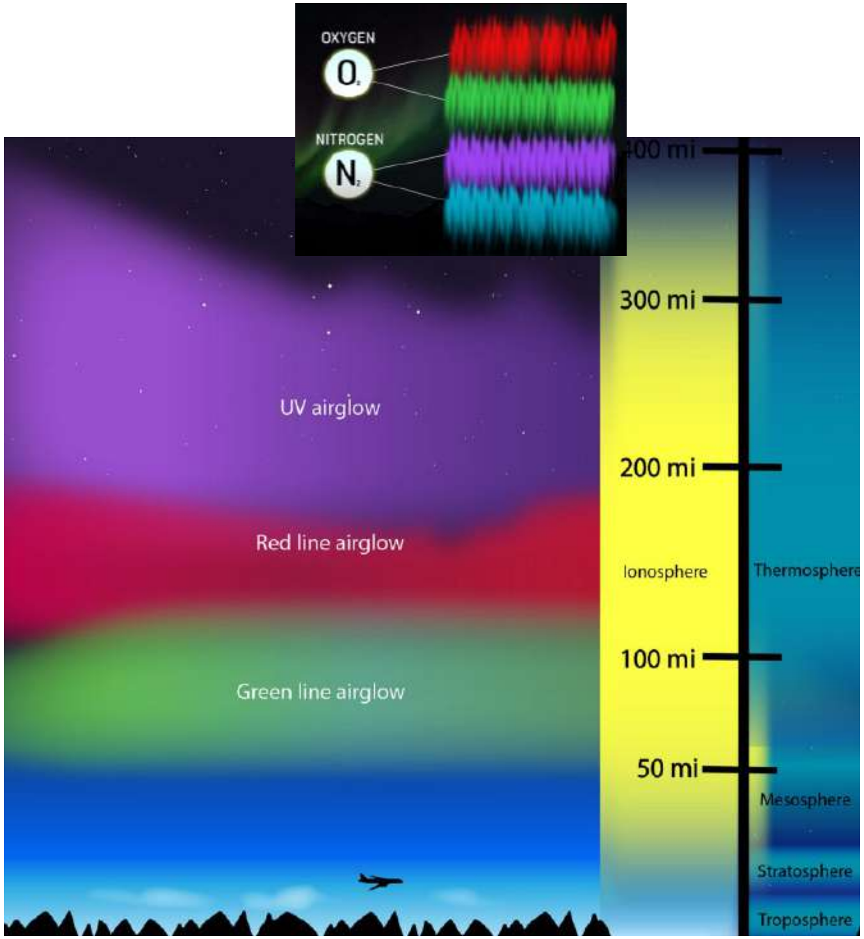


[Steigies et al. 2006]

→ They can be used to derive cut-off rigidity maps

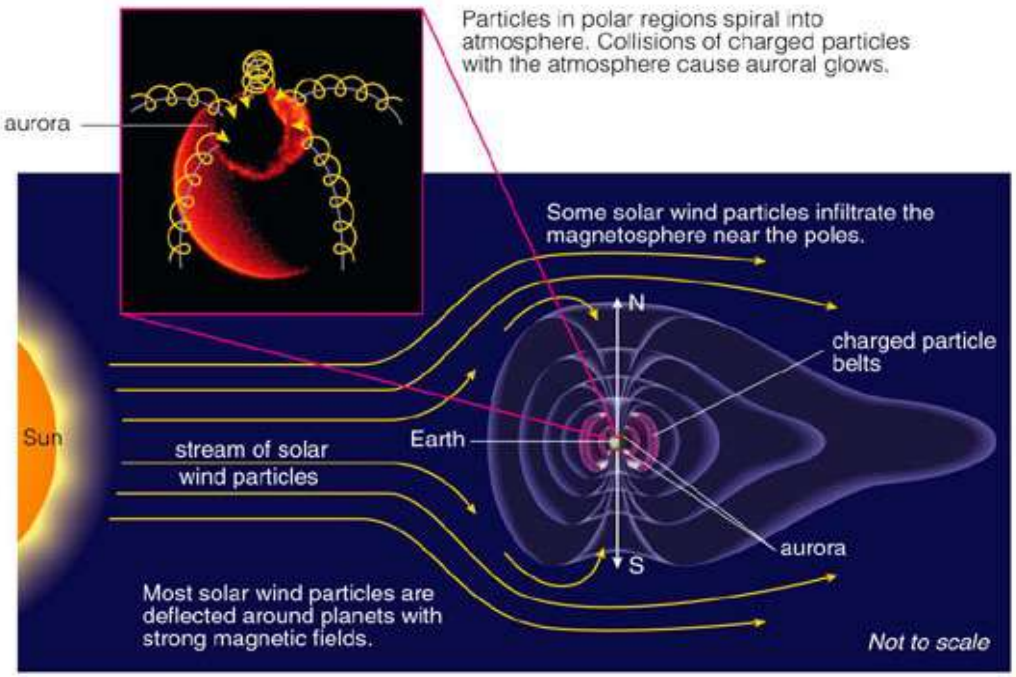
Les Couches atmosphériques de la Terre





→ La plus importante pour les aspects météorologie de l'espace est l'**ionosphère**, une couche électrifiée dans la thermosphère, où les **aurores boréales (australes)** apparaissent

Planète Terre: Magnétosphère



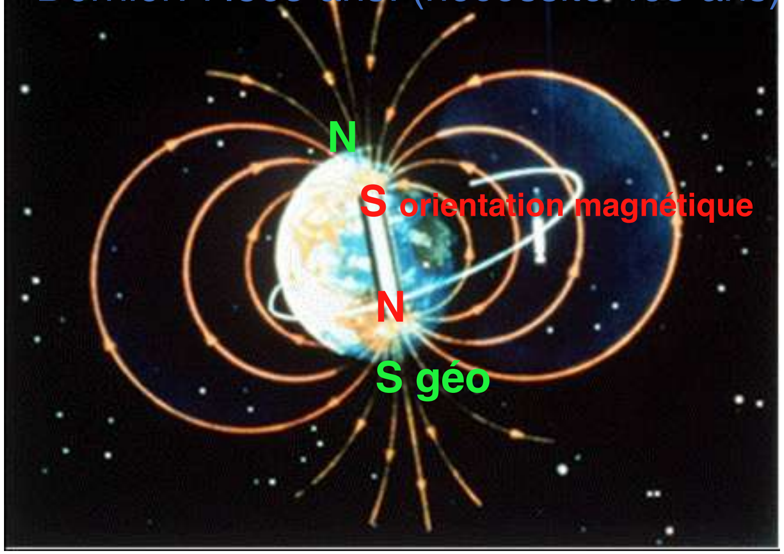
Molécules d'Oxygène (entre autre) excitées par le vent solaire

ucation, publishing as Addison Wesley.

B très stable dans cœur solide, champ dynamo B cœur de fer liquide, résiduel dans croute (l<13 vu surf)

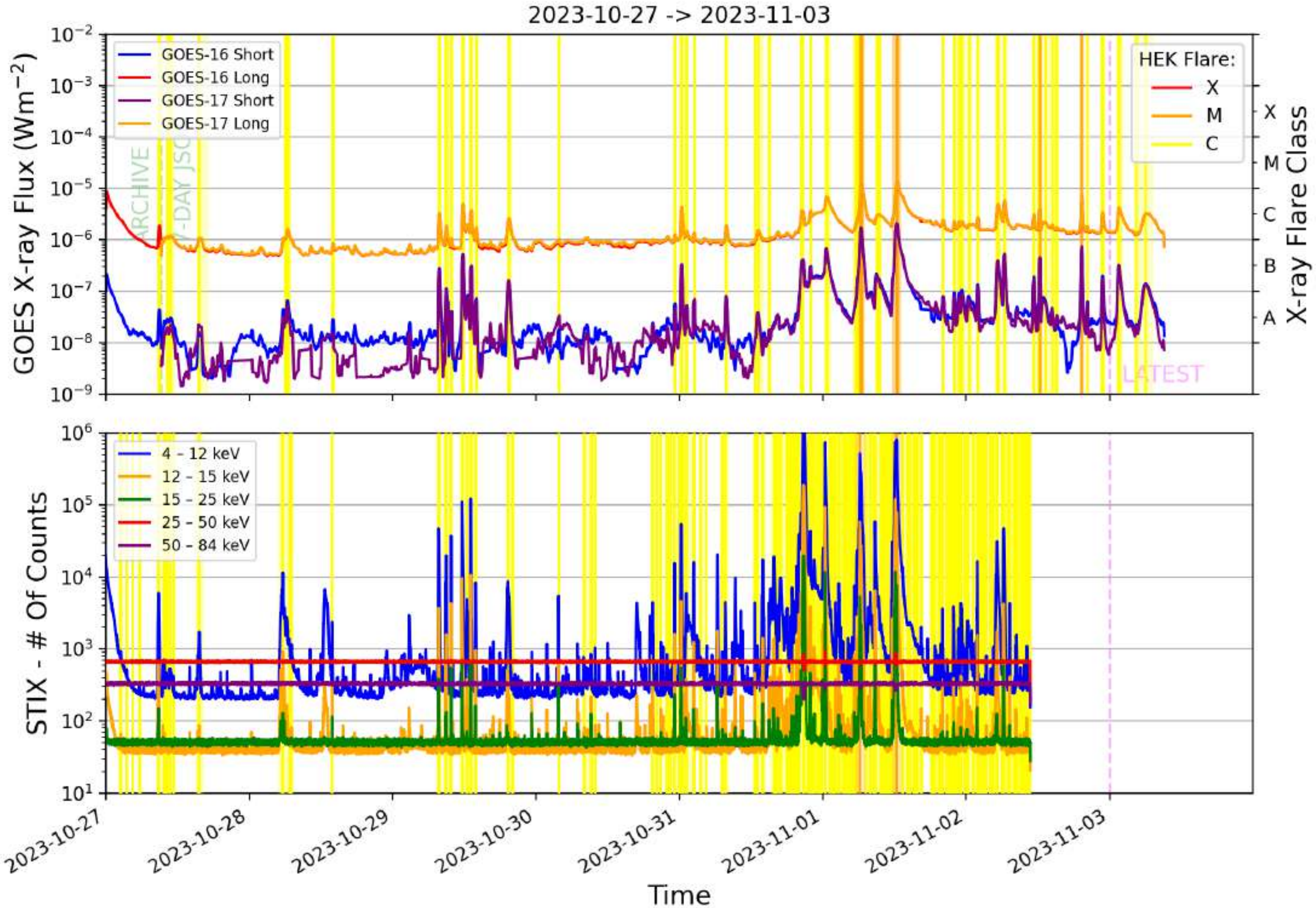
Renversement B sur Terre ~ 2e5 ans

Dernier: 7.8e5 ans! (nécessite 4e3 ans)



X-ray flux

The X-ray flux received at Earth is monitored vi the GOES satellites



→ It can be interesting to monitor it from other point of views (STIX on Solar Orbiter)

Magnetic indices

There are many ways to quantify the variations of the Earth magnetic field
→ mostly through magnetic indices

Nom	Date	Unité	Méthode	Δt
aa	1868	nT	Dérivé de K mesurés par deux observatoires antipodaux.	3h
AE	1957	nT	Dérivé des magnétogrammes de l'hémisphère Nord.	1 min
am	1959	nT	Dérivé de K à plusieurs longitudes en séparant Nord et Sud.	3h
$CK-Days$	1868	$\sim$	Dérivé de aa pour calculer le nombre de jours calmes.	24/48h
$D-Days$	1932	$\sim$	Dérivé de Kp pour donner les 5 jours les plus perturbés.	1 mois
Dst	1957	nT	Déviation à l'équateur du dipôle terrestre.	1h
Kp	1932	$\sim$	Moyenne arithmétique de K en échelle quasi-logarithmique.	3h
PC	1975	mV/m	Déduit des déviations du champ magnétique aux pôles.	1 min
$Q-Days$	1932	$\sim$	Dérivé de Kp pour donner les 10 jours les plus calmes.	1 mois

TABLE 5.2: Table récapitulative des indices géomagnétiques reconnus par l'IAGA (*International Association of Geomagnetism and Aeronomy*), classés par ordre alphabétique. Crédits : ISGI.

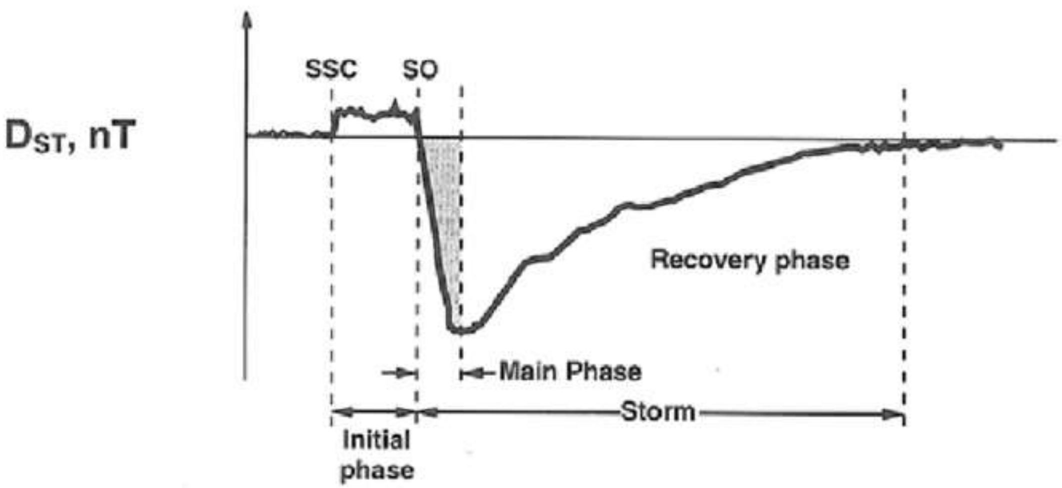
K is the largest geomagnetic variation within 3 hours (daily variations excluded)

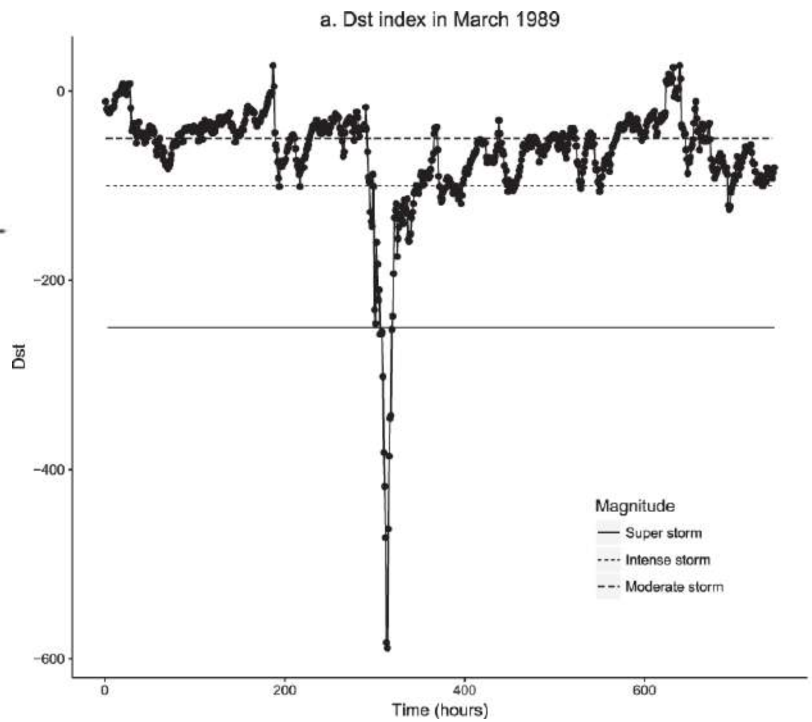
→ We will review in more details the most used indices: the Dst and the Kp

The Dst index

The Dst index measures the deviation of the Earth dipole at the equator
→ The most negative it gets, the strongest the geomagnetic storm

[Morina et al. 2019]

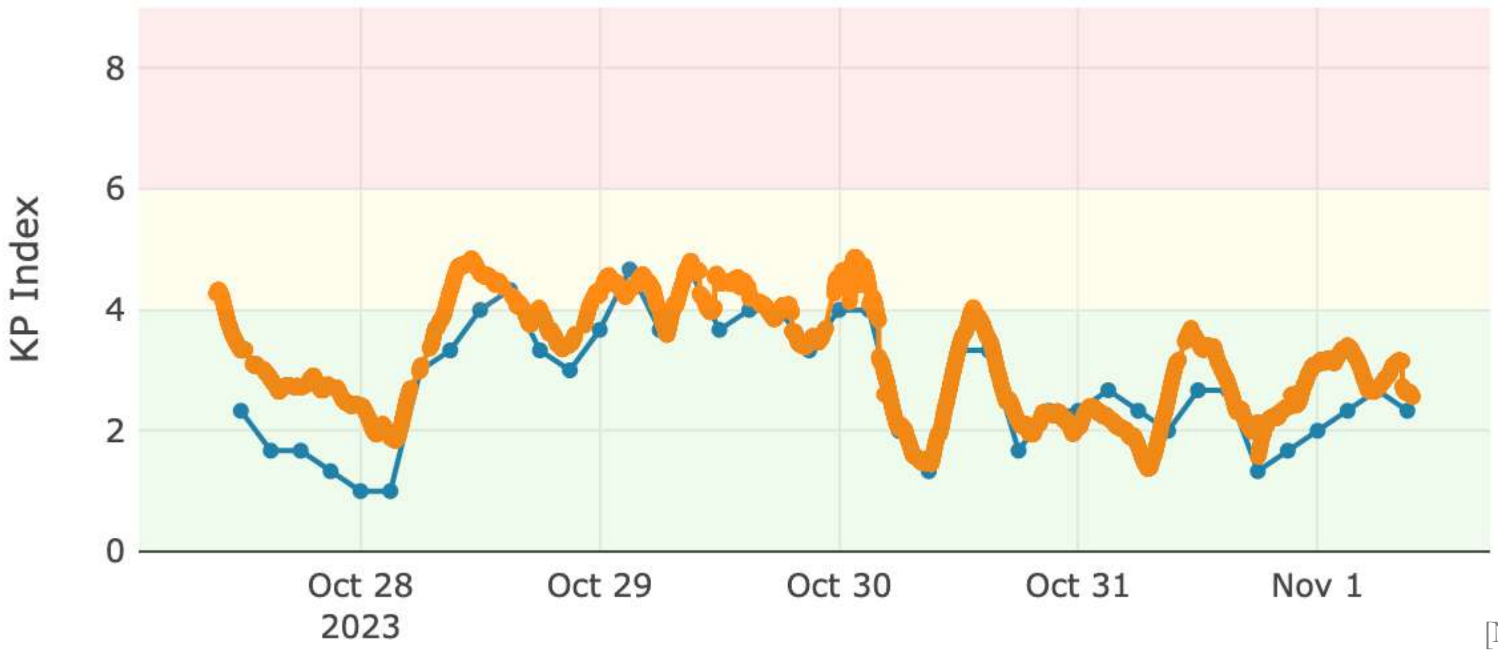




→ The threshold for an extreme event is at -150 nT

The Kp index

The Kp index is even more simple, with just a mean of K in logarithmic scale

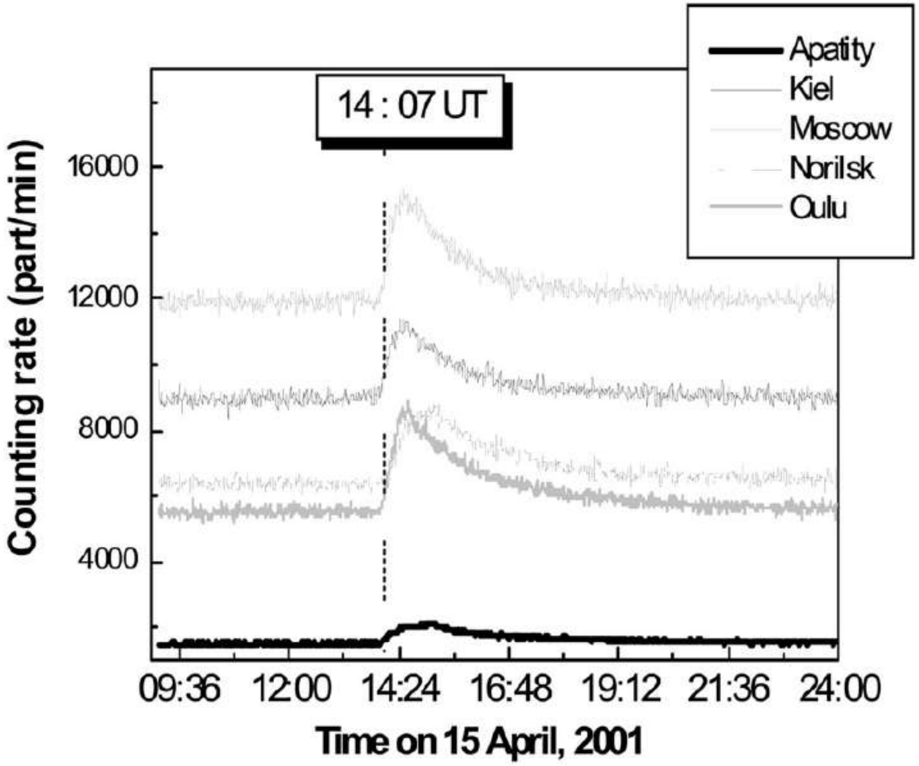


[NOAA]

→ Very useful to derive global trends (Kp>4 is active conditions)

Ground-Level Enhancements (GLEs)

GLEs are neutron enhancements that can be measured on the ground

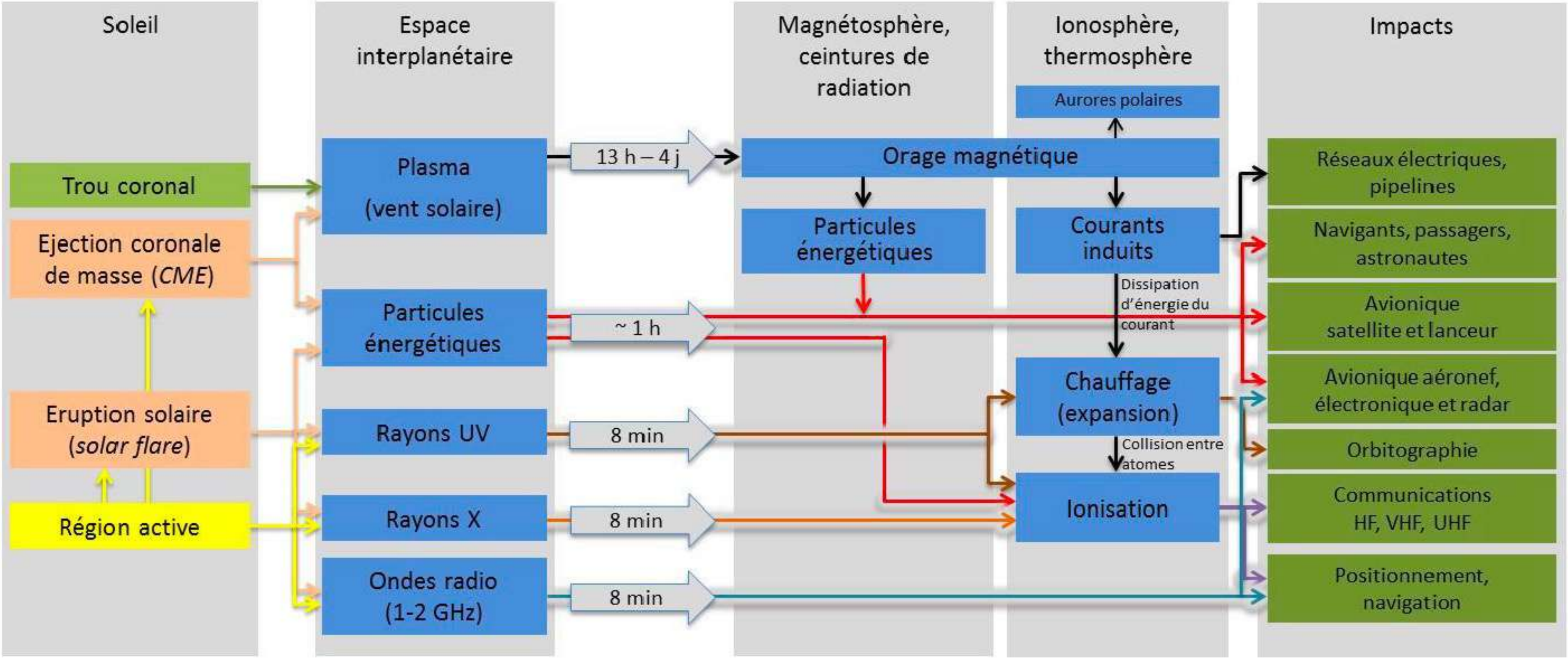


[Mavromichalaki+2007]

→ They are indicative of a solar flare
BUT they can also teach us things about additional events
(CMEs with Forbush decrease) and Earth conditions (latitudinal variations)

Limits of monitoring

Monitoring must be done, BUT certain events are too fast to rely only on that

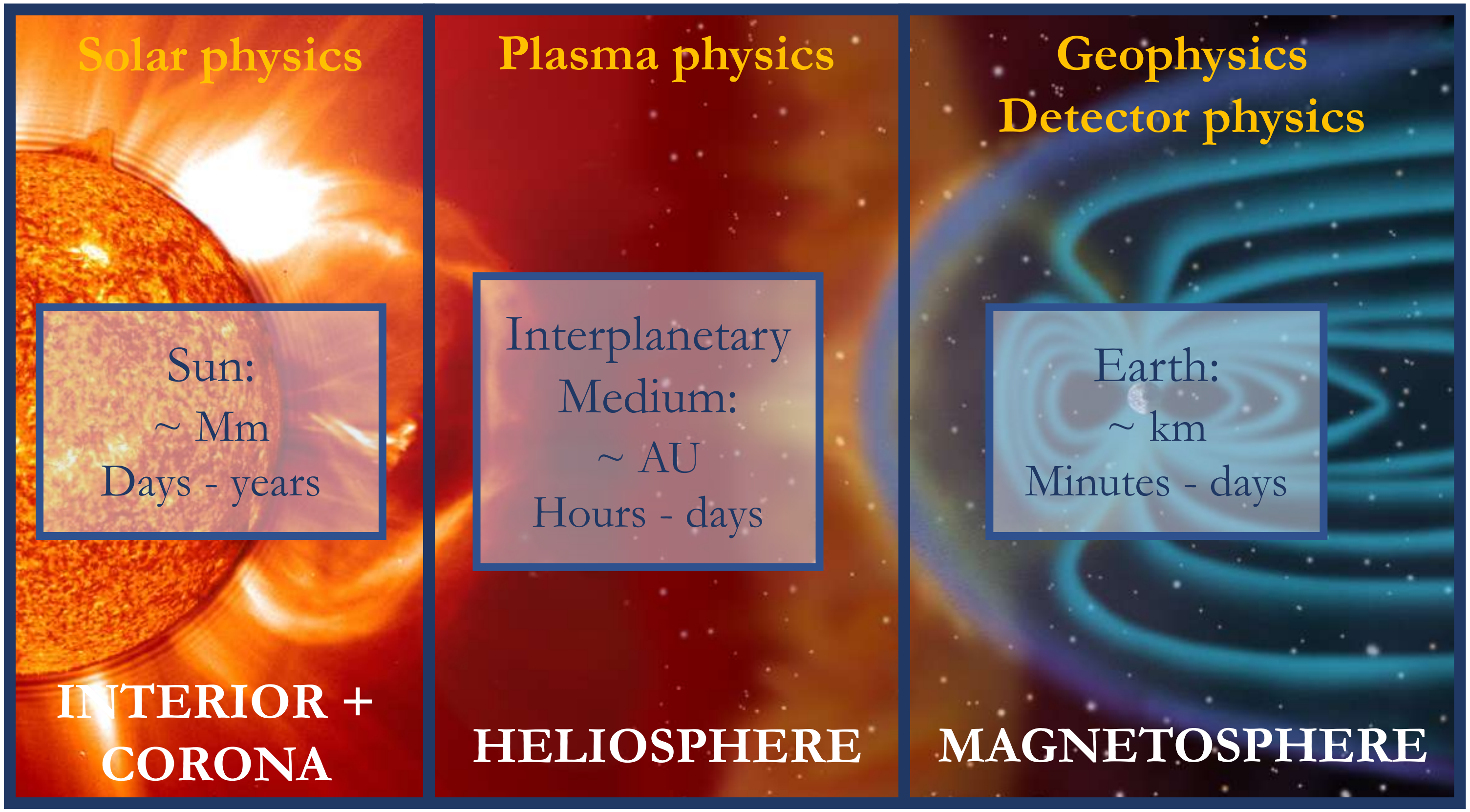


→ Need to go beyond with forecasting

Space weather forecasting

A transdisciplinary domain

Space weather covers a wide variety of **scales** and **physical phenomena**



[NASA]

[Wikipedia]

One model to rule them all? → **Impossible!**

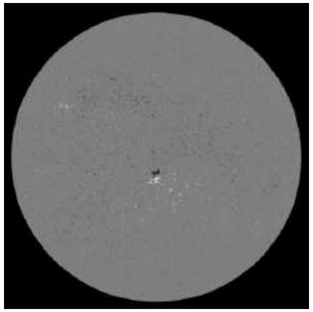
Rather **chains of models** with the **best numerical approach** depending on the region to model

Chains of models

Chain of data-driven simulations from the solar surface to the Earth (VSWMC)

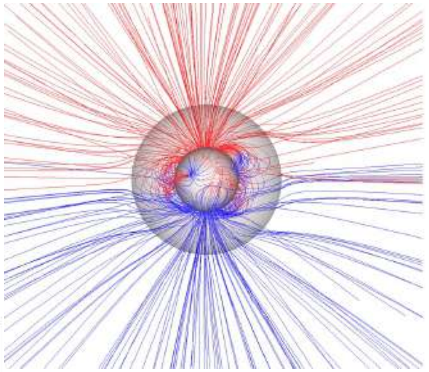
[Pomoell & Poedts 2018, Poedts+2020]

[SDO/HMI]

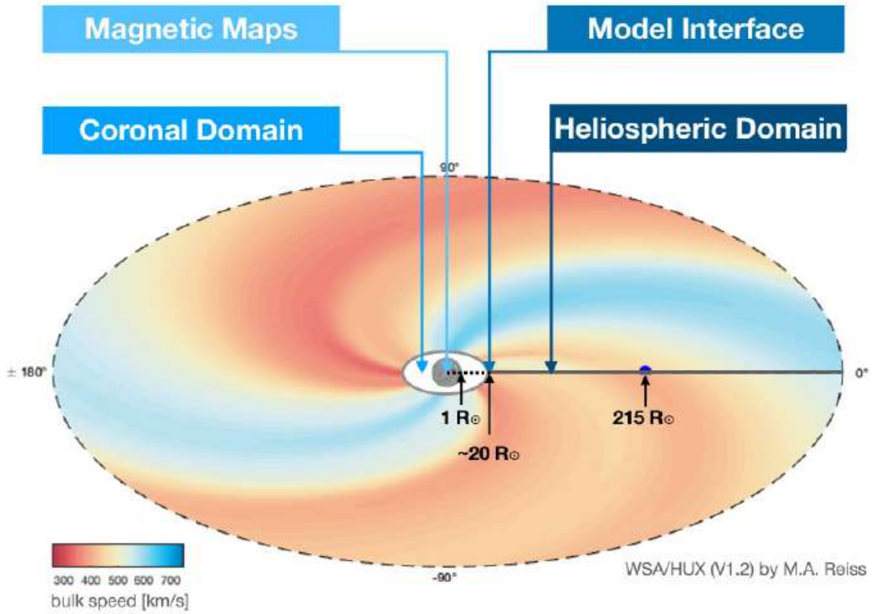


$1\ R_\odot$

observations



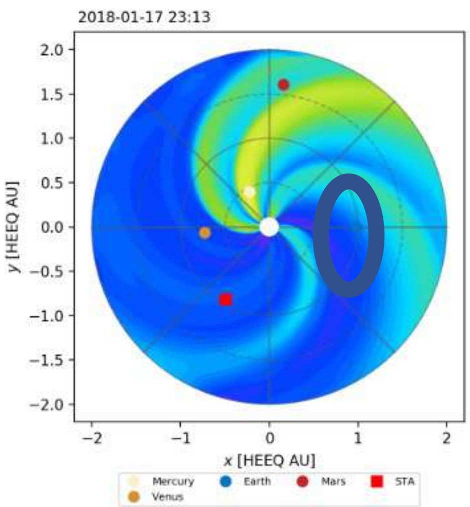
[Samara+2021]



[Reiss+2022]

$20\ R_\odot$

empirical



MHD

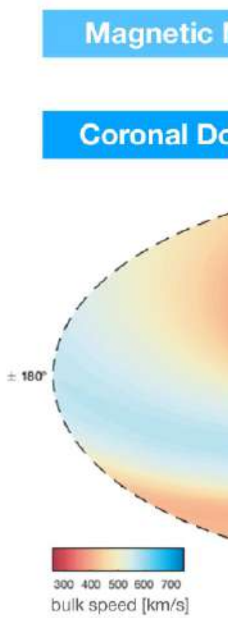
$20\ R_\odot - 2\ UA$

→ How to improve the models? Their connections? Incorporate AI and ML?

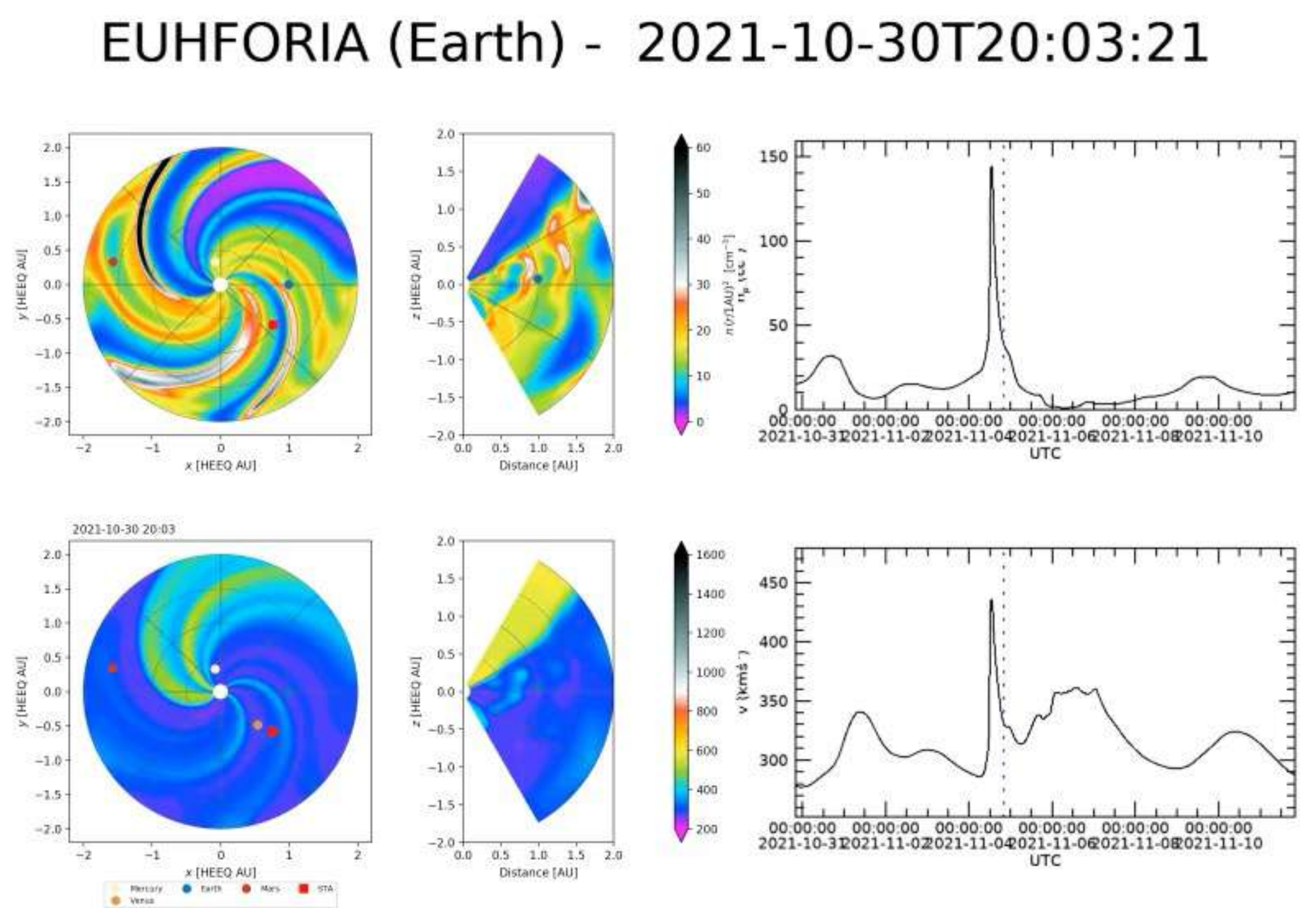
Chains of models

Chain of data-driven simulations from the solar surface to the Earth (VSWMC)

[Pomoell & Poedts 2018, Poedts+2020]

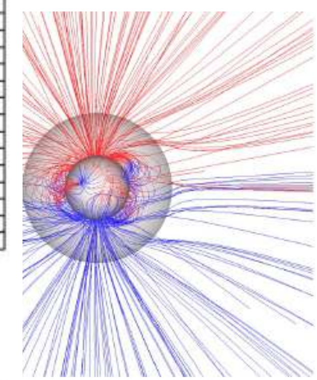


[Reiss+2022]



$R_\odot$

vations



[Samara+2021]

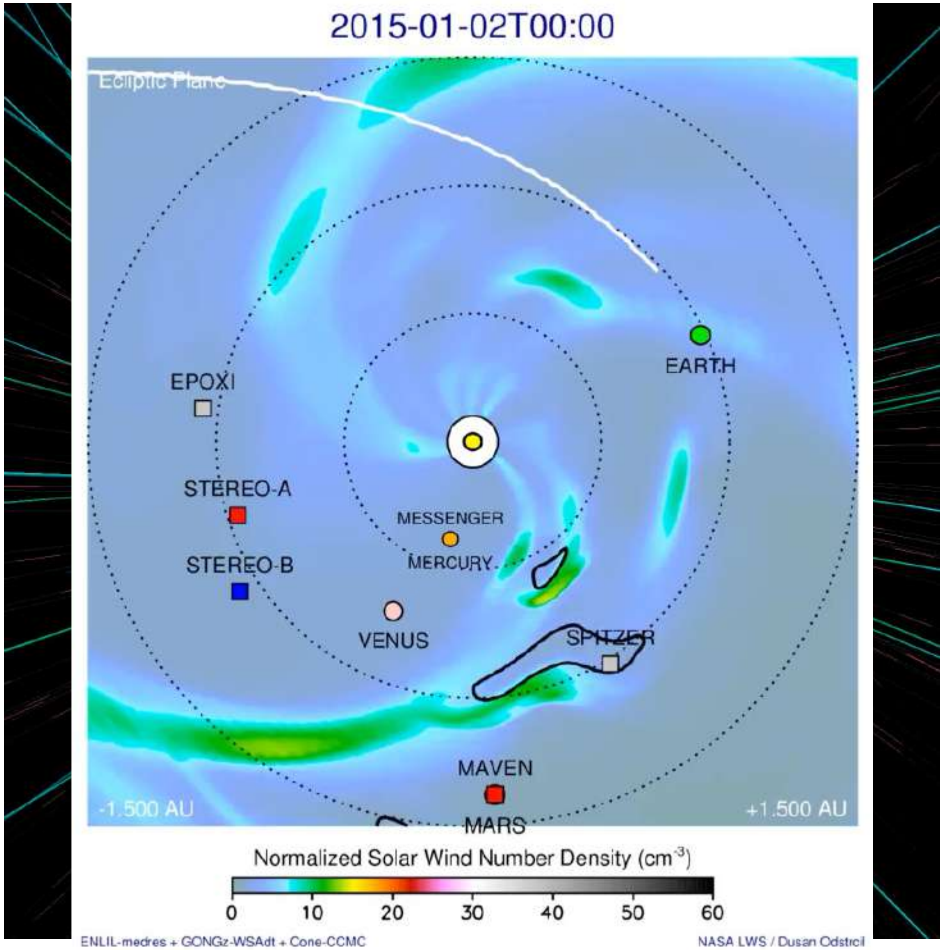
MHD

$R_\odot - 2\ UA$

→ How to improve the models? Their connections? Incorporate AI and ML?

Forecasting of the solar wind

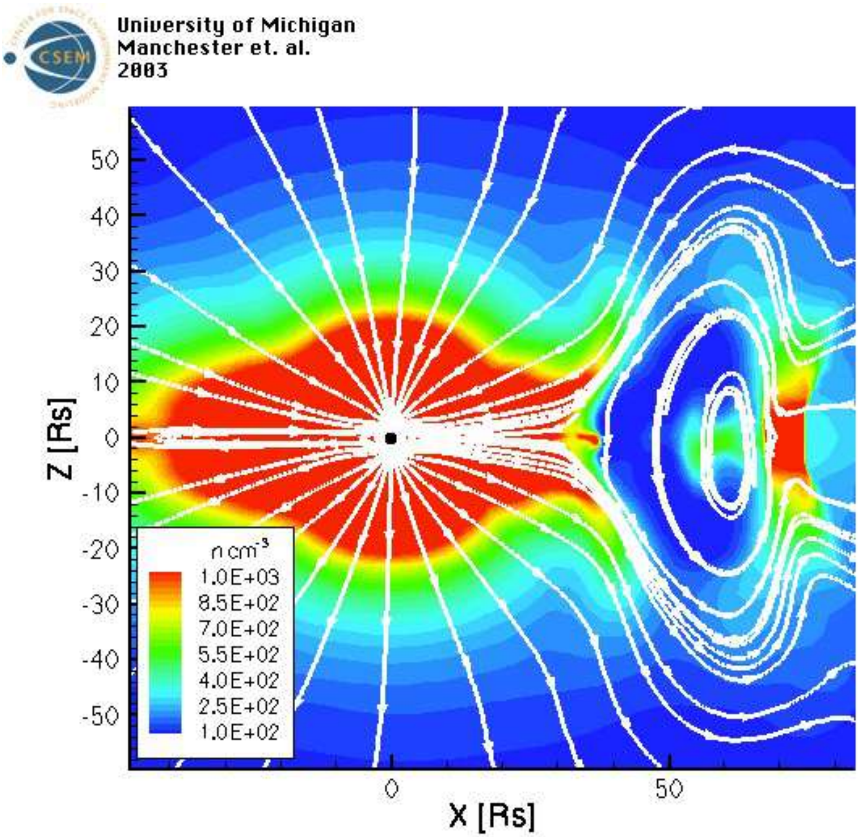
The solar wind is the medium in which everything else travels → crucial!!

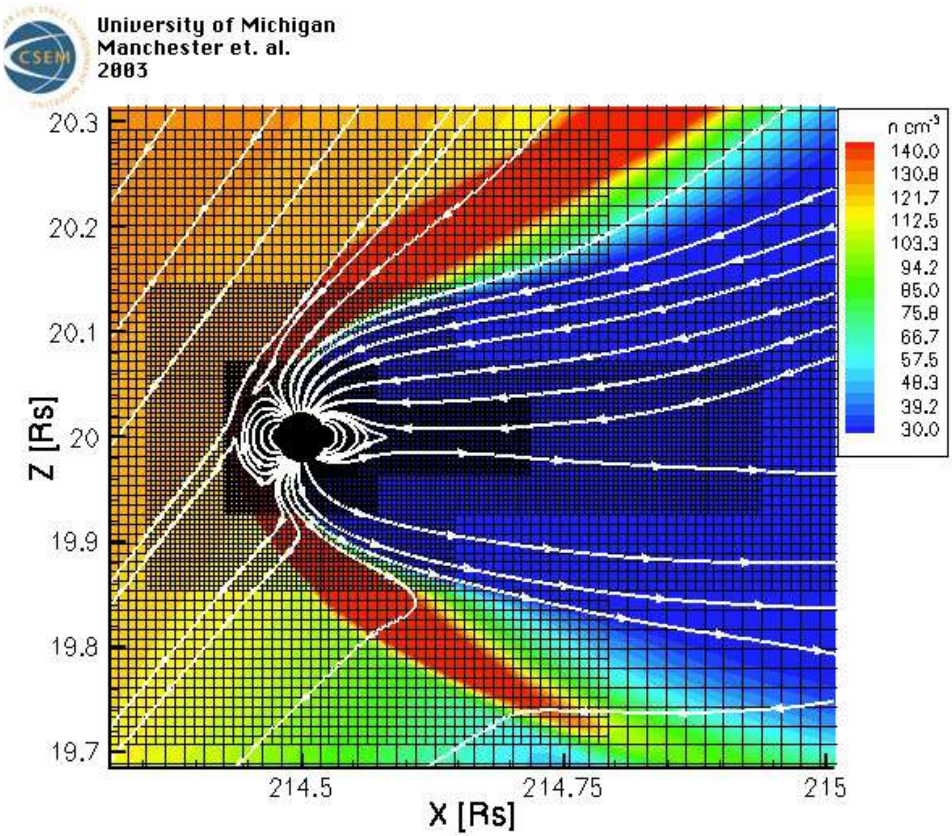


→ Main questions: slow or fast? which polarity? Parker spiral angle?

Forecasting of CMEs: Challenges

CMEs are objects that travel a great distance and rapidly change scales

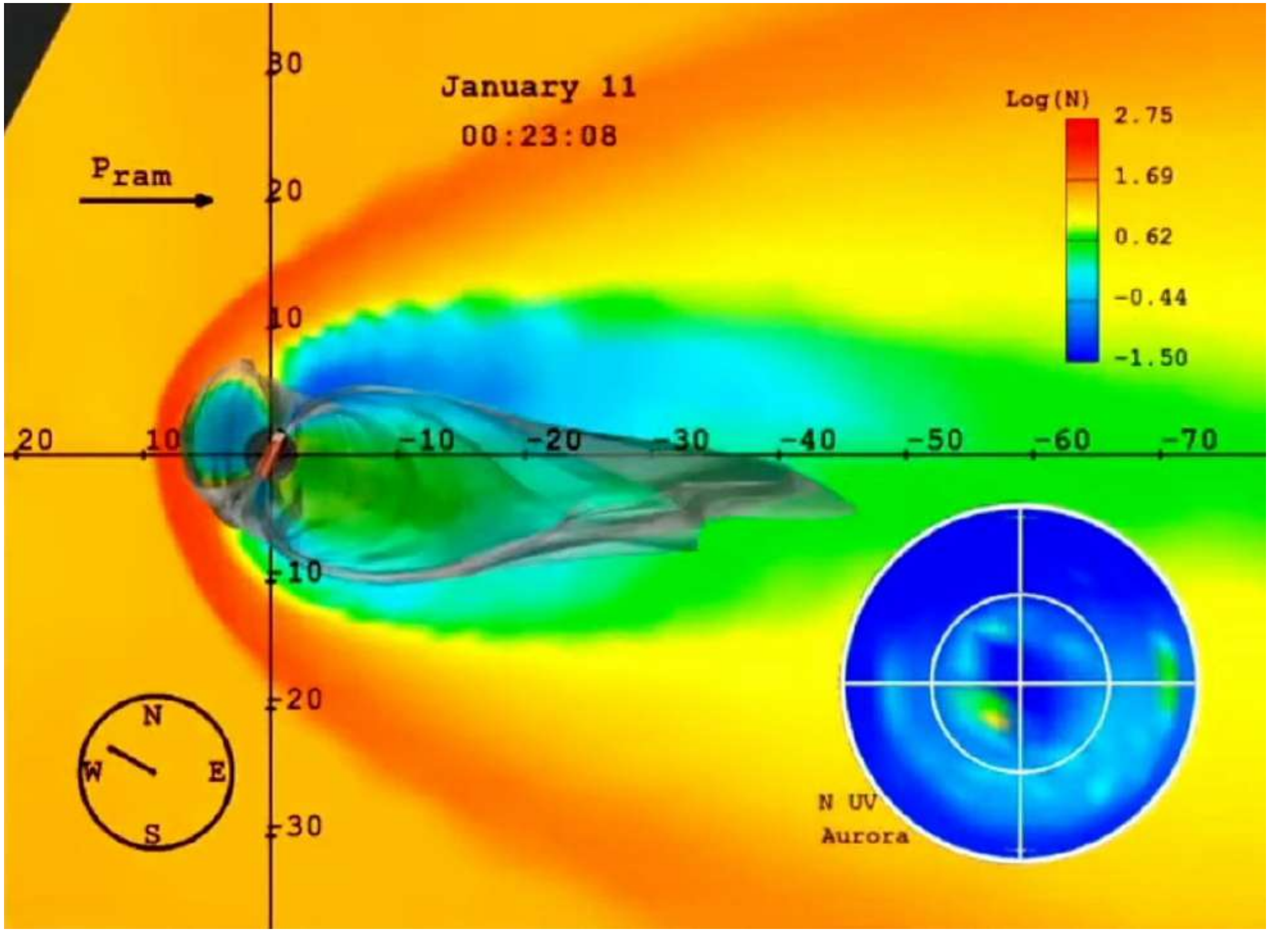


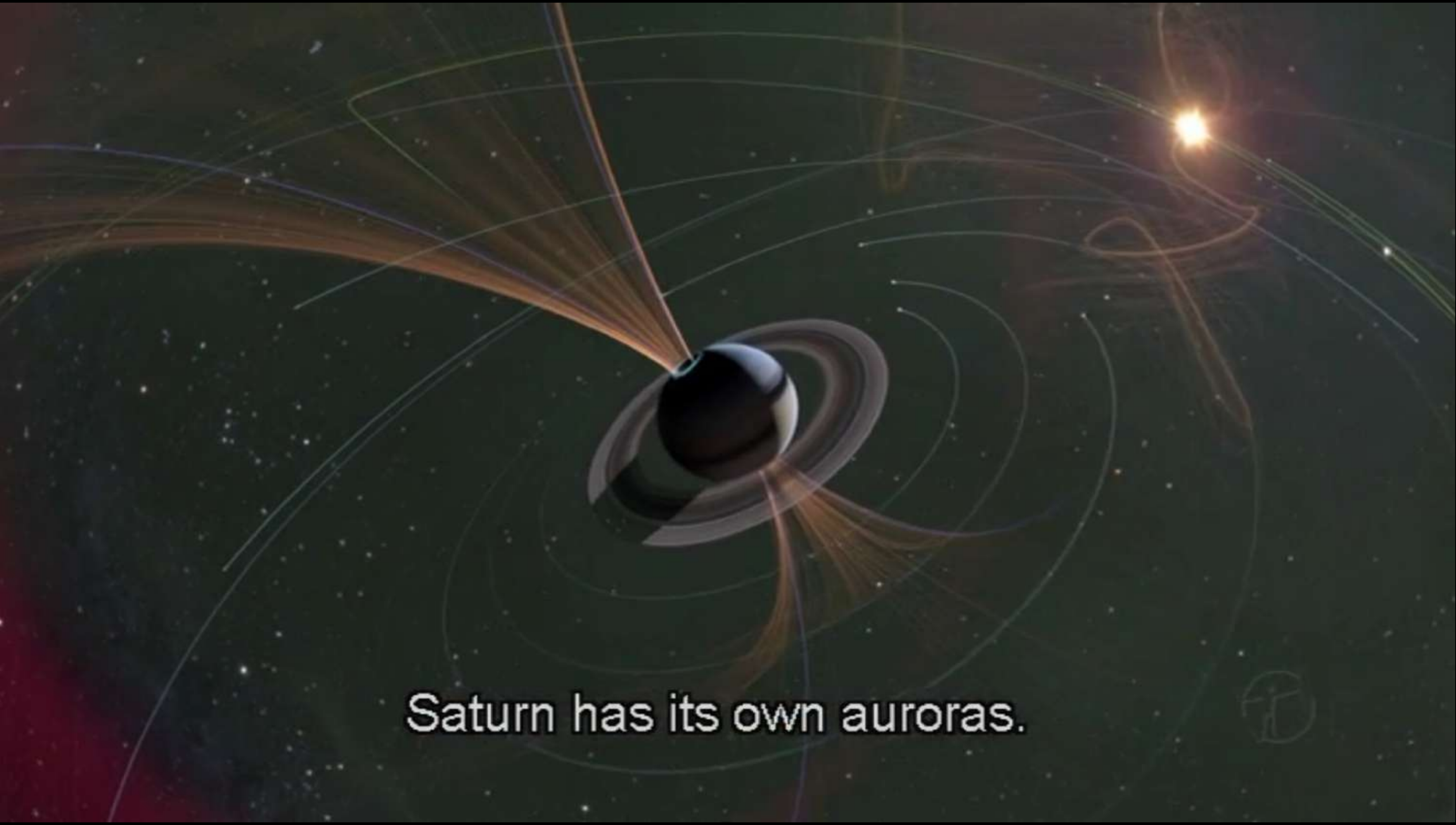


Forecasting of magnetosphere

Geo-effectiveness is not the end of the story

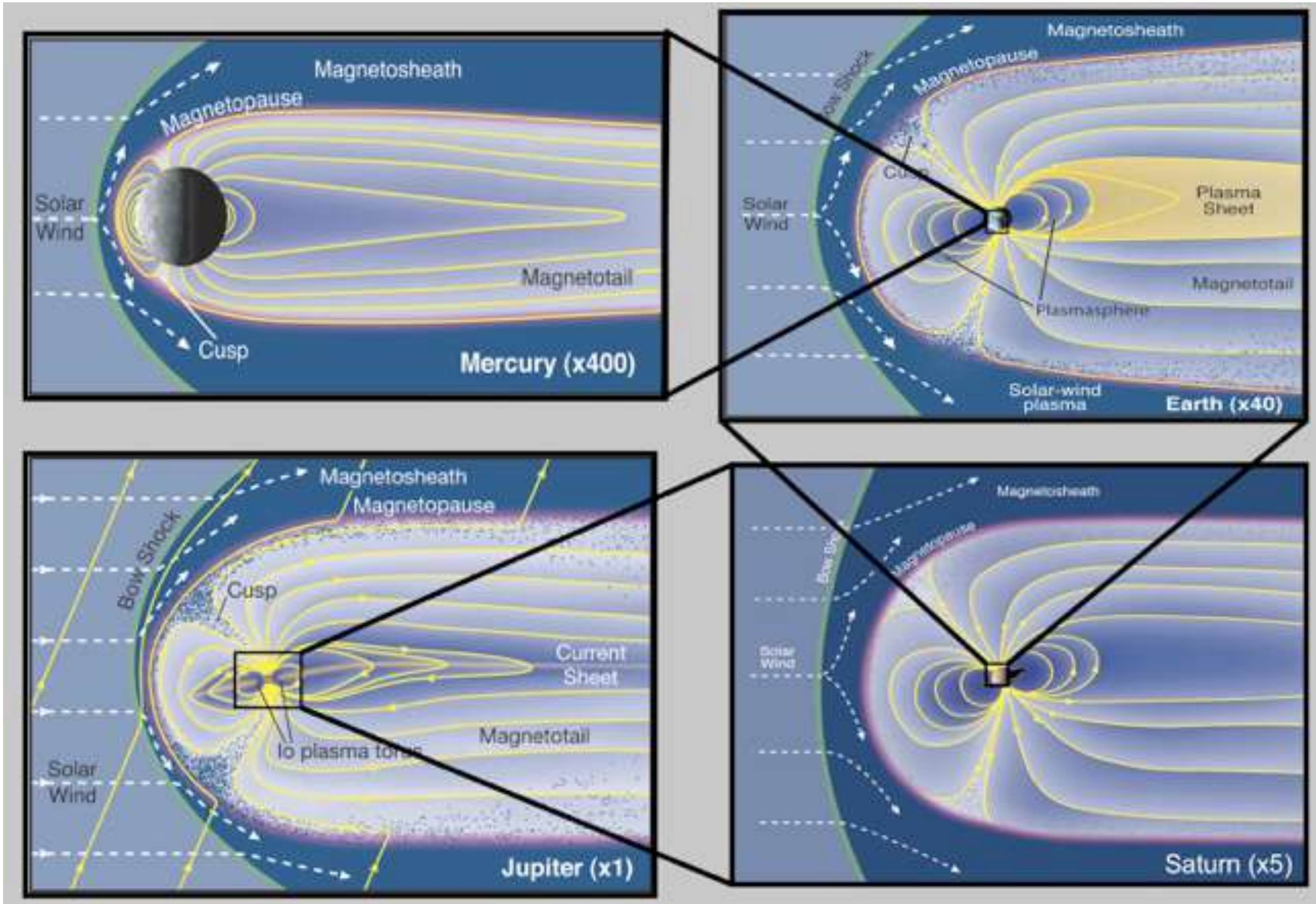
→ need to anticipate the reaction of the magnetosphere (double events)





Jouney to the stars movie

Magnetospheres in solar system



Next Lecture:

Star-Planet Interaction, Habitability & Drake equation