

# SPACE WEATHER INTRODUCTORY COURSE



Collaboration of



**Solar-Terrestrial Centre of Excellence**



**Koninklijke luchtmacht**



**Koninklijk Nederlands  
Meteorologisch Instituut**  
*Ministerie van Infrastructuur en Milieu*

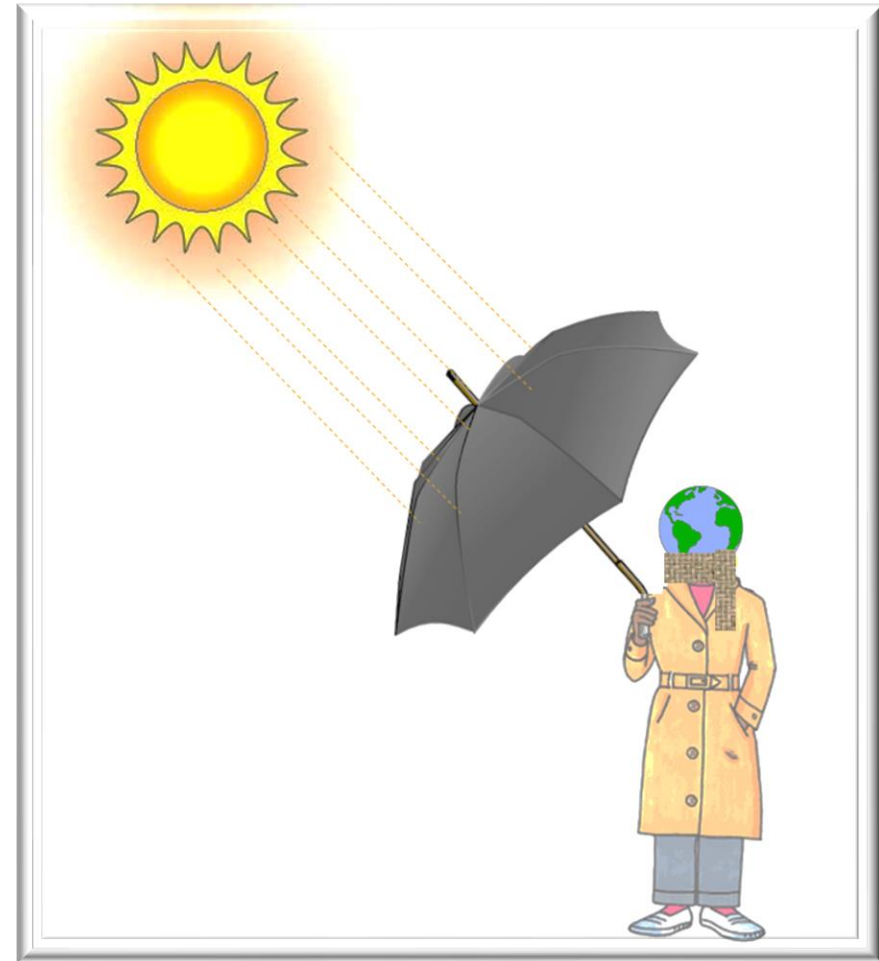


## **Space weather effects**

Jan Janssens

# Space Weather effects (SWx effects)

- ***Introduction***
- *SWx effects from*
  - *Solar flares*
  - *Proton events*
  - *ICMEs*
  - *Coronal holes*



# Space Weather (SWx)

- Space weather refers to the environmental conditions in Earth's magnetosphere, ionosphere and thermosphere due to the Sun and the solar wind that can influence the functioning and reliability of spaceborne and ground-based systems and services or endanger property or human health.
- Space Weather is the physical and phenomenological state of natural space environments. The associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the Sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them, and also at forecasting and nowcasting the potential impacts on biological and technological systems.



*NSWP*

*ESA, COST Action 724*



# Drivers of disturbed space weather

## Solar eruptions

## Solar corona

Magnetic Reconnection

Solar wind

Radiation

Particles

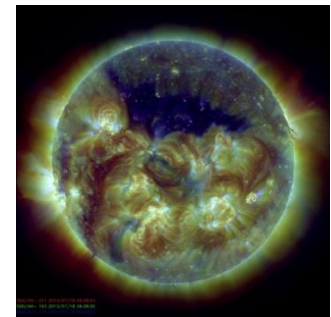
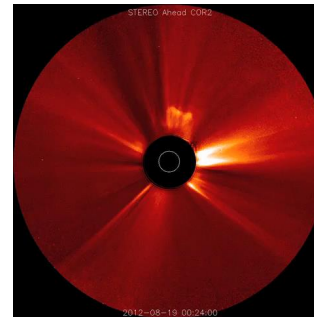
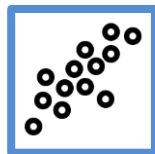
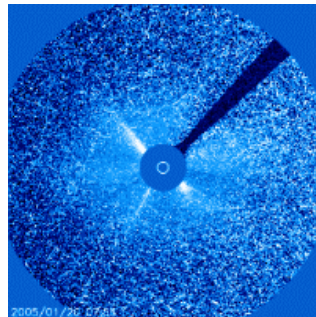
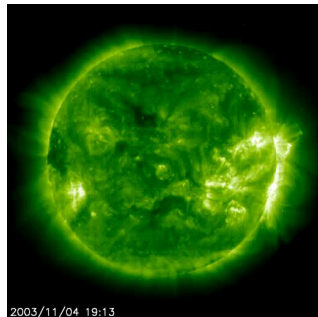
Particles

Solar flares

Proton events

Coronal Mass Ejections

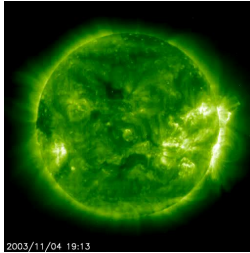
Coronal Hole



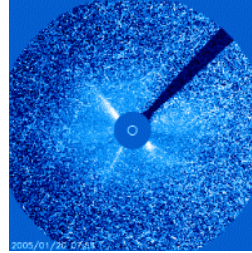
# Disturbed Space weather

## Causes

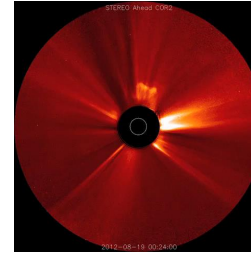
### Solar flares



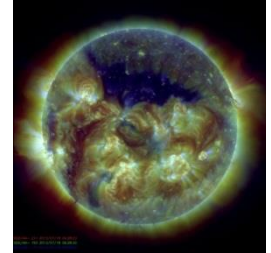
### Proton events



### Coronal Mass Ejections



### Coronal Holes



	Solar flares	Proton events	Coronal Mass Ejections	Coronal Holes
Arrival	Immediately (8')	15 min to a few hours	20 to 72+ hours	2 to 4 days
NOAA scales	R1 (minor) => R5 (extreme)	S1 (minor) => S5 (extreme)	G1 (minor) => G5 (extreme)	
Parameter	M1 => $\geq$ X20	pfu ( $>10\text{MeV}$ ): 10 => $10^5$	Kp = 5 => Kp = 9	
Duration	Minutes to hours	Hours to days	Days	
Protection	Earth's atmosphere	Earth's magnetic field	Earth's magnetic field	

## Effects

Radio communications	Satellites	Satellites	
Radar interference	Astronauts & Airplanes	Aurora	
	Communication/Navigation	Communication/Navigation	
1 pfu = 1 proton / $\text{cm}^2 \text{ s sr}$	Ozone	Electrical Currents (GIC)	

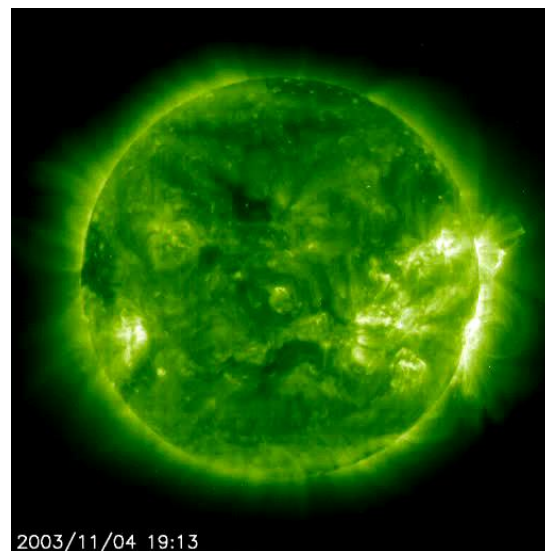




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Solar flares





# Effects from solar flares

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
R 5	Extreme	<b>HF Radio:</b> 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. <b>Navigation:</b> 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 ( $2 \times 10^{-3}$ )	Less than 1 per cycle
R 4	Severe	<b>HF Radio:</b> HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. <b>Navigation:</b> 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	<b>HF Radio:</b> Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. <b>Navigation:</b> Low-frequency navigation signals degraded for about an hour.	X1 ( $10^{-4}$ )	175 per cycle (140 days per cycle)
R 2	Moderate	<b>HF Radio:</b> Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. <b>Navigation:</b> Degradation of low-frequency navigation signals for tens of minutes.	M5 ( $5 \times 10^{-5}$ )	350 per cycle (300 days per cycle)
R 1	Minor	<b>HF Radio:</b> Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. <b>Navigation:</b> Low-frequency navigation signals degraded for brief intervals.	M1 ( $10^{-5}$ )	2000 per cycle (950 days per cycle)







# Effects from solar flares

- From EUV & X-ray radiation
  - Solar flare effect (“magnetic crochet”)
    - => Effects from ICMEs
  - Shortwave fadeout (“Radio Blackout”)
    - => PECASUS
- From radio emission
  - GNSS disturbances
  - Radar disturbances





# Effects from solar flares

- GNSS disturbance

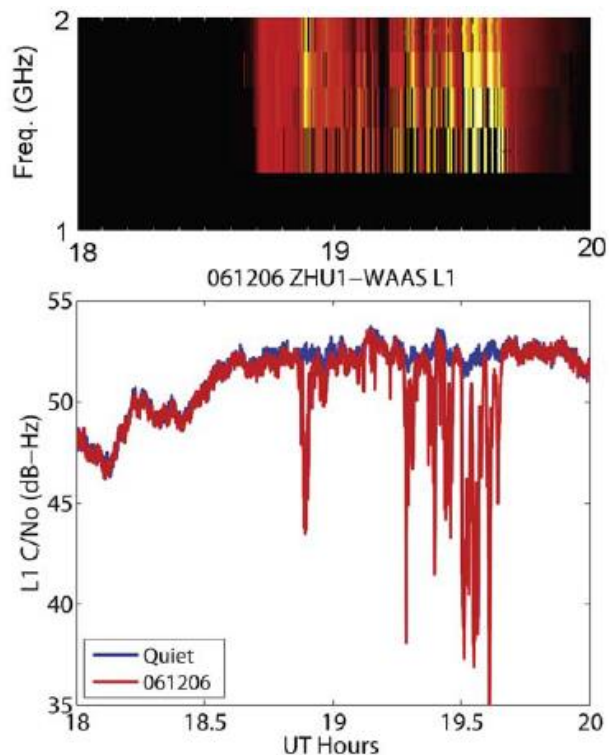


Figure 2. Response of a GPS receiver to the solar radio burst on 6 December 2006. The red line corresponds to  $C/N_0$  on 6 December 2006, and the blue line corresponds to the previous sidereal day.

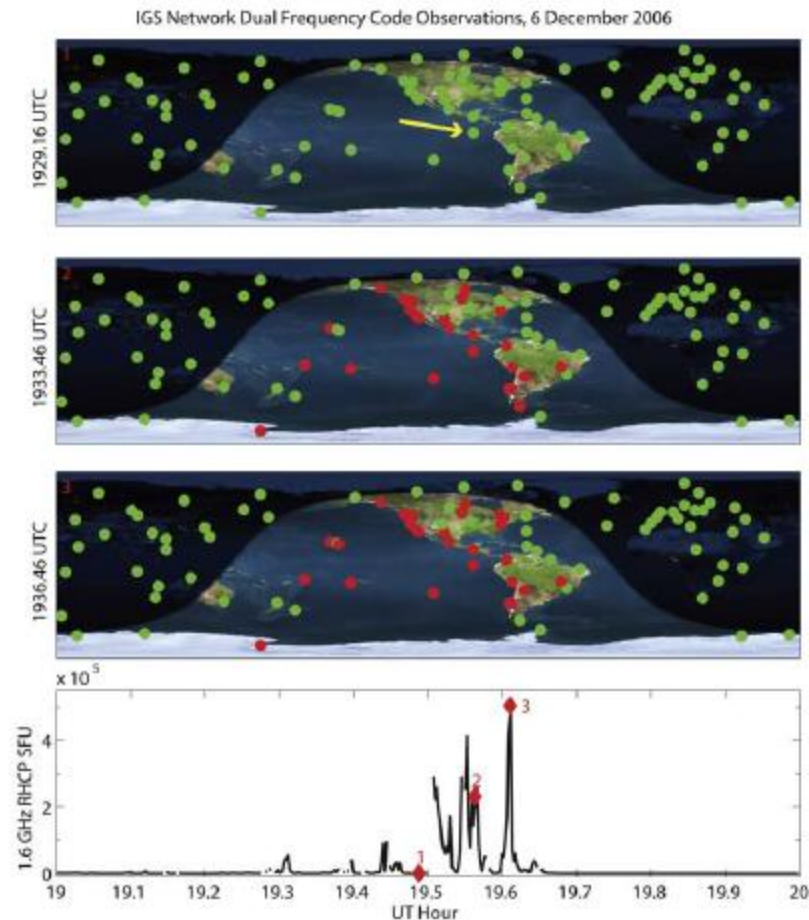
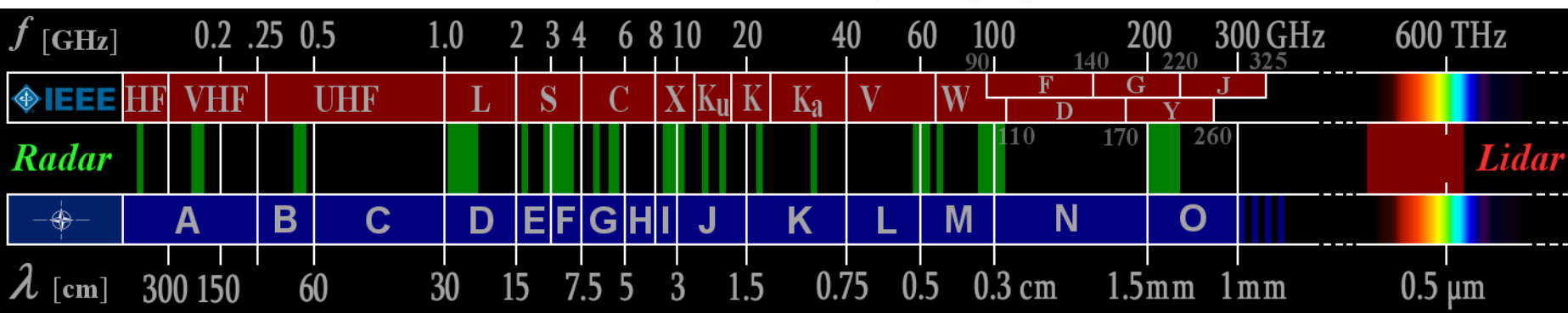
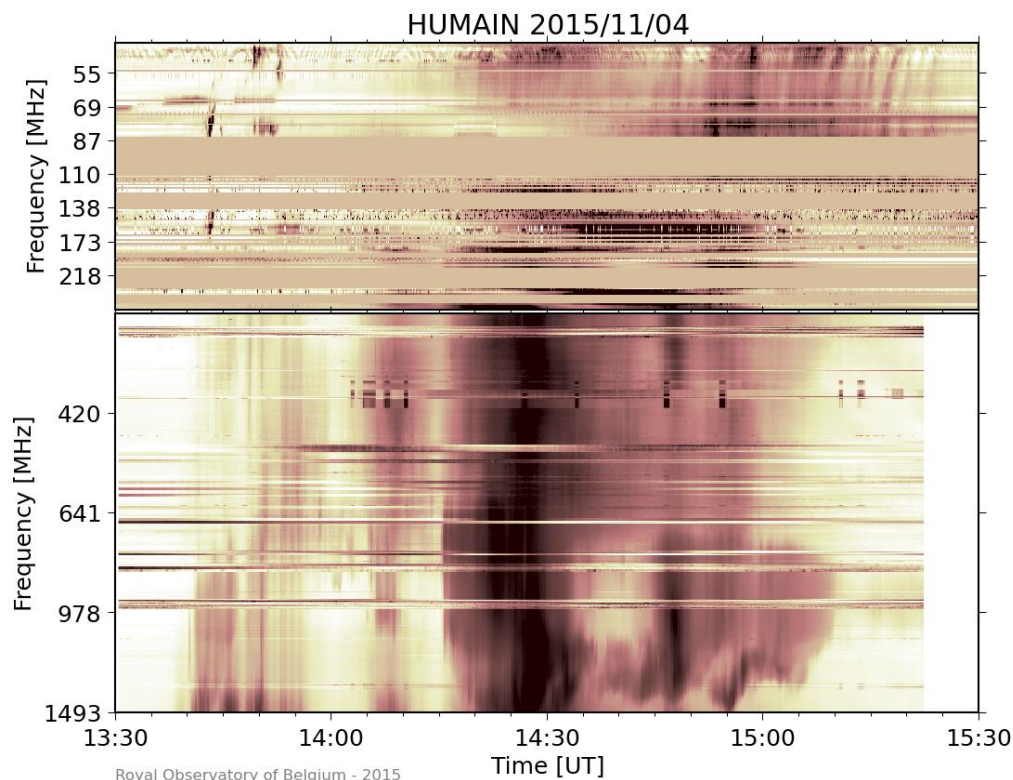


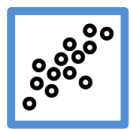
Figure 6. Receivers in the Global GPS Network that were analyzed during the solar radio burst. Green indicates the normal number of satellites being tracked. (fourth panel) During the burst (power at 1.6 GHz), several sunlit receivers tracked fewer than the four satellites needed for a full positioning solution (marked in red). (Image of Earth from the The Living Earth, 1996 and is used here by permission of the publisher. Day/night overlay created using Earth Viewer by J. Walker.)



# Effects from solar flares

- Radar disturbance
  - 4 November 2015
    - M3 flare paralyzes Swedish air traffic
  - 23 May 1967
    - BMEWS disturbed
  - Seems to require a set of special conditions

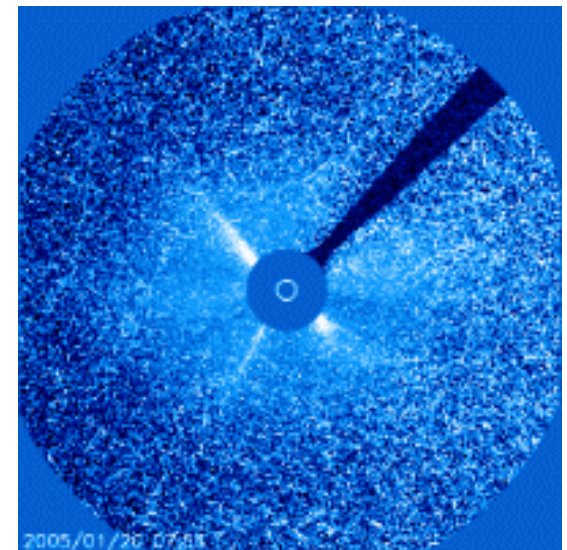


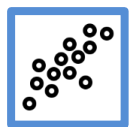


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  - *ICMEs*
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Proton events





# Effects from proton events

Scale	Description	Effect	Physical measure (Flux level of $\geq 10$ MeV particles)	Average Frequency (1 cycle = 11 years)
S 5	Extreme	<p><b>Biological:</b> 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.</p> <p><b>Satellite operations:</b> 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.</p> <p><b>Other systems:</b> Complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.</p>	$10^5$	Fewer than 1 per cycle
S 4	Severe	<p><b>Biological:</b> Unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.</p> <p><b>Satellite operations:</b> May experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded.</p> <p><b>Other systems:</b> Blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.</p>	$10^4$	3 per cycle
S 3	Strong	<p><b>Biological:</b> Radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.</p> <p><b>Satellite operations:</b> Single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely.</p> <p><b>Other systems:</b> Degraded HF radio propagation through the polar regions and navigation position errors likely.</p>	$10^3$	10 per cycle
S 2	Moderate	<p><b>Biological:</b> Passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.</p> <p><b>Satellite operations:</b> Infrequent single-event upsets possible.</p> <p><b>Other systems:</b> Small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.</p>	$10^2$	25 per cycle
S 1	Minor	<p><b>Biological:</b> None.</p> <p><b>Satellite operations:</b> None.</p> <p><b>Other systems:</b> Minor impacts on HF radio in the polar regions.</p>	10	50 per cycle



# Effects from proton events

- Polar Cap Absorption (PCA)
  - => PECASUS
- Radiation
  - Astronauts, Polar flights
    - => PECASUS
- Satellites
  - Star trackers
  - Single Event Effects (SEE)
  - Solar arrays
- Ground Level Enhancement (GLE)

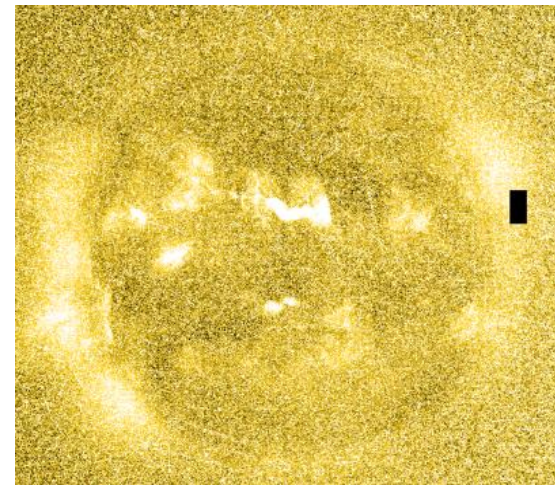
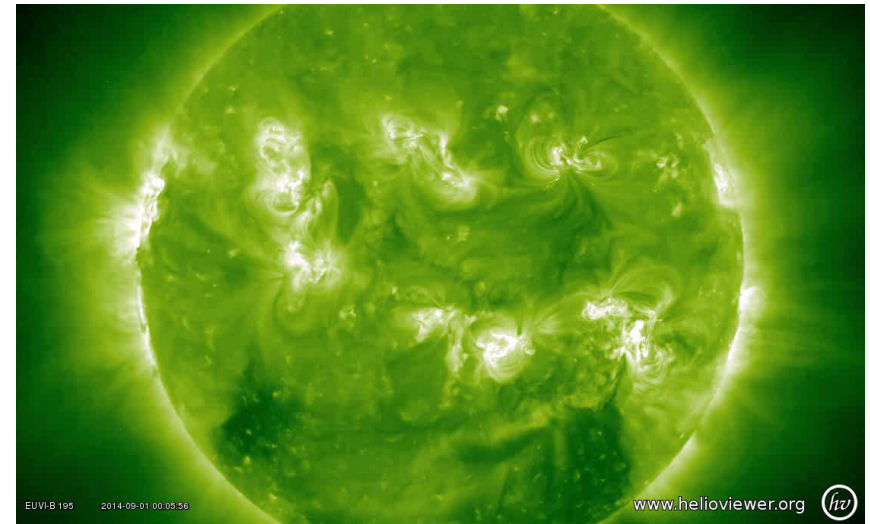






# Effects from proton events

- Satellites
  - Star trackers
    - Spacecraft orientation
    - Photonics noise
      - Proton « impacts »
        - » True stars?
      - Misorientation
        - » Solar panels
          - No energy
          - » Loss sun-lock
      - Data loss
        - » Gravity Probe-B





# Effects from proton events

- Satellites
  - Single Event Effect (SEE)
    - Direct hit of an electronic component by an energetic particle resulting in an anomaly
  - Several variations
    - SEU (bit flip), SEL, SEB,...
  - Sources
    - Galactic Cosmic Rays (GCR)
      - » [DSCOVER](#)
    - Solar proton storms
    - Radiation belts

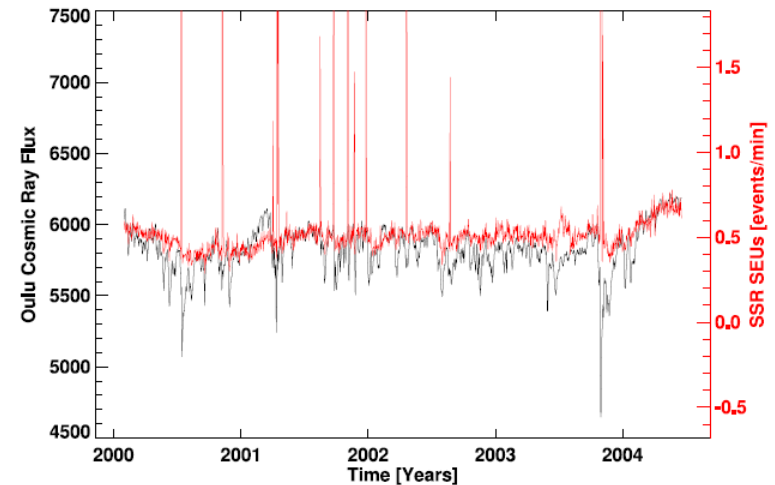
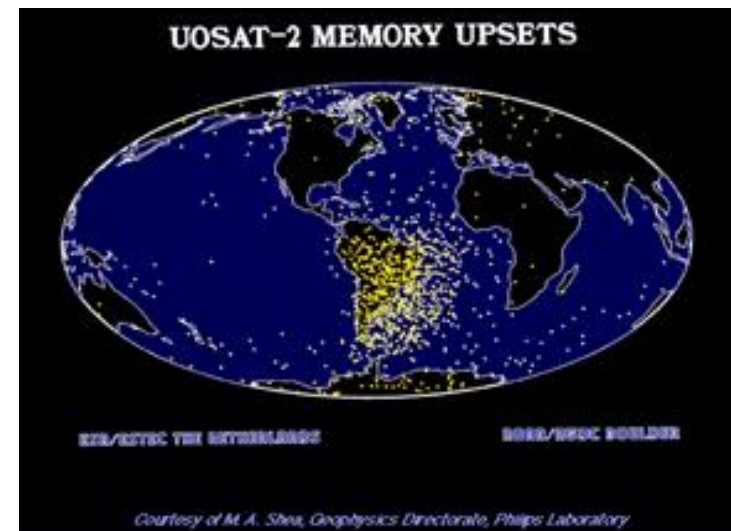
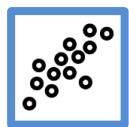


Figure 3: Subset of the data in Fig. 1 during solar maximum. The plot shows a dozen sharp spikes on top of the solar-cycle-modulated background of SSR SEUs triggered by cosmic ray hits. These spikes are caused by isolated strong SEP events. Most of them coincide with a CRF down spike.



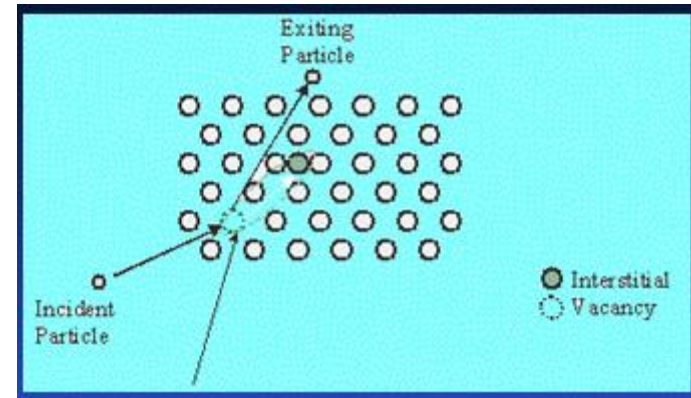
SEU: Single Event Upset  
SEL: Single Event Latchup  
SEB: Single Event Burnout  
DSCOVER: Deep Space Climate Observatory



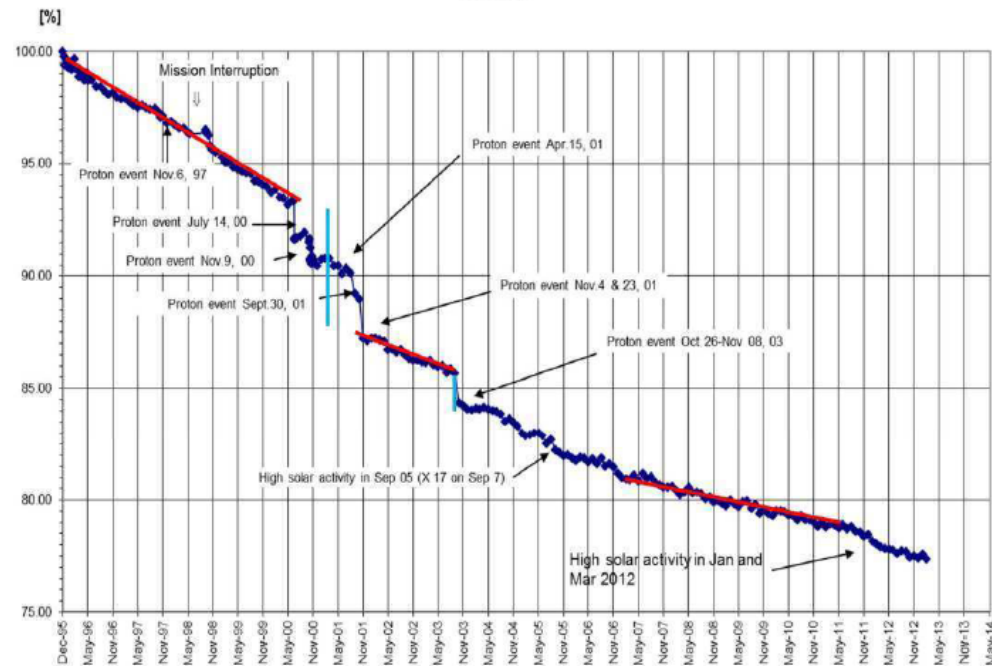


# Effects from proton events

- Satellites
  - Solar Arrays
    - Displacement damage
    - Reduces efficiency in electricity production
    - Several % loss from one proton event is possible
      - 2% loss during Bastille Day event (14 July 00)
      - 5% loss during extreme 4 August 1972 event
  - Overall aging process of satellite and its instruments



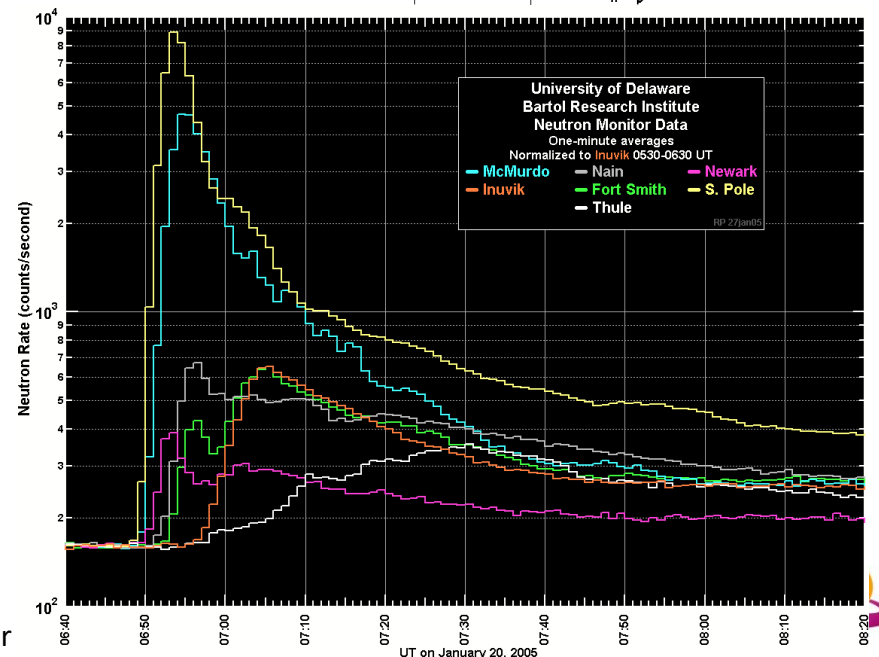
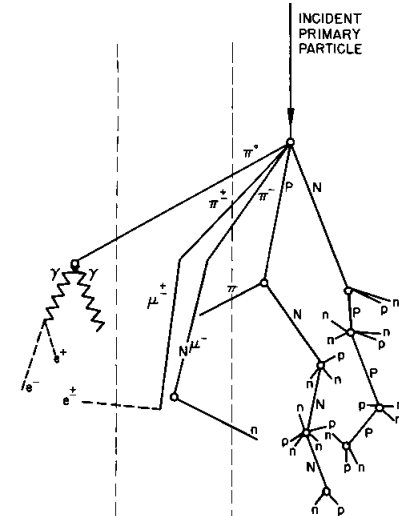
SOHO Solar Array Degradation, based on the average of the two section currents (PISW1 and PISW2)





# Effects from proton events

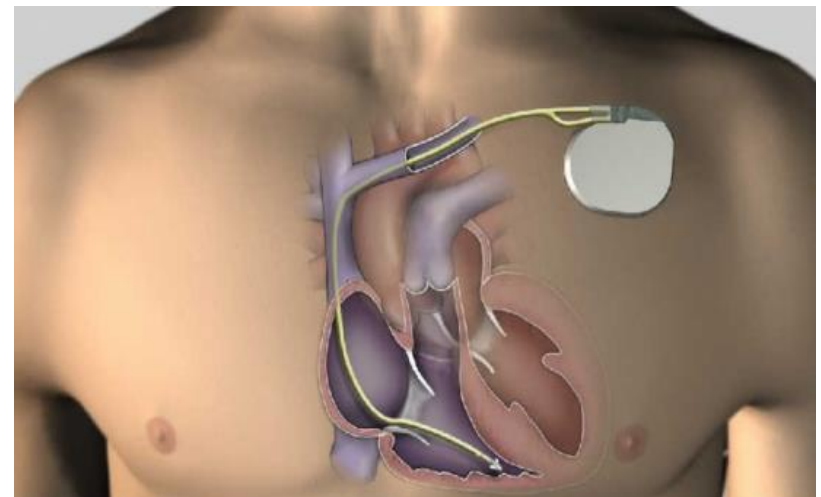
- Ground Level Enhancement (GLE)
  - Sharp increase of #neutrons @ ground
  - Main source
    - Strong SEPs ~500 MeV/nucleon
      - X-class flares
      - Western hem.
      - Fast halo CMEs
      - => RARE!!
        - » Only 74 GLEs since the 1940s
        - » GLE#73/74: 28 Oct 2021 and 11 May 2024 (both weak events)
  - Thresholds GLE
    - SWPC: 10% above B/Gr GCR
      - » Practice: 3% above B/Gr
    - At least 2 independent stations
  - Realtime monitoring
    - <https://www.nmdb.eu/>
    - List: <https://gle oulu.fi/#/>





# Effects from proton events

- Ground Level Enhancements
  - Various systems
    - Computer glitches, servers,...
      - Errors increase with altitude
    - Pacemakers, defibrillators, and other medical devices,...
      - SEUs (very low rates)
  - Solar cycle (SC) effect noted
    - More errors during SC min than SC max



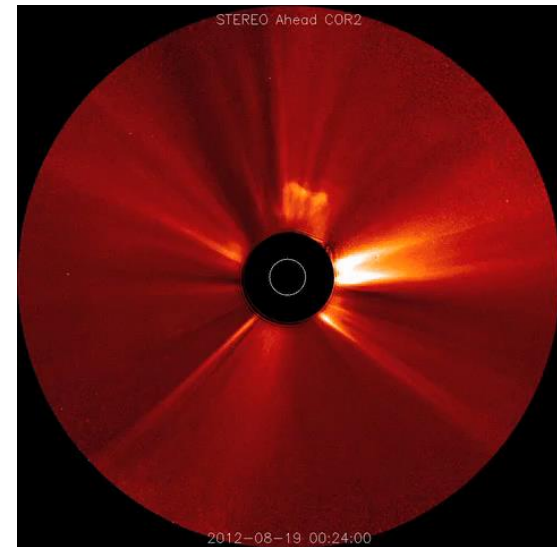




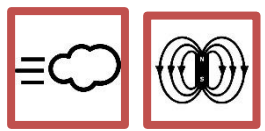
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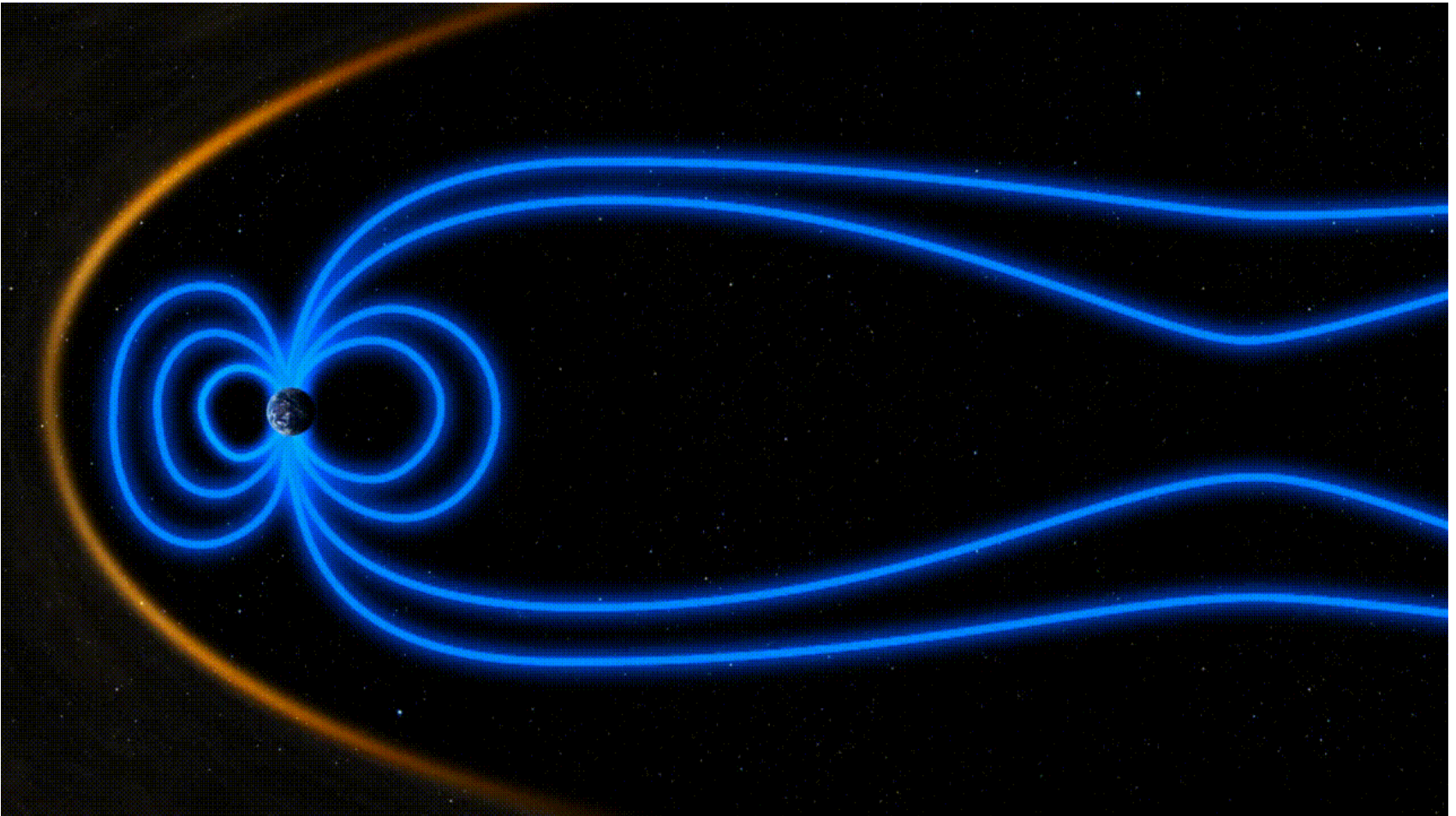
## Coronal Mass Ejections







# Effects from ICMEs

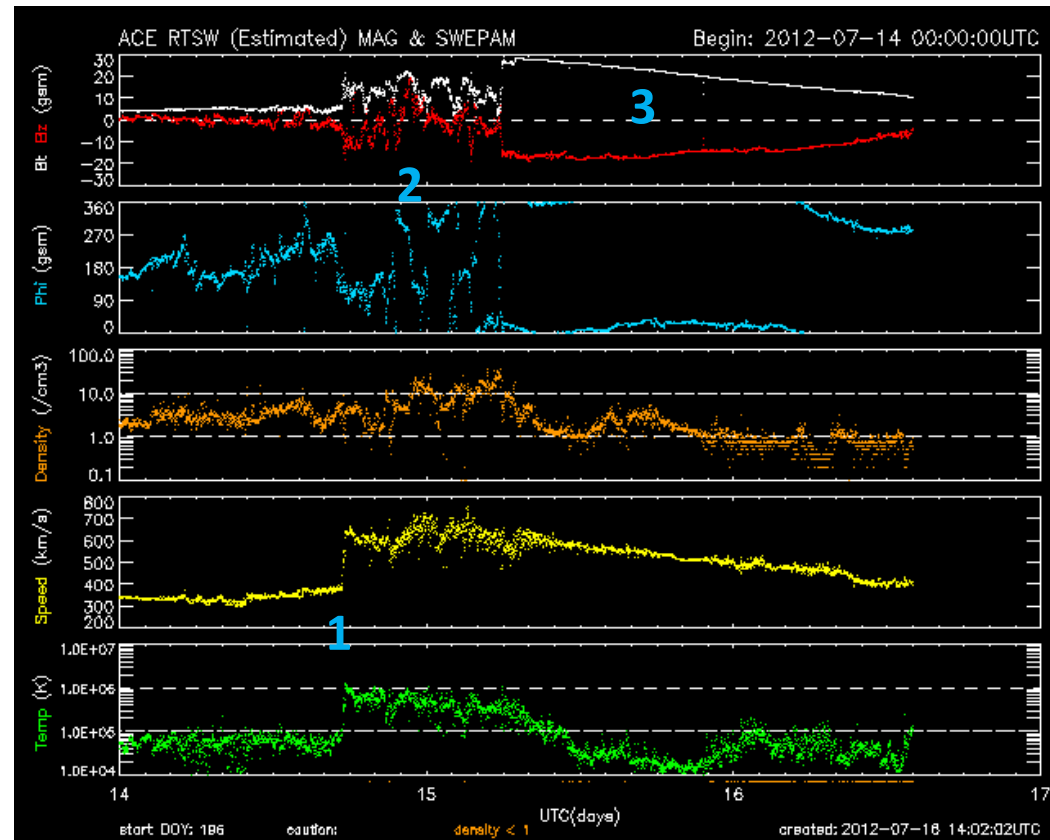
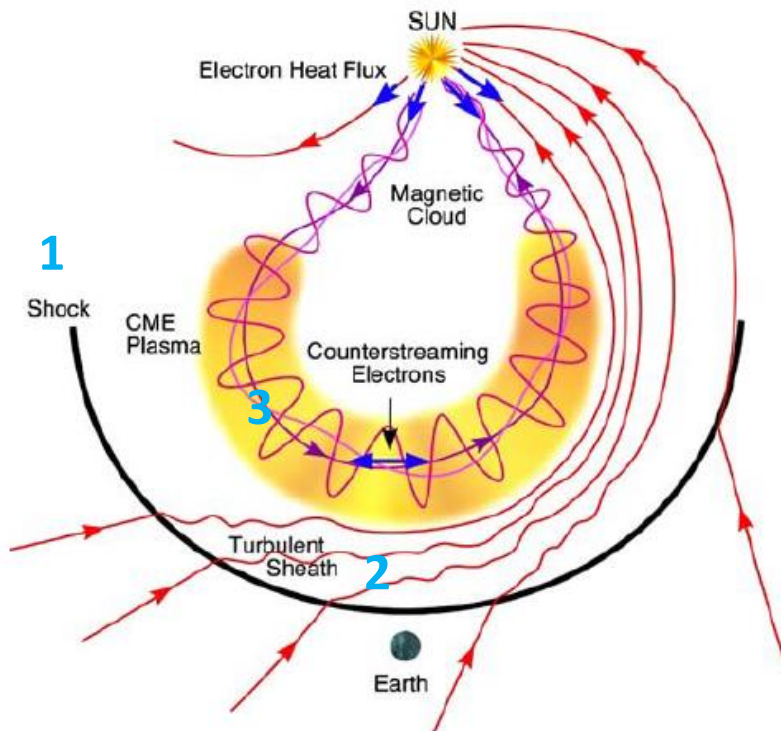


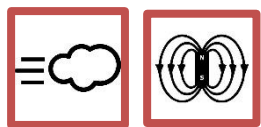
*Credits: ESA*



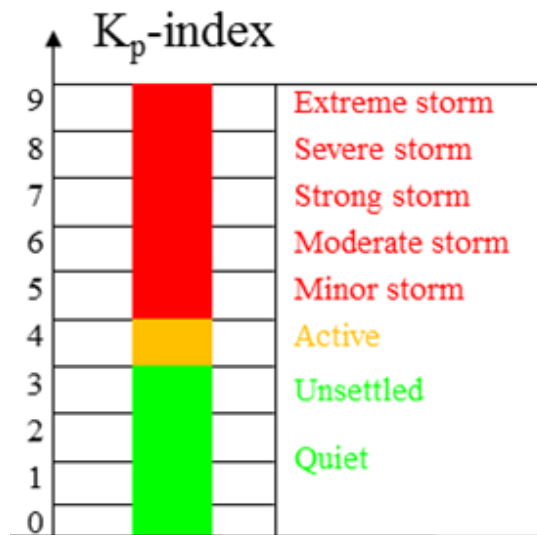
# Effects from ICMEs

- Solar wind features

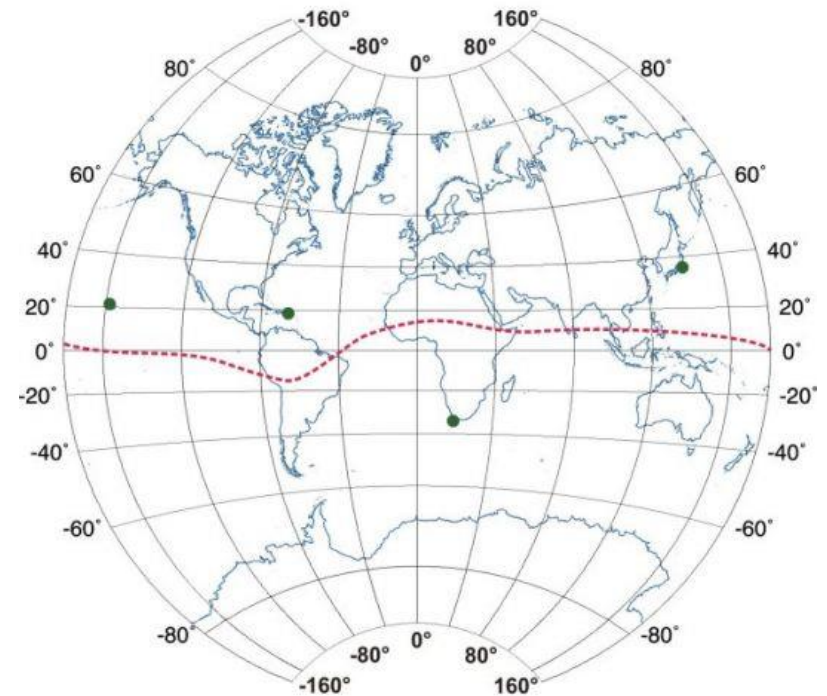




# Geomagnetic indices



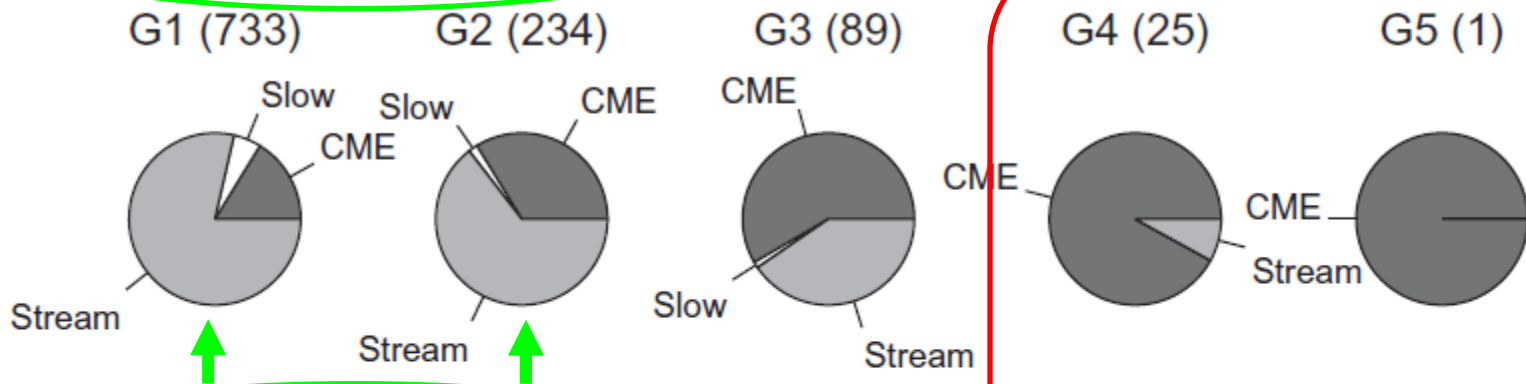
K	a
0	0
1	3
2	7
3	15
4	27
5	48
6	80
7	140
8	240
9	400



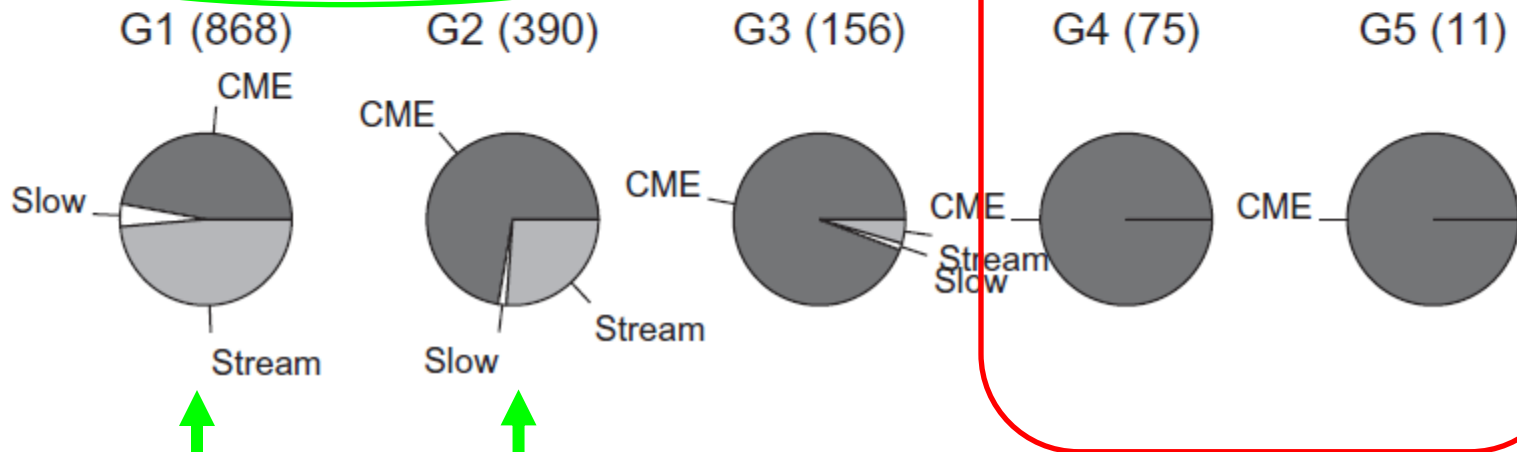


# Effects from ICMEs

## Solar Minimum Storms



## Solar Maximum Storms



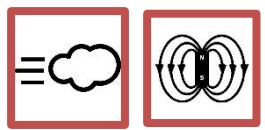


# Effects from ICMs

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	<p><b>Power systems:</b> Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage.</p> <p><b>Spacecraft operations:</b> May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites.</p> <p><b>Other systems:</b> 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.).</p>	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	<p><b>Power systems:</b> Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid.</p> <p><b>Spacecraft operations:</b> May experience surface charging and tracking problems, corrections may be needed for orientation problems.</p> <p><b>Other systems:</b> 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.).</p>	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	<p><b>Power systems:</b> Voltage corrections may be required, false alarms triggered on some protection devices.</p> <p><b>Spacecraft operations:</b> Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems.</p> <p><b>Other systems:</b> 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.).</p>	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	<p><b>Power systems:</b> High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage.</p> <p><b>Spacecraft operations:</b> Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions.</p> <p><b>Other systems:</b> HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).</p>	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	<p><b>Power systems:</b> Weak power grid fluctuations can occur.</p> <p><b>Spacecraft operations:</b> Minor impact on satellite operations possible.</p> <p><b>Other systems:</b> Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).</p>	Kp = 5	1700 per cycle (900 days per cycle)





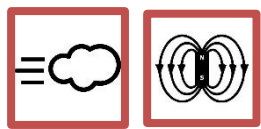


# Effects from ICMs

- From magnetic field
  - Satellites
    - Magnetopause crossings
  - High-Precision industry
  - GCR: Forbush decrease
- From particles
  - Satellites
    - Drag
    - Charging effects
    - Satellite-based Comms/Nav applications (GNSS)
      - => PECASUS
  - HF Communication (aviation)
    - => PECASUS
  - Geomagnetically Induced Currents (GIC)
  - Aurora

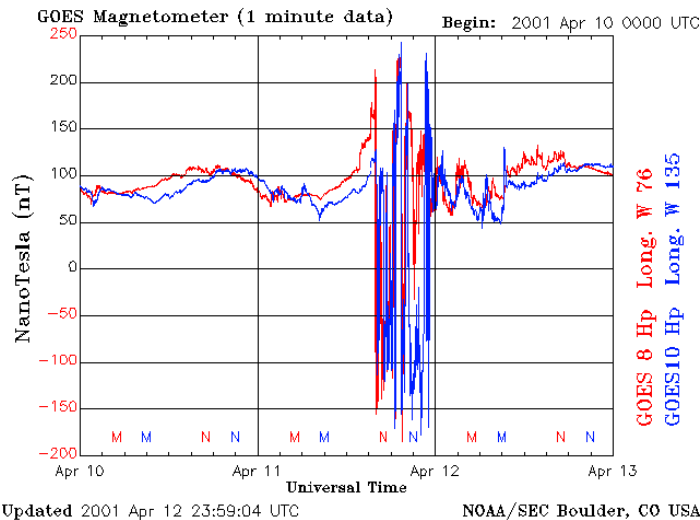




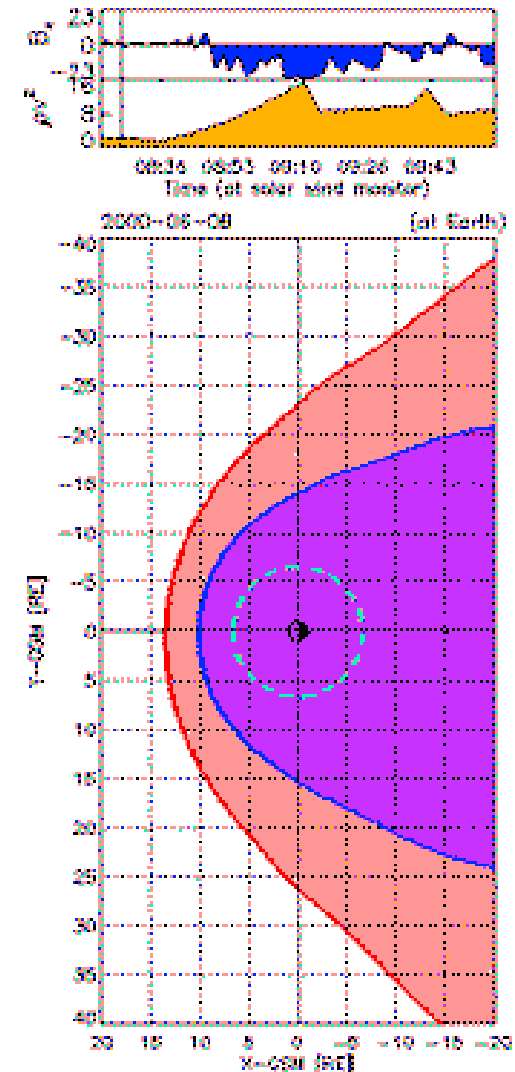


# Effects from ICMs

- Satellites
  - Magnetopause crossings
    - CME pushes magnetopause inside GEO
    - Satellites directly exposed to solar wind
  - Orientation problem



GEO: geostationary (equatorial) orbit





# Effects from ICMs

- Satellites

- Atmospheric drag

- Low Earth Orbit (LEO)

- Sources

- Shortterm: ICME

- » NOAA:  $K_p \geq 6$

- Longterm: Solar EUV radiation (solar cycle)

- » NOAA:  $F_{10.7} \geq 250$  sfu

- Slows down satellite

- Burns up in atmosphere

- Examples

- March 1989

- » 1000 satellites off-track

- Premature mission end

- » Solar Max, Skylab, Starlink

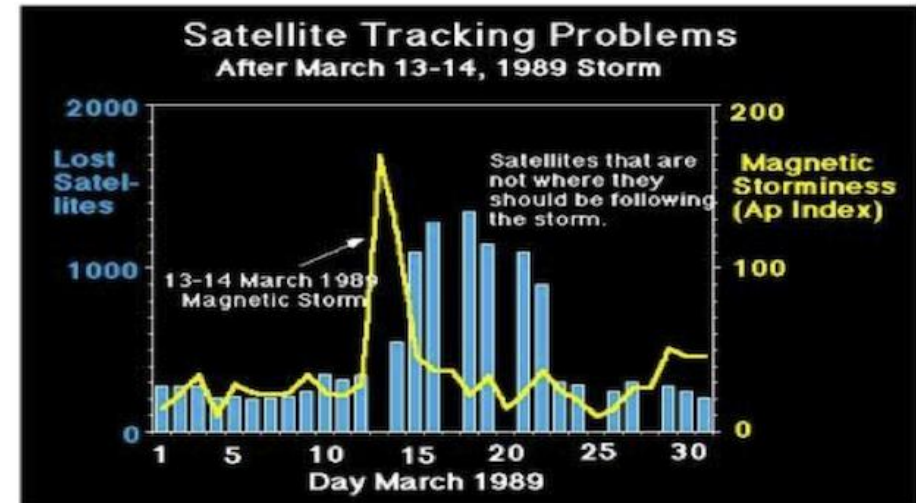
- 10-11 May 2024: ISS lost 0.5 km

- Space debris

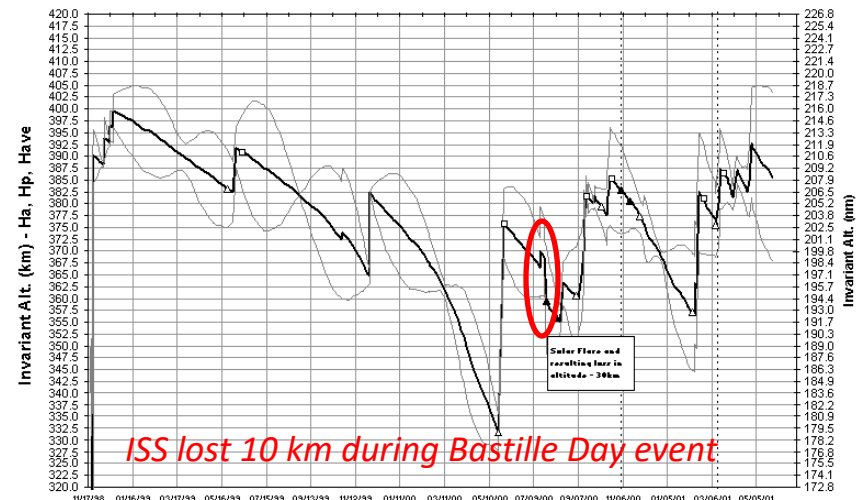
- Cleaned up by high solar activity

- » SpaceX Dragon crew capsule trunk

- Early re-entry (27 April 2023)



International Space Station As Flown Altitude Profile  
(Based on MCC-MUJSP Tracked SV Data)





# Effects from ICMEs

- Satellites

- **Surface charging**

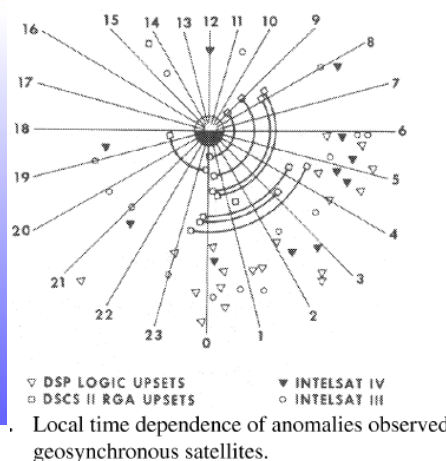
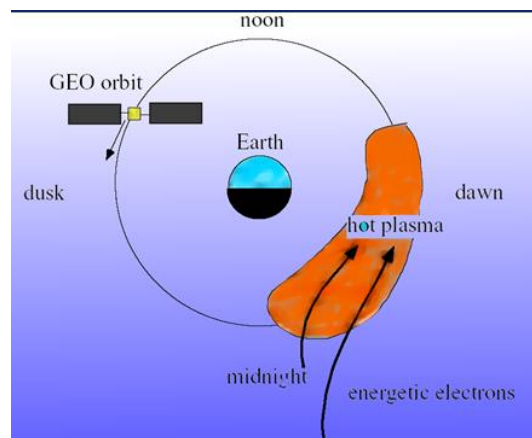
- Low energy plasma
      - 0-100 keV electrons
    - Midnight to dawn region
      - Substorm related
      - SWPC: likely if  $K \geq 6$
    - Differential charging
      - Shadow effect (GEO/HEO)
      - Wake effect (LEO)
    - Electrostatic discharge (ESD)
      - Surface damage
      - Phantom commands



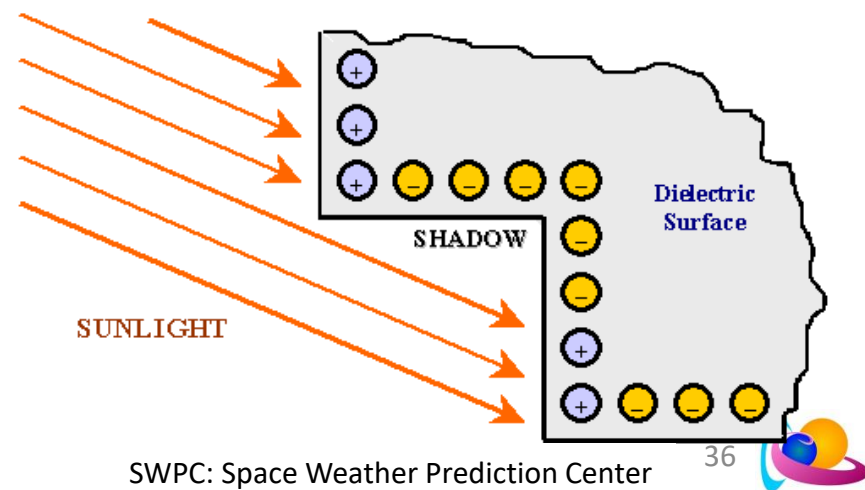
- **Internal charging**

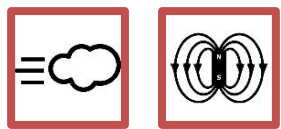
- 100s keV electrons
      - More uniform distribution
      - Galaxy 15 outage in April 2010

- **Accumulation effect**



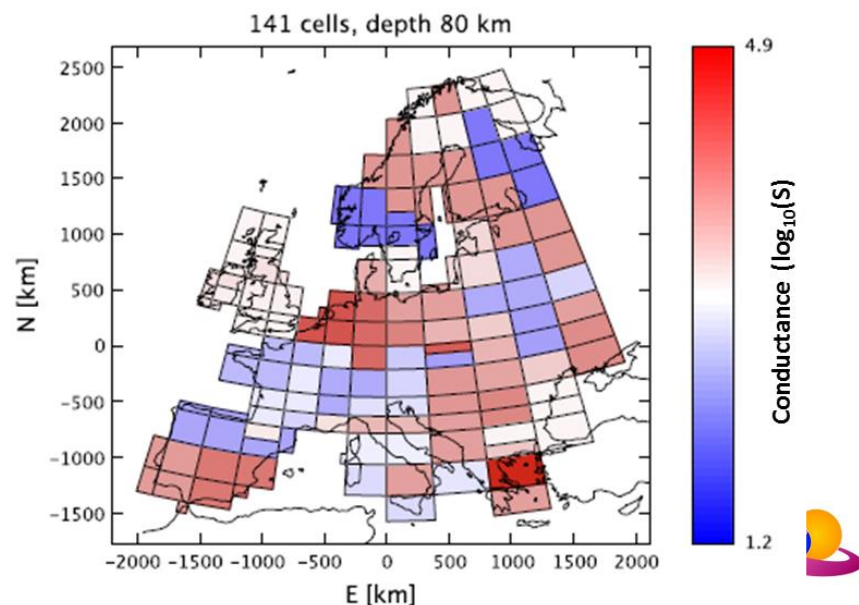
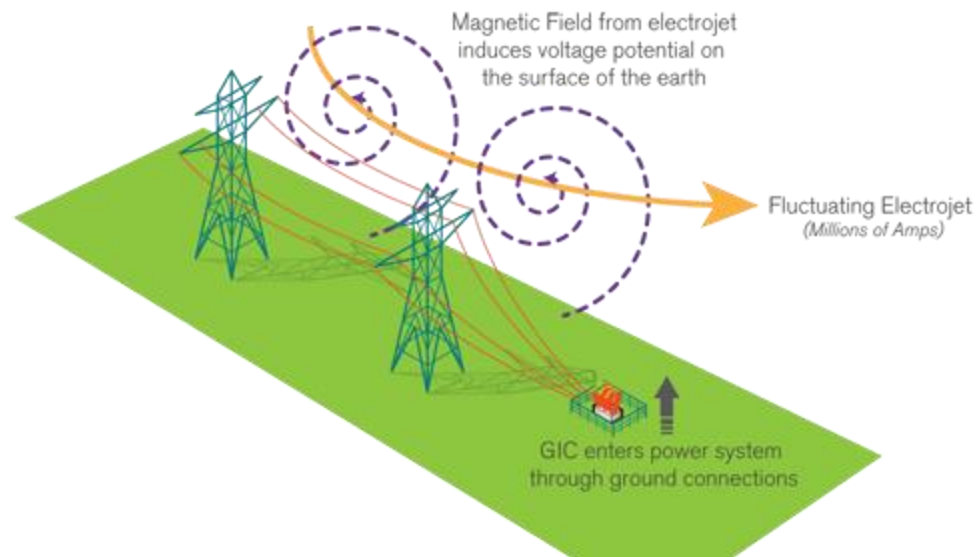
Low Earth orbit (LEO) ; Medium Earth orbit (MEO)  
Geosynchronous orbit (GEO) ; High Earth orbit (HEO)

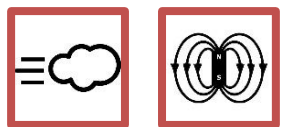




# Effects from ICMEs

- Geomagnetically Induced Currents (GIC)
  - Electrons from magnetotail => ionospheric currents => Magnetic field => currents in crust surface
  - Affects all long conductors
    - Enters via ground connections
  - GIC depends on
    - Strength ICME
    - Geomagnetic latitude
      - Eq. Latitudes too!
    - Local conductance
    - Network details



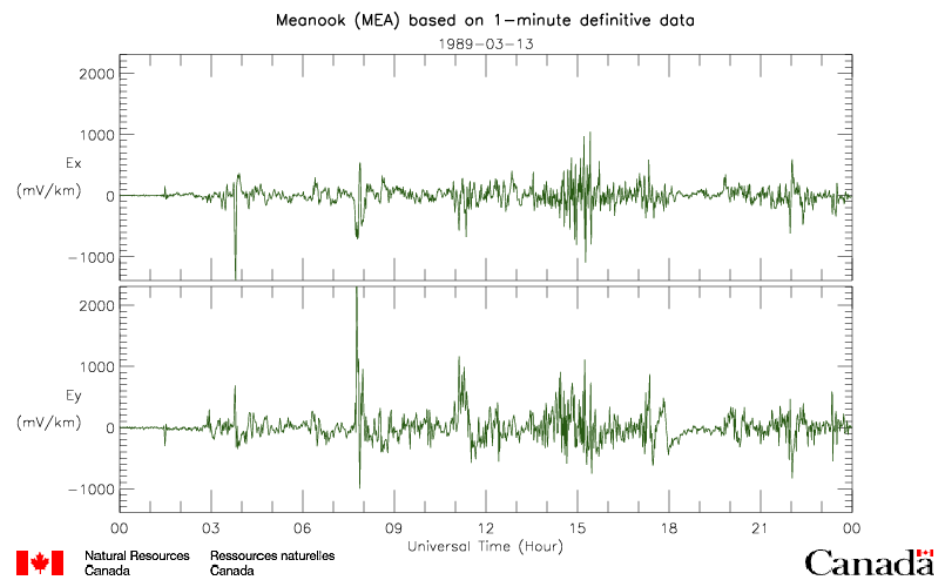


# Effects from ICMEs

- GICs

- Power grids

- Distortions voltage pattern
    - Transformer damage
      - South-Africa, Oct 2003
    - Grid collapse
      - Québec, March 1989
      - Malmö, Sweden, 2003
  - 10-11 May 2024
    - No major impacts on grids
  - Longterm effects of power loss!



**Table 3** Parameters for the GIC emergency alert model. The criterion for each alert level is shown in the second column, and the following columns show the expected extreme  $dB/dt$  values for RC-, AE-, and SC-type GICs

Alert level	Criterion	$dB/dt$ of GICs		
		RC (nT/h)	AE (nT/min)	SC (nT/s)
Caution	$Dst < -300$ nT	100-150	2000	40-110
Warning	$Dst < -600$ nT	150-400	4000	40-110
Emergency	$Dst < -900$ nT	400-1250	6000	40-110
Transient alert	High SEP flux			40-110





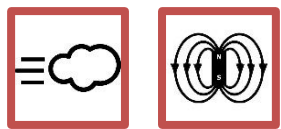


# Effects from ICMs

- GICs
  - Railways
    - New York (USA), 14-15 May 1921
    - Sweden, 13-14 July 1982
    - China, 17 March & 23 June 2015
  - Pipelines
    - Corrosion => Oil leaks
  - Telephone/Telegraph
    - Carrington event (1859),...
    - Transcontinental cables
      - 4 August 1972
  - Transatlantic cables
    - Copper to optical fibre
      - But « optical repeaters »!
      - March 1989 event
  - High-precision industry
    - Wellbore drilling
      - Manitoba, Canada, 27 February 2023

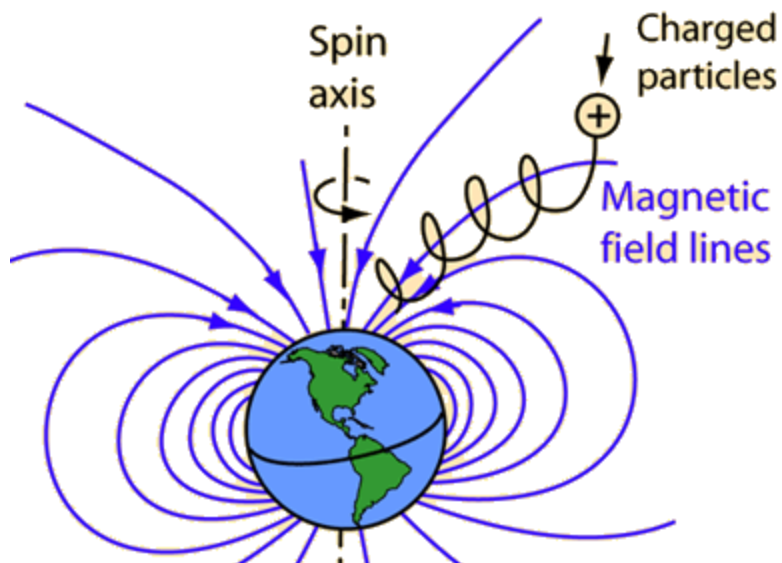


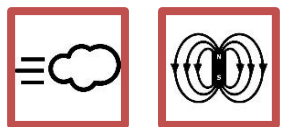




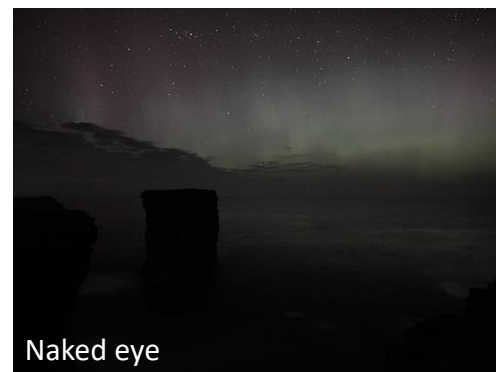
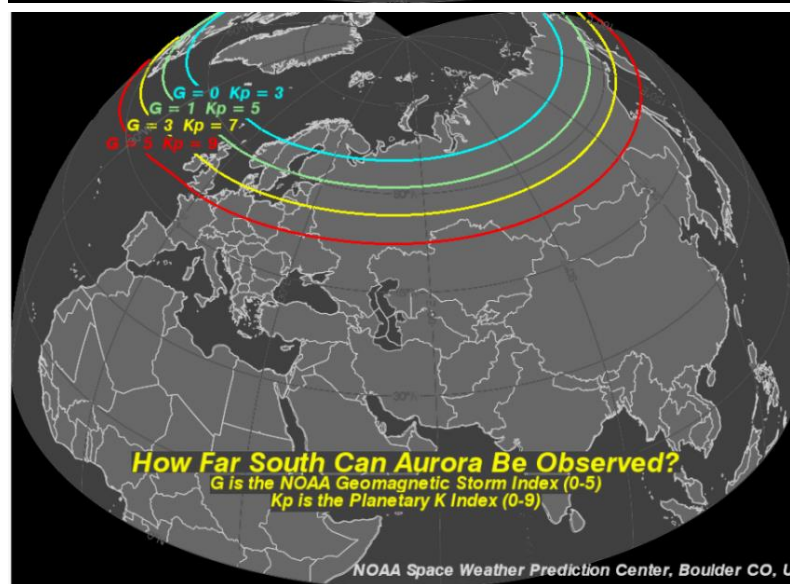
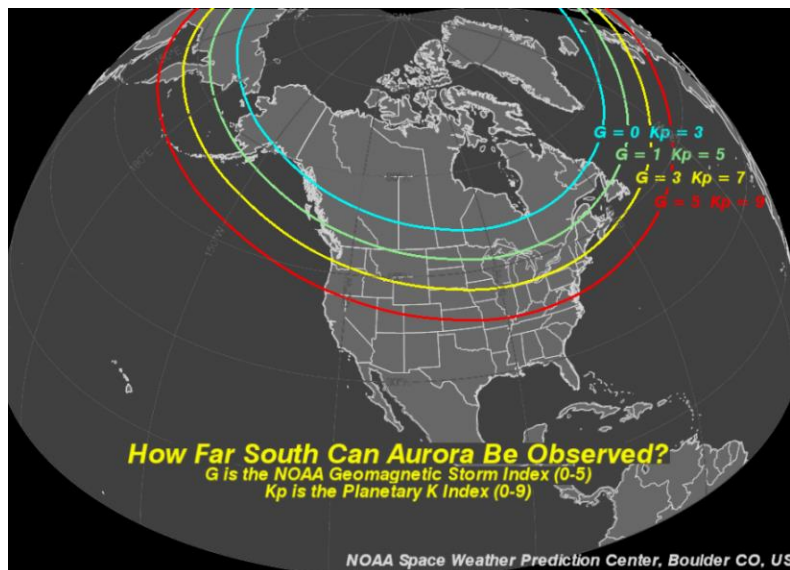
# Effects from ICMs

- Aurora

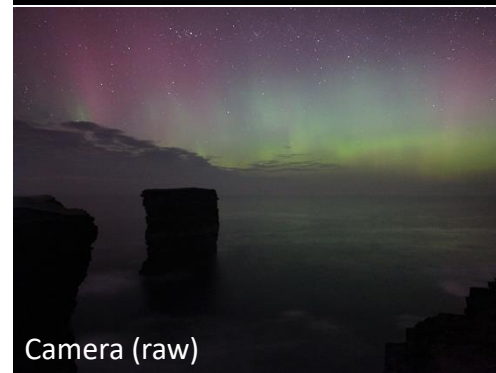




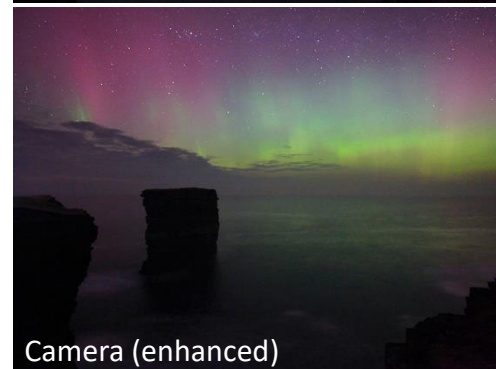
# Effects from ICMs



Naked eye



Camera (raw)



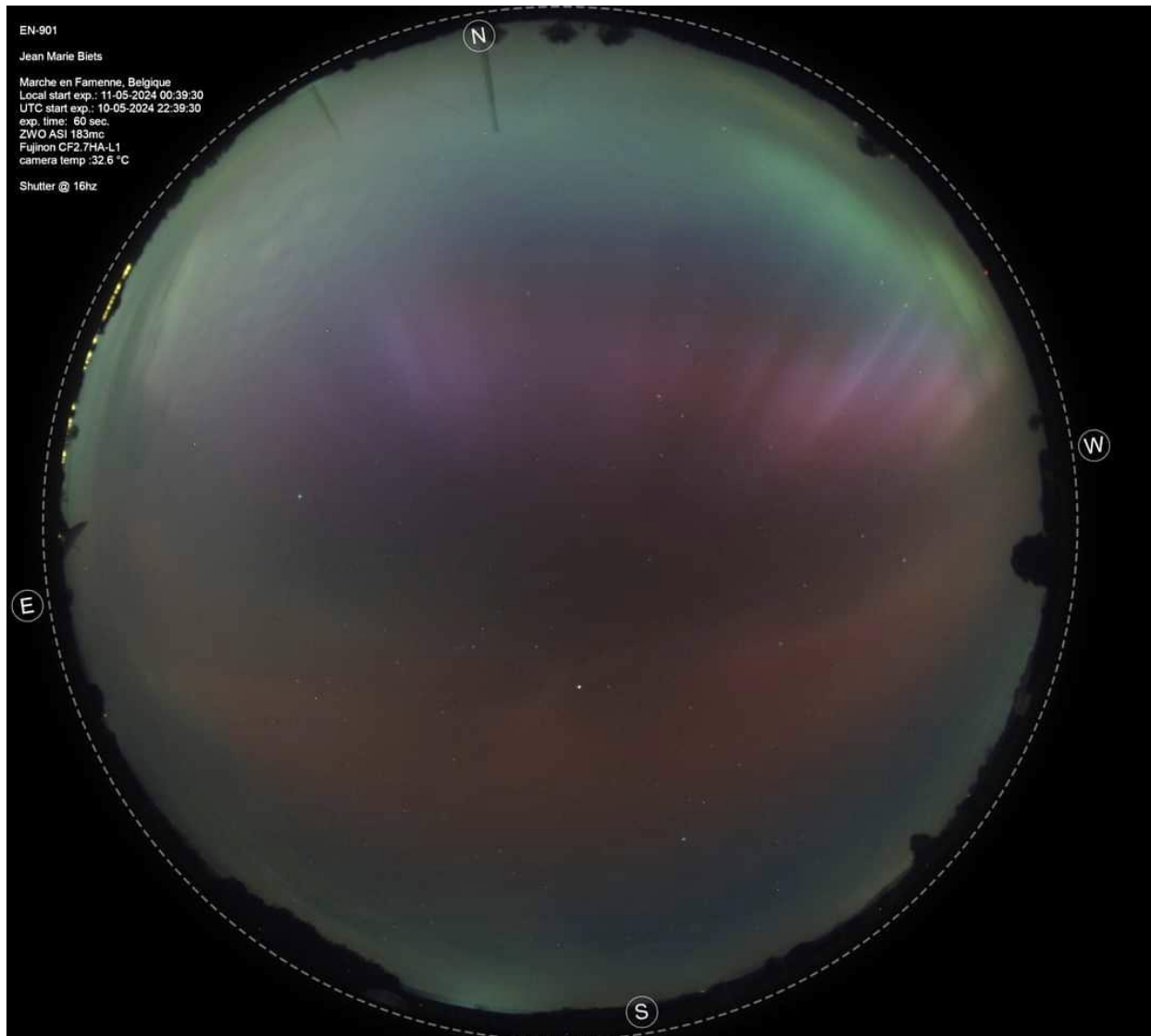
Camera (enhanced)



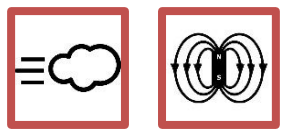


# Effects from ICMEs

## *Aurora on 10-11 May 2024*

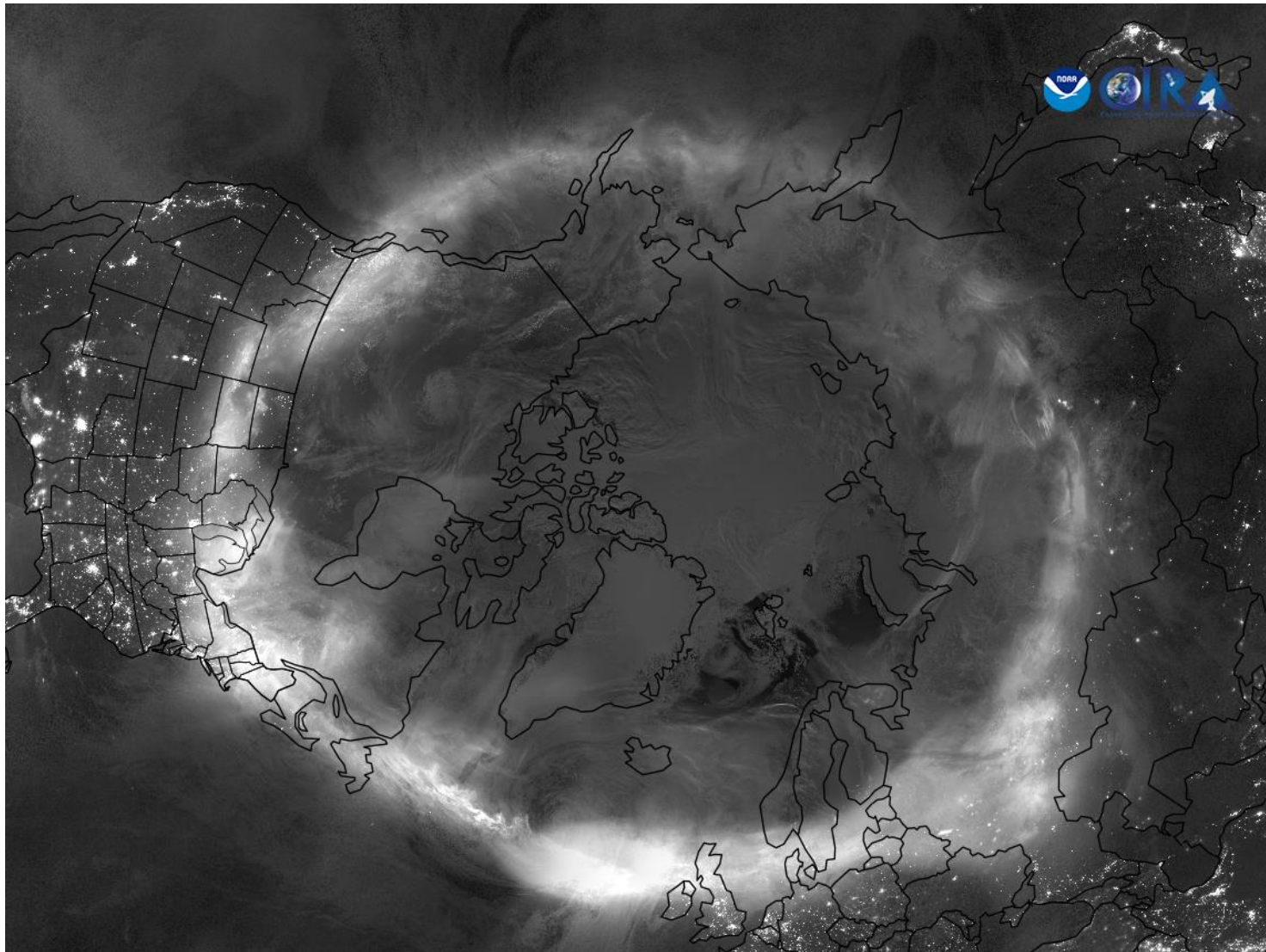






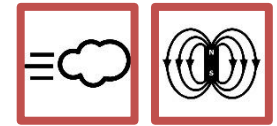
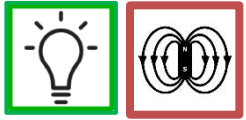
# Effects from ICMs

## *Aurora on 10-11 May 2024*



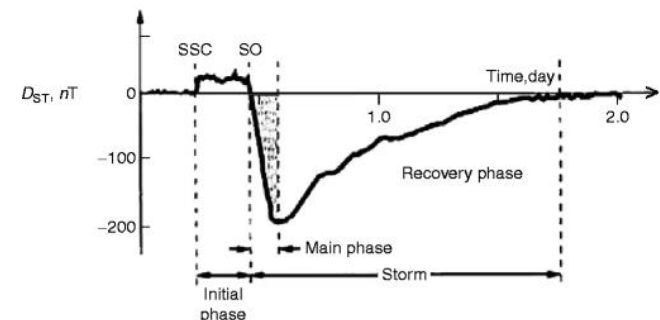
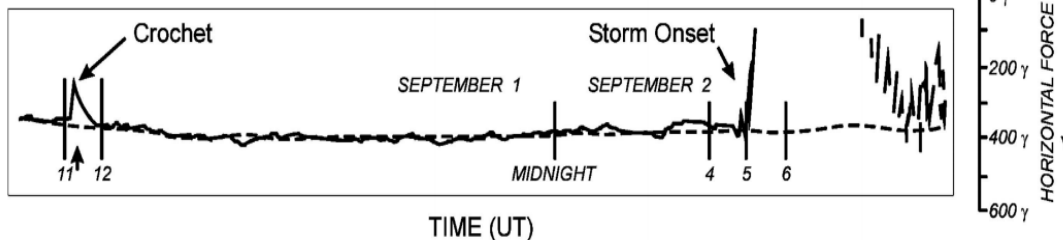
# Effects from ICMEs

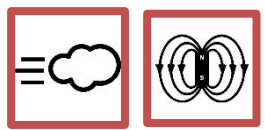
## *Rapid geomagnetic variations*



- Solar flare effect (SFE)
  - Aka “magnetic crochet”
  - Source
    - Strong solar flare
      - H- $\alpha$ : 2B (30%)
      - X-ray: X1 (50%)
    - f(local time & latitude)
  - Examples
    - 4 Nov 2003: + 115nT
    - 1 Sep 1859: + 110nT

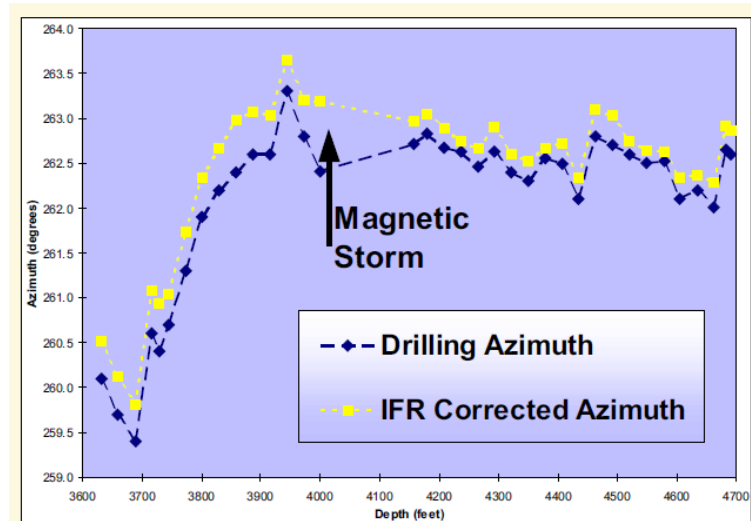
- Storm Sudden Commencement (SSC)
  - Sudden impulse (SI)
    - = no geomagnetic storm
  - Source
    - Dayside compression by strong ICME
    - Global, but f(local sit.)
  - Max. Amplitude: +/- 300 nT
    - 10-11 May 2024: 108 nT





# Effects from ICMs

- High-precision industry
  - Industries depending on amplitude of magnetic field
    - magnetic anomaly surveys
    - directional wellbore drilling
  - Performance degradation
    - Mitigation possible
  - 4 August 1972
    - Vietnam: sea mine detonation
  - 10-11 May 2024
    - ONC – Ocean Networks Canada
      - Deep-sea compasses activated

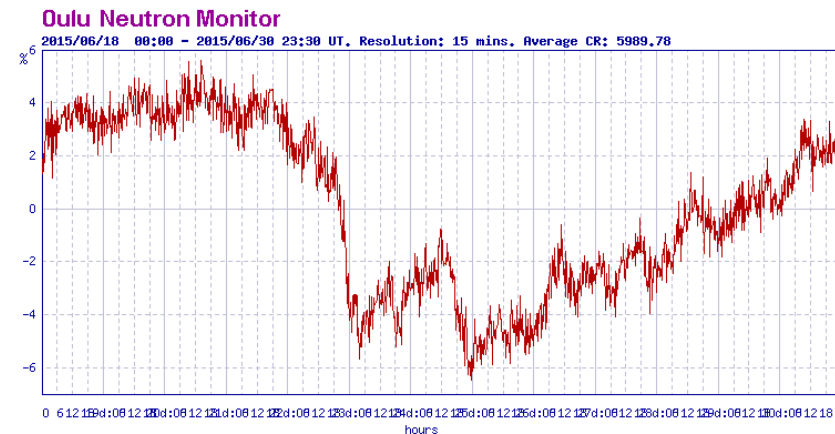
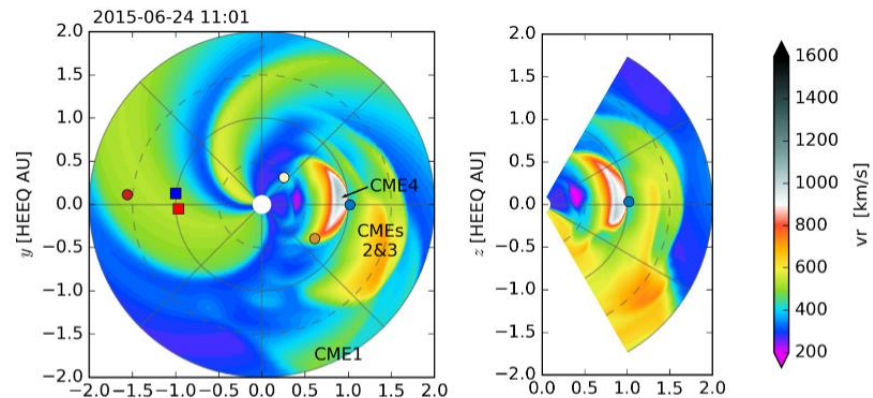






# Effects from ICMEs

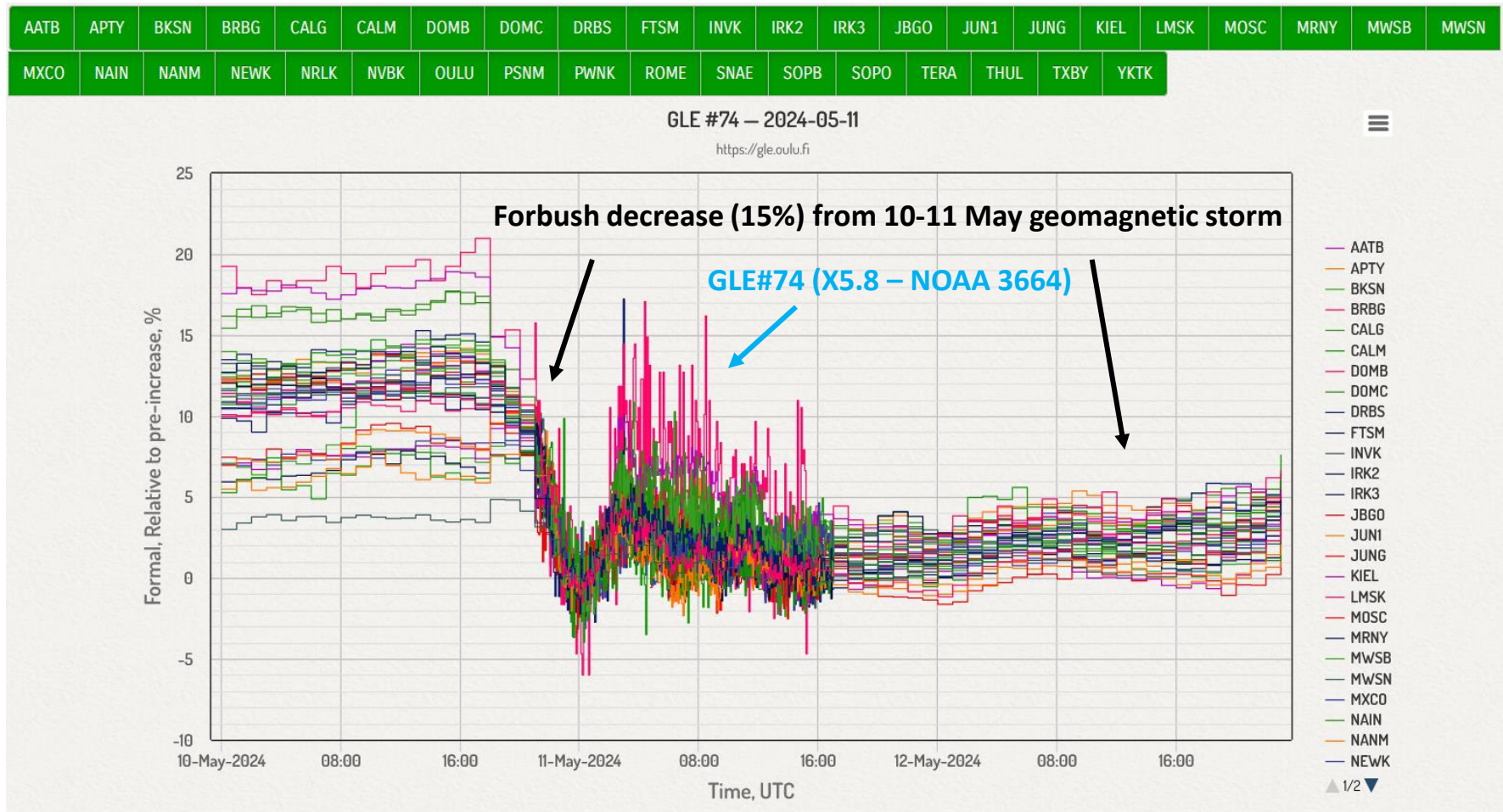
- Cosmic rays
  - Forbush decrease
    - Decrease in neutron count over background levels
      - Due to the passage of strong ICME / multiple ICMEs
  - Threshold:  $> 3\%$
  - Amplitude:
    - Typical: 3-20%
    - Depends on
      - » Size and # CMEs
      - » B of CME
      - » Proximity CME to Earth
      - » cut-off rigidity (GCR)
  - Gradual recovery
    - 3-10 days





# Effects from ICMs

## *Forbush decrease and GLE on 10-11 May 2024*

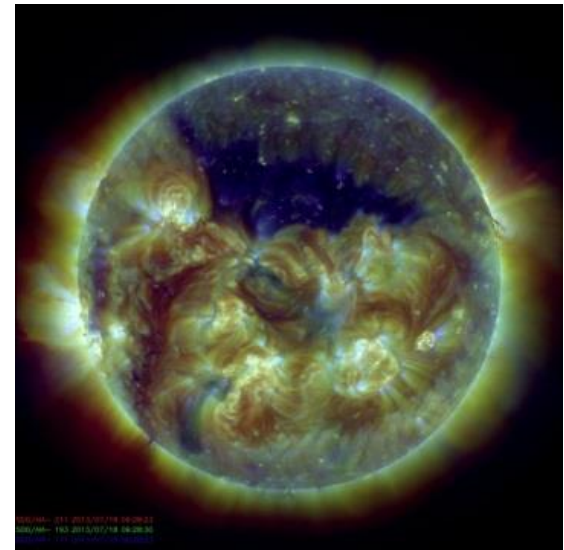




# Space Weather effects (SWx effects)

- *Introduction*
- ***SWx effects from***
  - *Solar flares*
  - *Proton events*
  - *ICMEs*
  - ***Coronal holes***

## Coronal Holes





# Effects from CHs

## Co-rotating interaction regions (CIR)

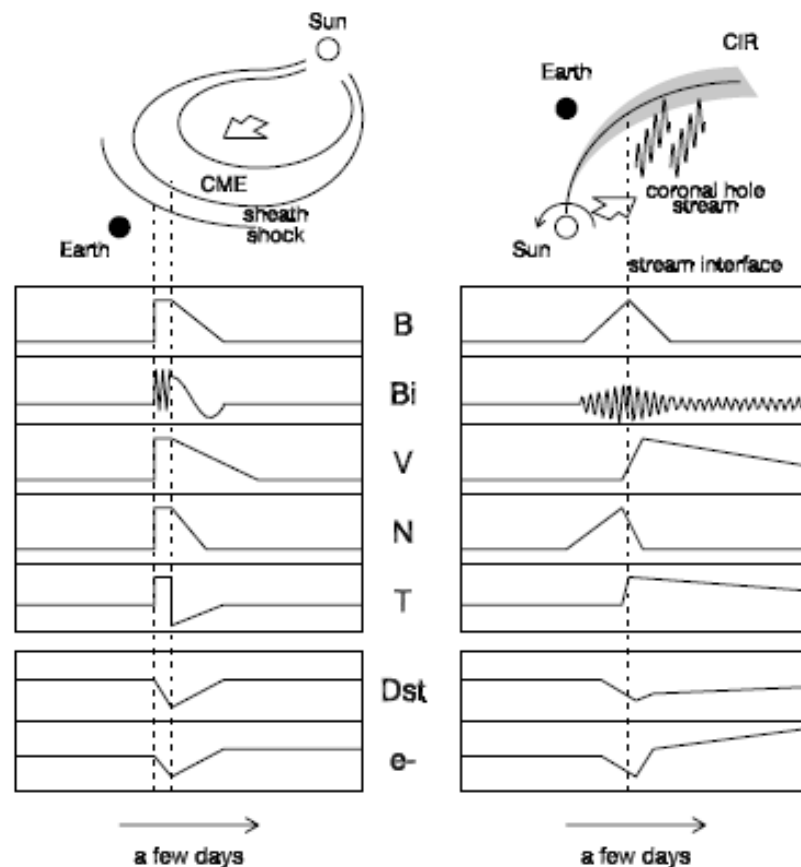
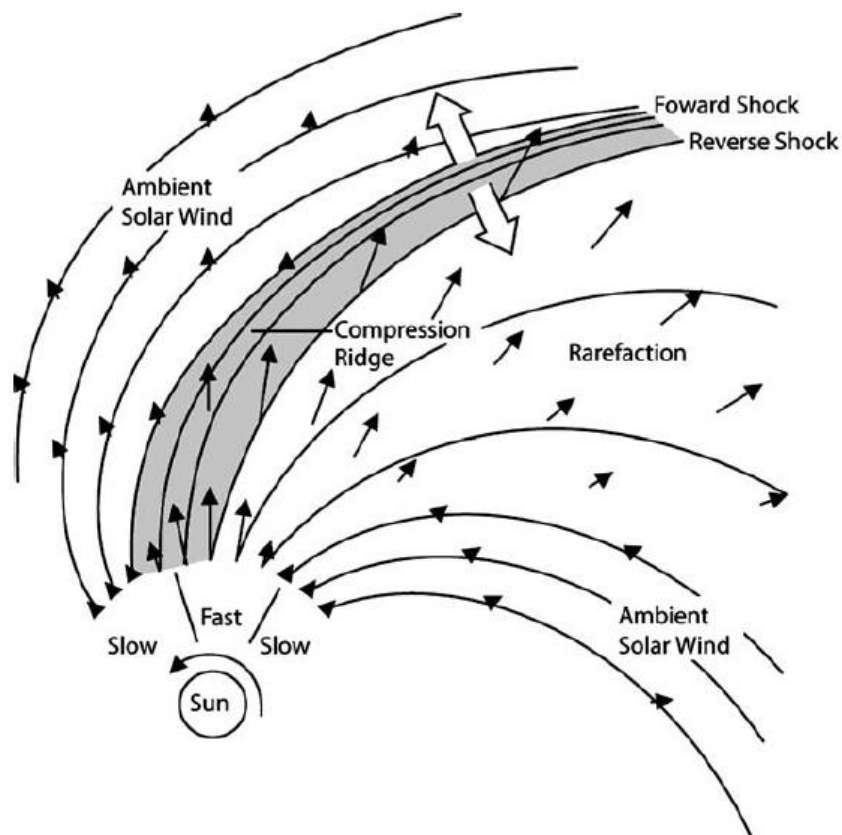


Figure 1. Schematic illustration of typical solar wind structures of coronal mass ejections (CMEs) and corotating interaction regions (CIRs): (top to bottom) magnetic field strength  $B$ , one of the Cartesian component  $B_i$ , solar wind speed  $V$ , density  $N$ , temperature  $T$ , expected response of the  $Dst$  index, and  $>2.0$  MeV electron flux at geosynchronous orbit.

Figure 1. Schematic illustrating 2-D corotating stream structure in the solar equatorial plane in the inner heliosphere (after Pizzo, 1978).



# Effects from CHs

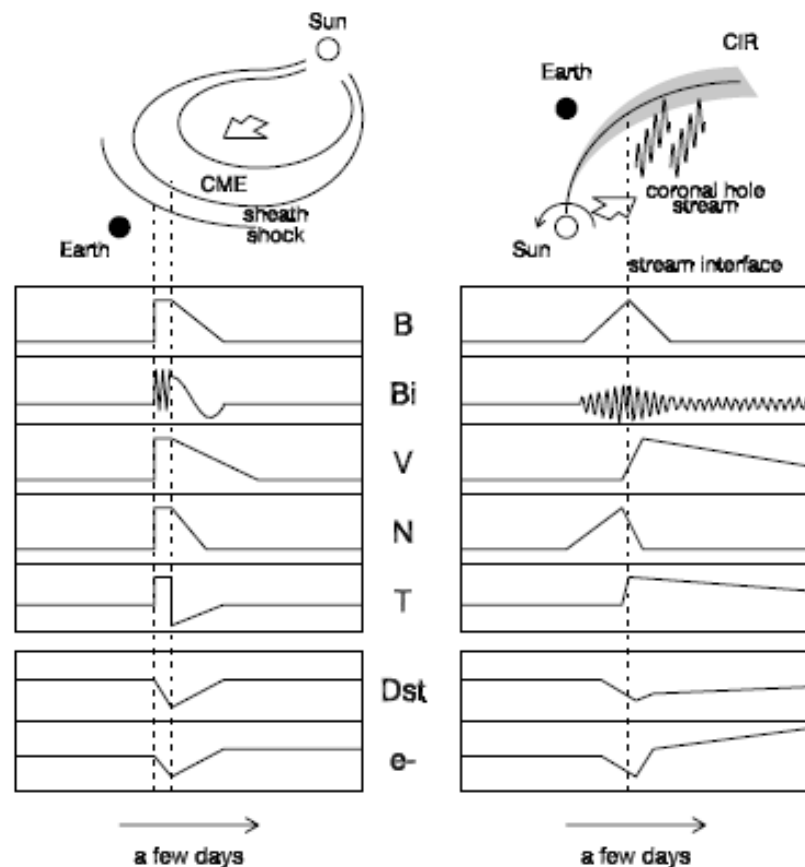
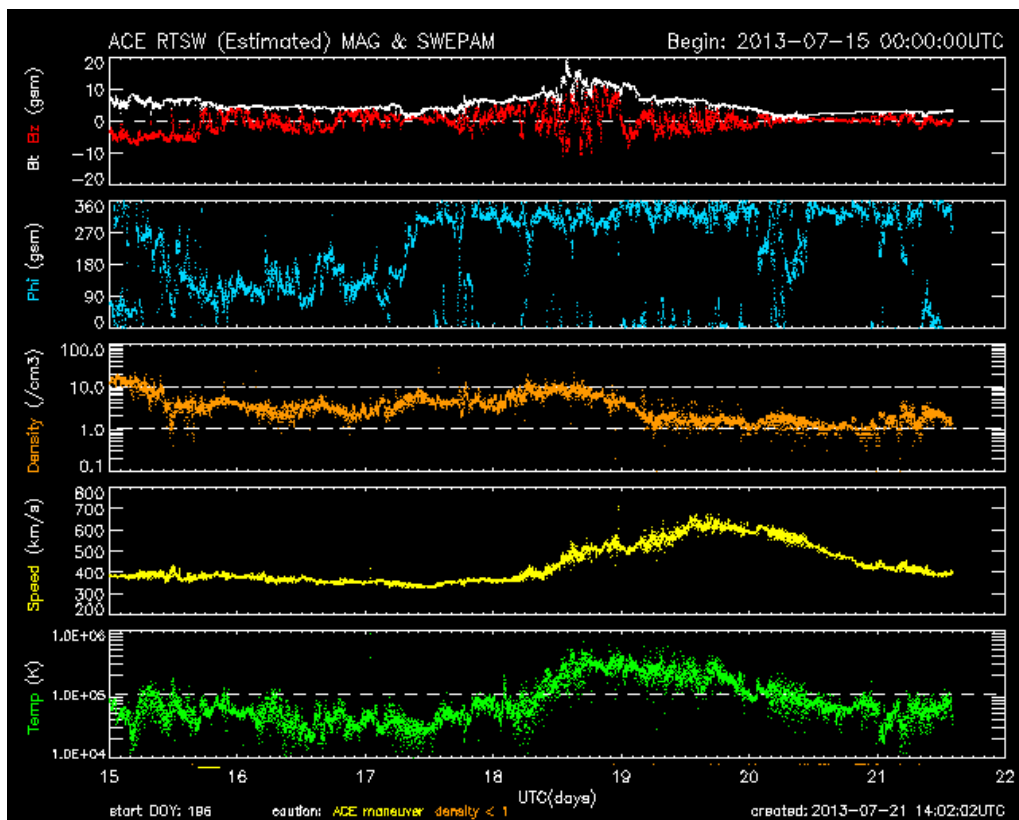


Figure 1. Schematic illustration of typical solar wind structures of coronal mass ejections (CMEs) and corotating interaction regions (CIRs): (top to bottom) magnetic field strength  $B$ , one of the Cartesian component  $B_i$ , solar wind speed  $V$ , density  $N$ , temperature  $T$ , expected response of the  $Dst$  index, and  $>2.0$  MeV electron flux at geosynchronous orbit.



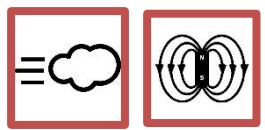


# Effects from CHs

Scale	Description	Effect	Physical measure	Average Frequency (1 cycle = 11 years)
G 5	Extreme	<p><b>Power systems:</b> Widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage.</p> <p><b>Spacecraft operations:</b> May experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites.</p> <p><b>Other systems:</b> 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.).</p>	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	<p><b>Power systems:</b> Possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid.</p> <p><b>Spacecraft operations:</b> May experience surface charging and tracking problems, corrections may be needed for orientation problems.</p> <p><b>Other systems:</b> 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.).</p>	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	<p><b>Power systems:</b> Voltage corrections may be required, false alarms triggered on some protection devices.</p> <p><b>Spacecraft operations:</b> Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems.</p> <p><b>Other systems:</b> 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.).</p>	Kp = 7	200 per cycle (130 days per cycle)
G 2	Moderate	<p><b>Power systems:</b> High-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage.</p> <p><b>Spacecraft operations:</b> Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions.</p> <p><b>Other systems:</b> HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.).</p>	Kp = 6	600 per cycle (360 days per cycle)
G 1	Minor	<p><b>Power systems:</b> Weak power grid fluctuations can occur.</p> <p><b>Spacecraft operations:</b> Minor impact on satellite operations possible.</p> <p><b>Other systems:</b> Migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine).</p>	Kp = 5	1700 per cycle (900 days per cycle)



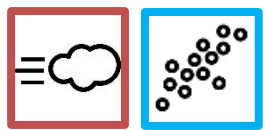




# Effects from CHs

- Similar to effects from ICMEs but less intense
- except...
- From particles
  - Satellites
    - **Deep di-electric charging**





# Effects from CHs

- High-Speed Stream (HSS)
  - Satellite charging
    - Deep di-electric charging
      - Also called « Internal charging »
        - » Several 100 keV to a few MeV ( $e^-$ )
        - » Penetrate S/C
        - » Accumulation effect within S/C (ESD)
        - » Dayside effect
        - » More during equinox
          - SNAP!
  - CHs in declining phase SC
    - Also 1-2 days after strong ICME, e.g. 3-4 Nov 2021

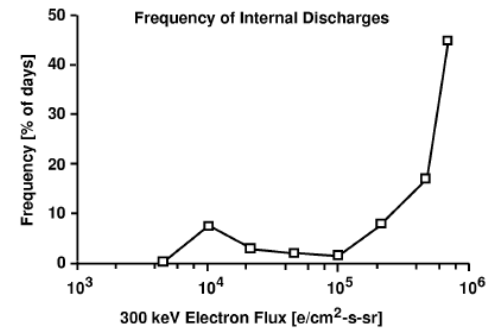
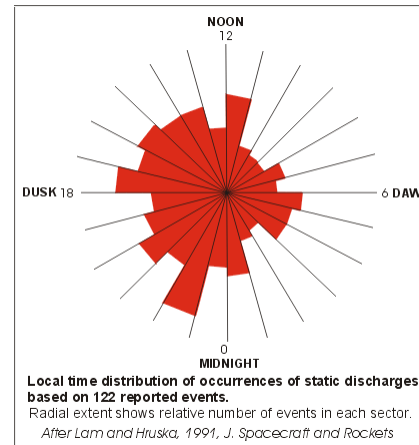
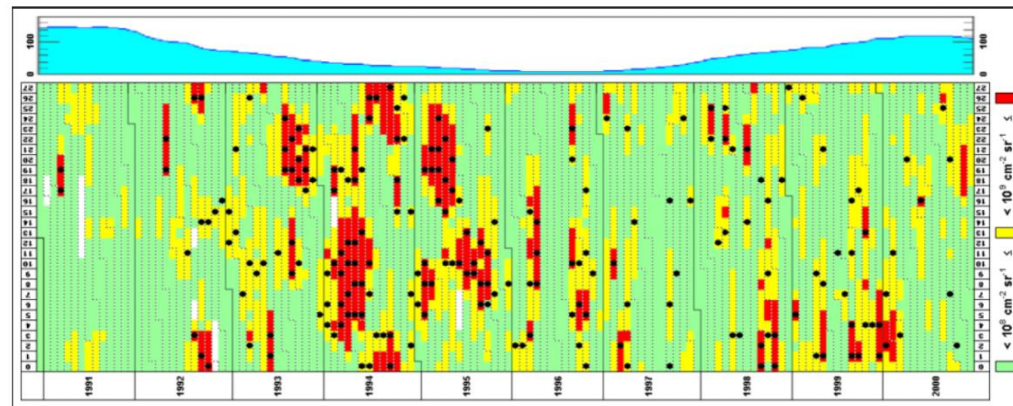
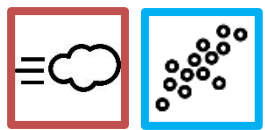


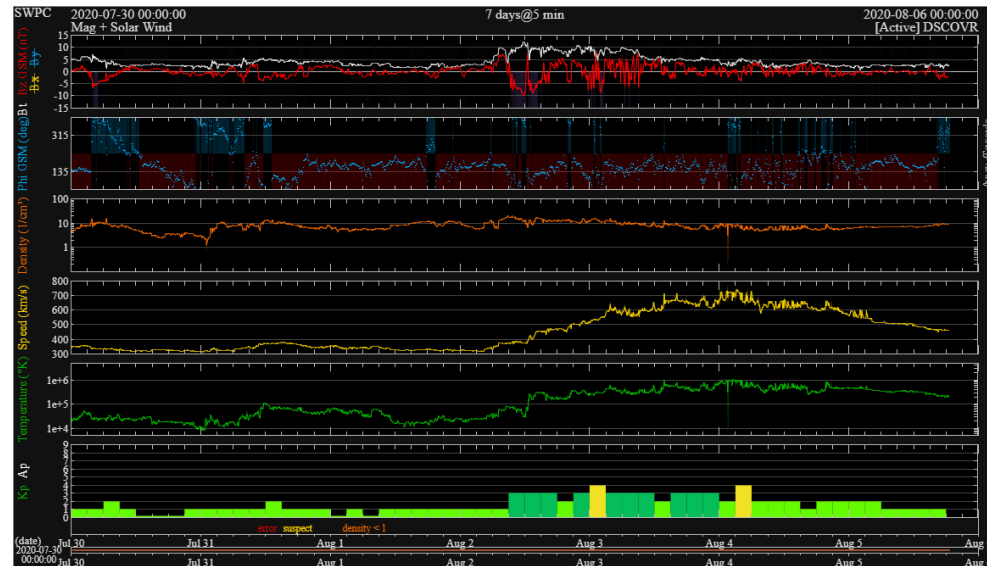
Figure 11. Comparison of SCATHA anomalies with energetic electron fluxes.



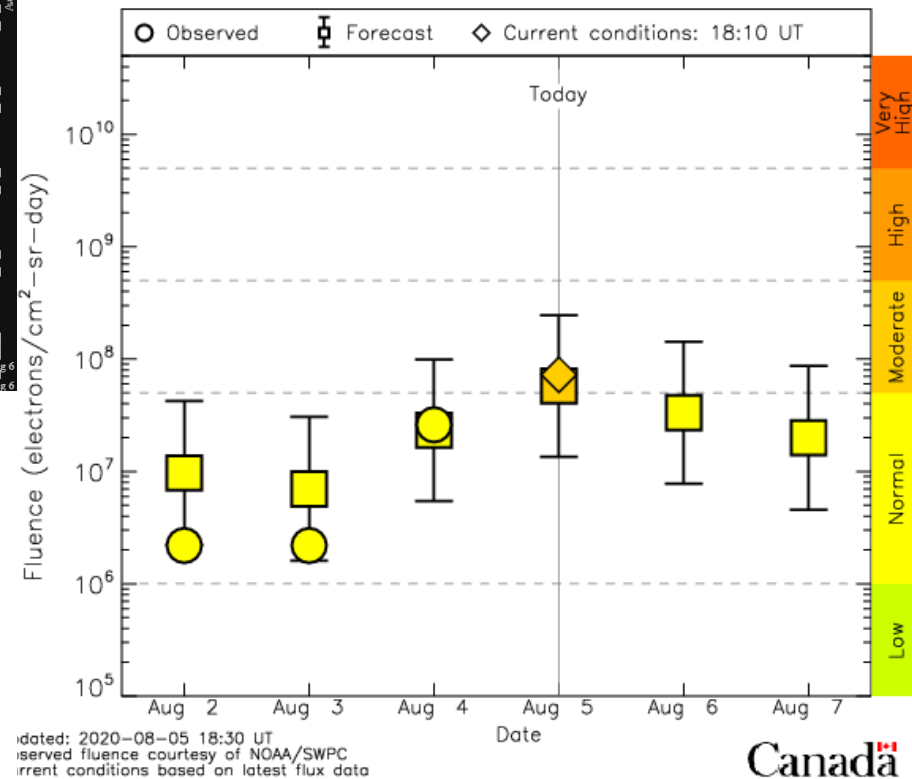
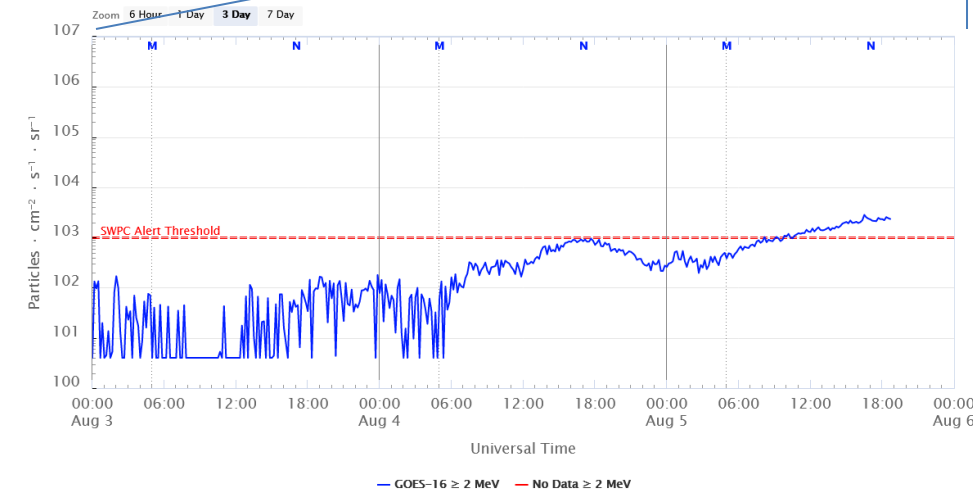


# Effects from CHs

## HSS from 2-6 August 2020

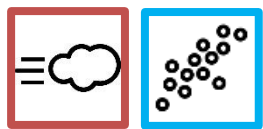


GOES Electron Flux (5-minute data)

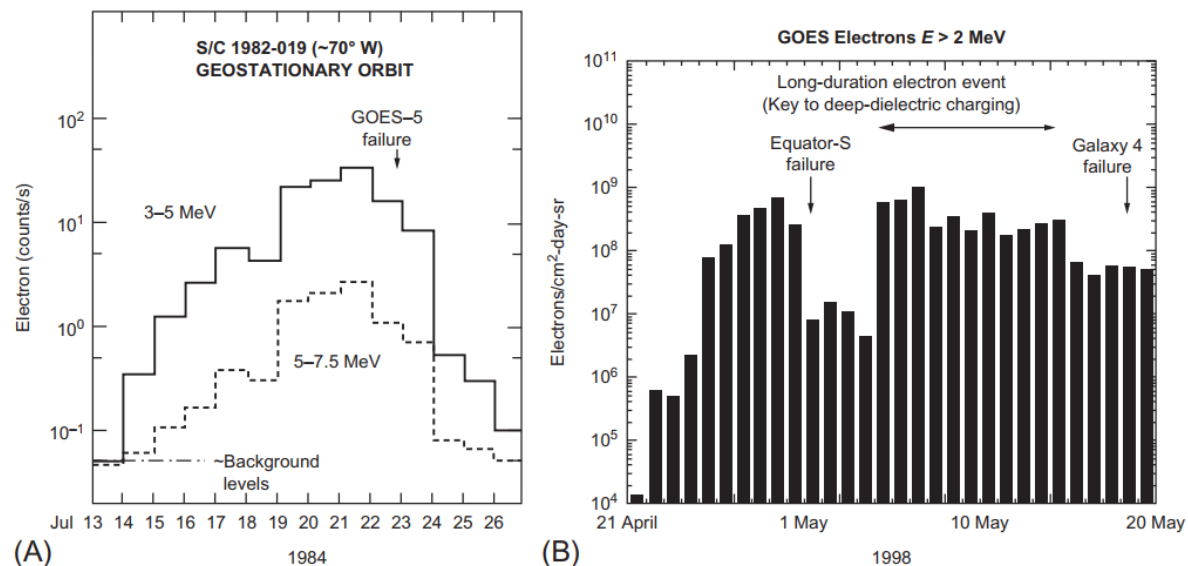


Canada



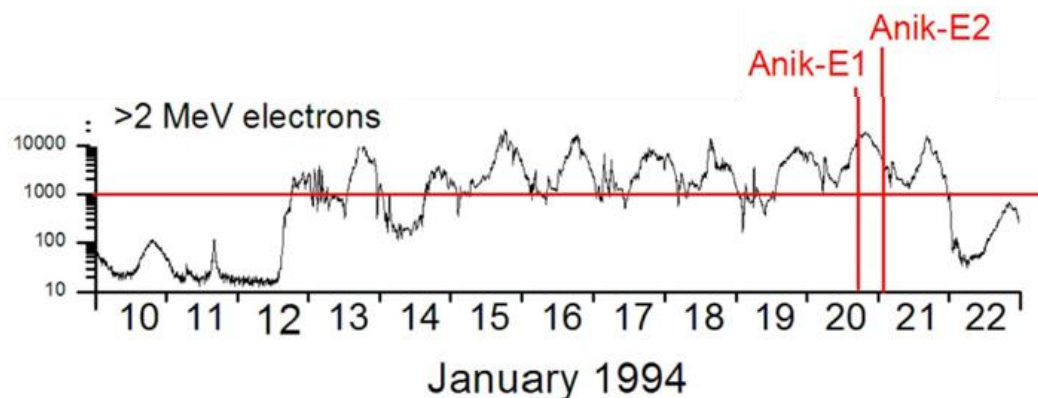
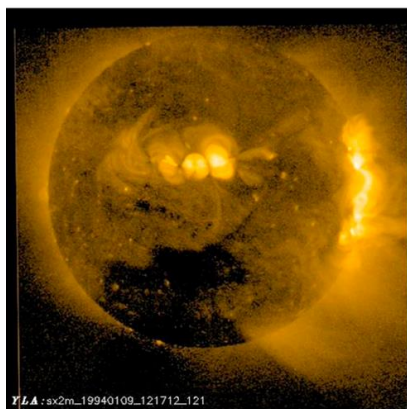


# Effects from CHs



**FIG. 7**

(A) High-energy electron counts during the period July 13–26, 1984. The satellite GOES-5 failed after, but not during, the peak flux high energy electron flux (Baker et al., 1987). (B) Galaxy-4 and Equator-5 spacecraft failure events showing delays of failures occurring after the peak of the electron fluence (Baker et al., 1998).



24 1 UTC  
at <http://www.sidc.be/products/tot>  
-----#  
DAILY BULLETIN ON SOLAR AND GEOMAGNETIC ACTIVITY from the SIDC #  
-----#  
SIDC URSIGRAM 40317  
SIDC SOLAR BULLETIN 17 Mar 2024, 1231UT  
SIDC FORECAST  
SOLAR FLARES : M-class flares expected (probability >=50%)  
GEOMAGNETISM : Quiet (A<20 and K<4)  
SOLAR PROTONS : Quiet  
PREDICTIONS FOR 17 Mar 2024 10CM FLUX: 144 / AP: 007  
PREDICTIONS FOR 18 Mar 2024 10CM FLUX: 146 / AP: 007  
PREDICTIONS FOR 19 Mar 2024 10CM FLUX: 148 / AP: 007



**Solar Active Regions and flaring:** There are five active regions visible on the solar disk. They all have simple beta or alpha magnetic field configuration and produced minor C-class flaring. The main activity in the last 24 hours has been observed from active regions behind the east limb, that will rotate into view in the next hours. The strongest was an M3.5 flare peaking at 16:35 UTC on 16 March, from a region not yet visible, located behind the east limb. As these regions rotate into view, we expect more M-class and possible X-class flares in the next 24 hours.

**Coronal mass ejections:** There was a partial halo CME (angular width about 180 degrees) directed towards the south, first seen at 03:24 UTC by LASCO C2. This CME originates from a filament eruption in the southern hemisphere. Since the filament was located close to the disk center, an ICME may arrive to the Earth on 20-21 March (a better estimation will be given when more data become available).

**Solar wind:** The Earth is inside slow solar wind, with speeds close to 350 km/s and an interplanetary magnetic field around 5 nT. Similar conditions are expected for the next 24 hrs.

**Geomagnetism:** Geomagnetic conditions were quiet both global and locally (NOAA\_Kp up to 1 and K\_BEL up to 1). Similar conditions can be expected for the next 24 hours.

**Proton flux levels:** The 10 MeV proton flux (measured by GOES-18) has come below the 10 pfu threshold, but remains elevated. It is expected that it will go back to low levels in the next 24 hrs.

**Electron fluxes at GEO:** The greater than 2 MeV electron flux from GOES 16 was below the threshold level in the last 24 hours. It is expected to remain below the threshold during the next 24 hours. The 24h electron fluence was at normal level and is expected to remain so.

**TODAY'S ESTIMATED ISN :** 074, BASED ON 10 STATIONS.

**SOLAR INDICES FOR 16 Mar 2024**

**WOLF NUMBER CATANIA :** ///

**10CM SOLAR FLUX :** 144

**AK CHAMBON LA FORET :** 005

**AK WINGST :** 002

**ESTIMATED AP :** 002

**ESTIMATED ISN :** 058, BASED ON 23 STATIONS.

**$\geq 2\text{MeV}$  electron flux & fluence**

**NOTICEABLE EVENTS SUMMARY**

**DAY BEGIN MAX END LOC XRAY OP 10CM Catania/NOAA RADIO\_BURST\_TYPES**

16 1622 1635 1644 // M3.5 //

16 2127 2155 2211 // M1.1 //

END

# Summary SWx effects (1/2)

- **Solar flares**



- NOAA scale (R)
- From EUV & X-ray radiation
  - Solar flare effect
    - “magnetic crochet”
    - => Effects from ICMEs
- Shortwave fadeout
  - “Radio Blackout”
  - => PECASUS
- From radio emission
  - GNSS disturbances
  - Radar disturbances

- **Proton events**



- NOAA scale (S)
- Polar Cap Absorption (PCA)
  - => PECASUS
- Radiation
  - Astronauts, Polar flights
  - => PECASUS
- Satellites
  - Star trackers
  - Single Event Effects (SEE)
  - Solar arrays
- Ground Level Enhancement (GLE)





# Summary SWx effects (2/2)

- **ICMEs**



- NOAA scale (G)
- From magnetic field
  - Satellites
    - Magnetopause crossings
  - High-Precision industry
  - GCR: Forbush decrease
- From particles
  - Satellites
    - Drag
    - Charging effects
      - » Electrostatic Discharges (ESD)
    - Satellite-based Comms/Nav applications (GNSS)
      - » => PECASUS
  - HF Communication (aviation)
    - => PECASUS
  - Geomagnetically Induced Currents (GIC)
  - Aurora

- **Coronal Holes**



- NOAA scale (G)
  - Impacts similar but less severe than with (strong) ICMEs
  - Especially during the declining phase of Solar Cycle
  - SNAP (Spring - Autumn +)
- Satellites
  - Deep di-electric charging

