Who Cares About Space Weather?

Alex Hands (University of Surrey)

TRIUMF, Vancouver, 8th July 2016

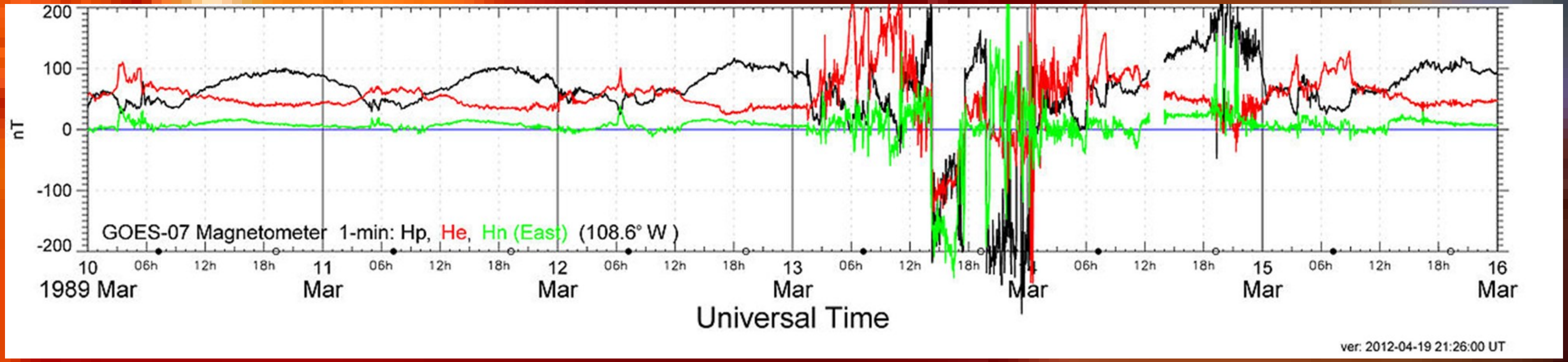
What is Space Weather?

- European Space Agency: *“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.”*
- NOAA (US): *“the variations in the space environment between the sun and Earth. In particular Space Weather describes the phenomena that impact systems and technologies in orbit and on Earth. Space weather can occur anywhere from the surface of the Sun to the surface of Earth.”*
- Key point is that it affects all regions, including the terrestrial surface.
- So who should care?

Canadians for a start!

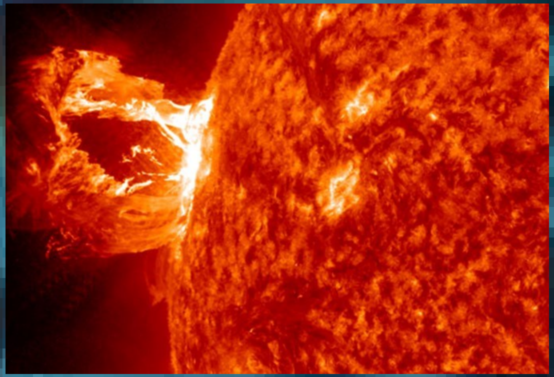
- Quebec, 1989 - large geomagnetic storm strikes Earth on March 13th
- Geomagnetically Induced Currents (GICs) cause violent fluctuations, tripping a “protection system” leading to voltage collapse
- Hydroelectric grid go from nominal operation to lights out in less than 90 seconds (outage lasted >9 hours)
- More suitable protection measures now in place, but not invulnerable

Magnetic field strength



The ‘other’ 1989 events

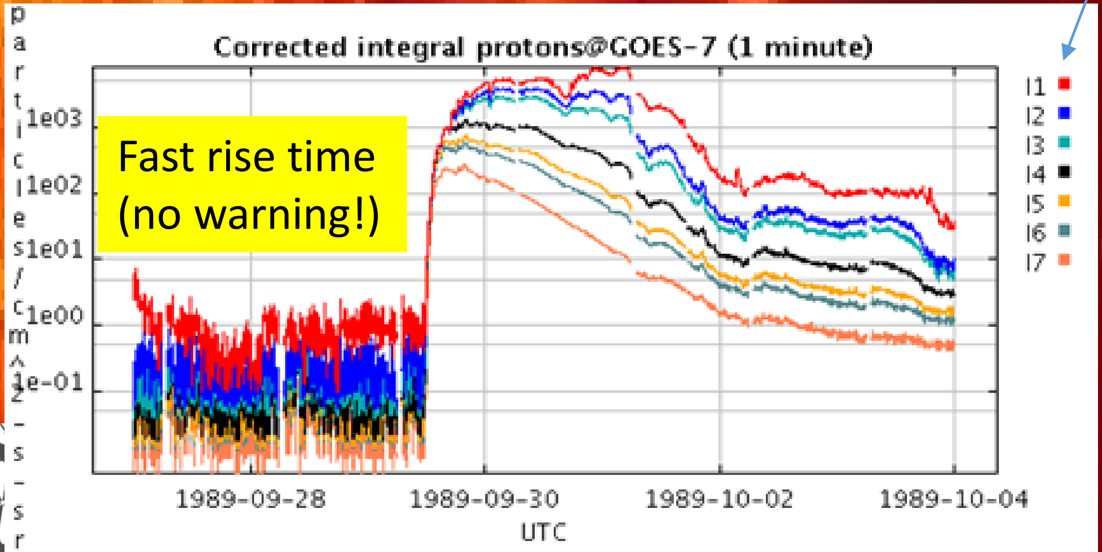
- Power grid effects during geomagnetic storms get the most attention (and funding!)
- Energetic particles from Coronal Mass Ejections (CMEs) and Solar Particle Events (SPEs) also pose a very significant threat, especially to satellites
- Series of SPEs in late 1989 (still used by some as worst case)

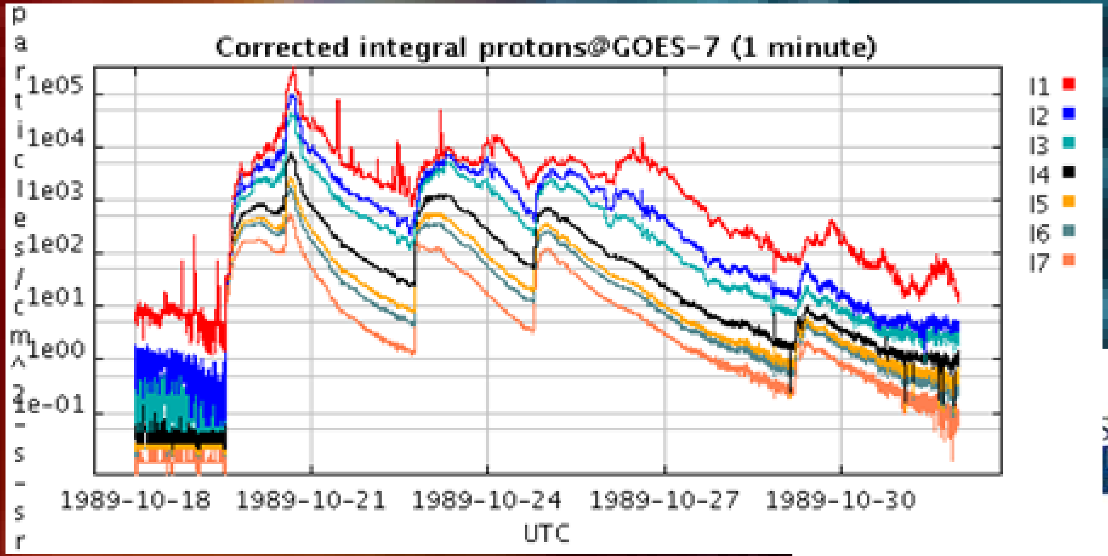


September

High energy proton channels

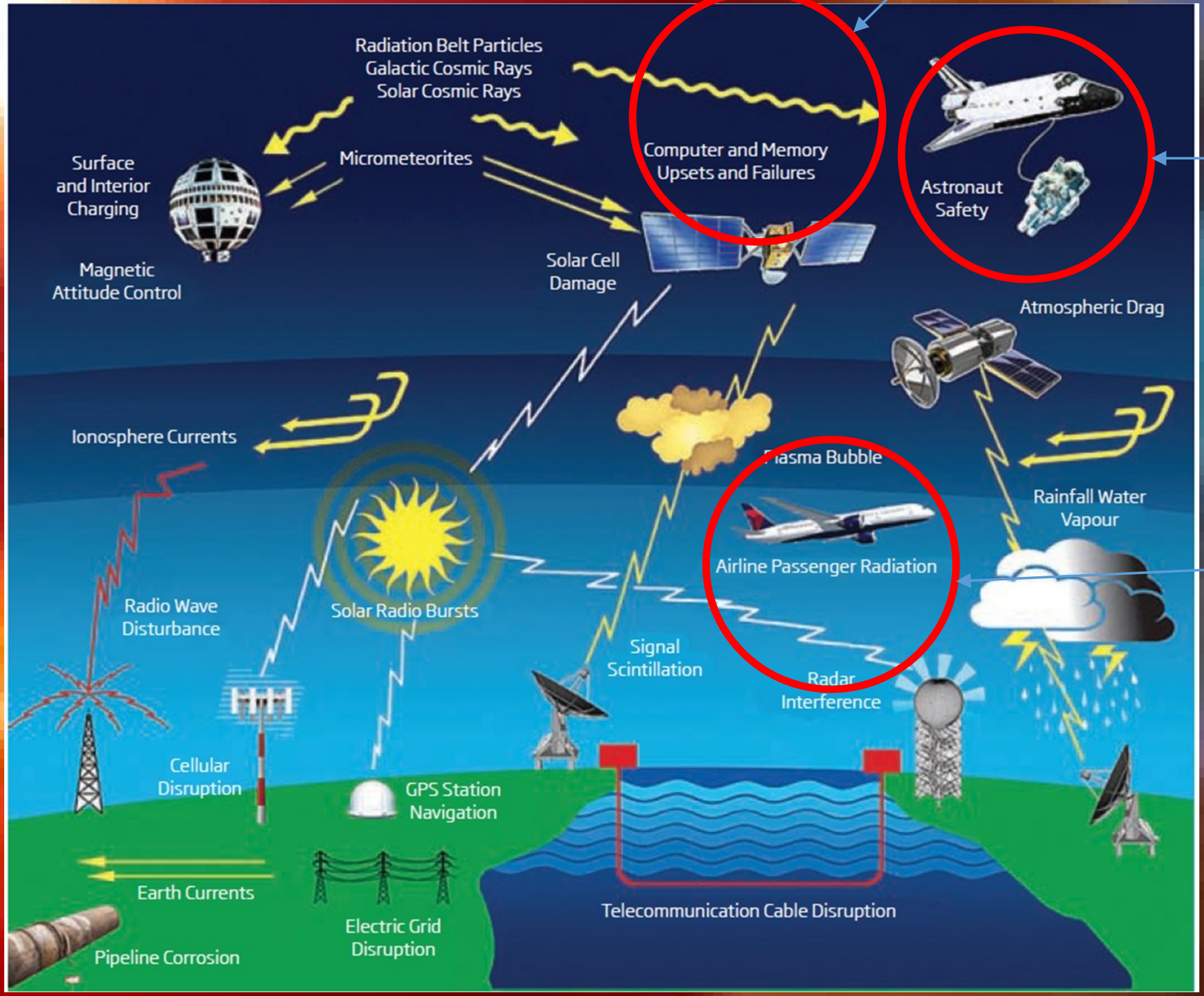
October





Wider Picture

Effects on Electronics



Manned Missions

Effects on Aviation (including avionics)

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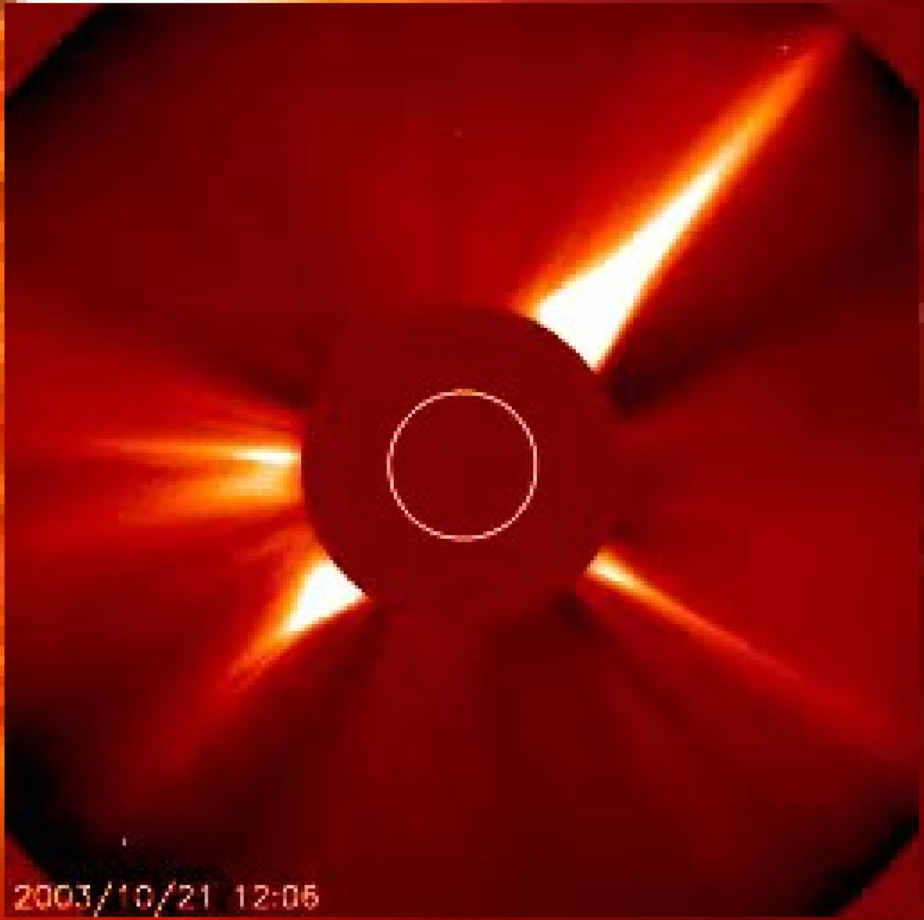
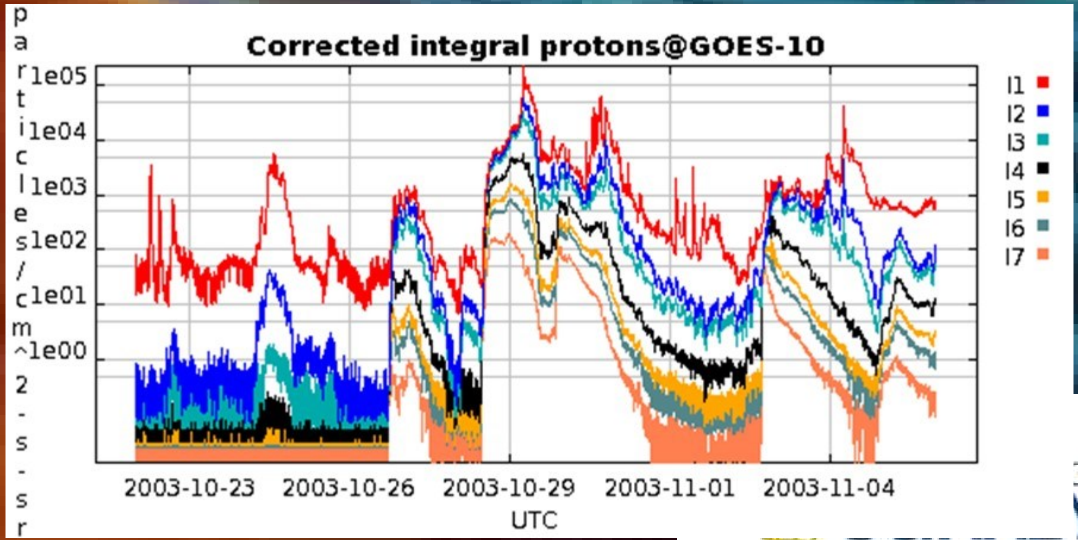
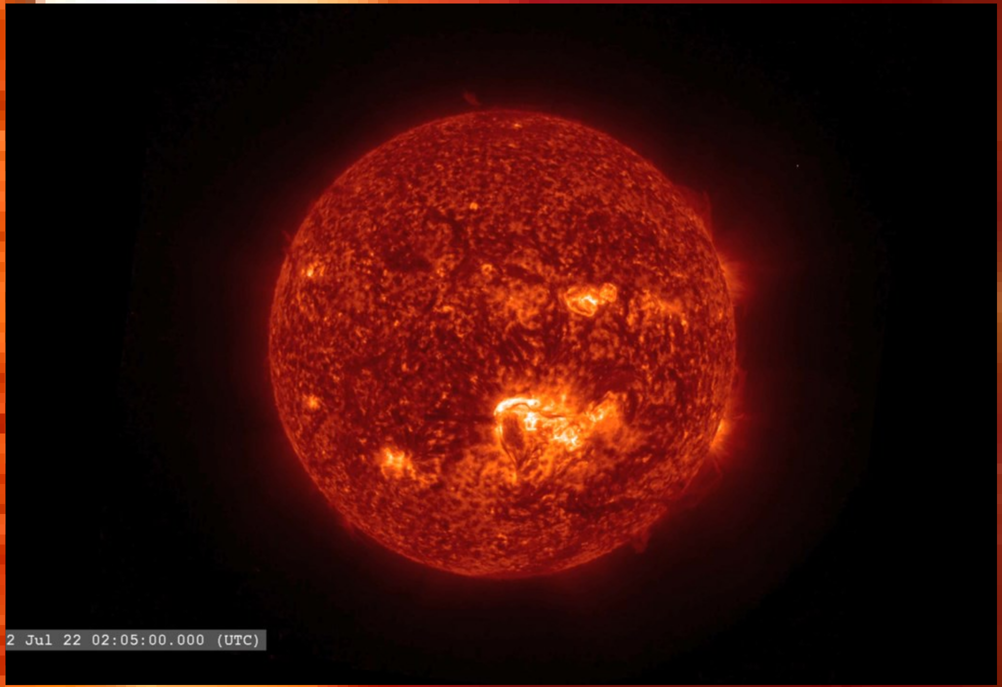
Halloween Storm, 2003



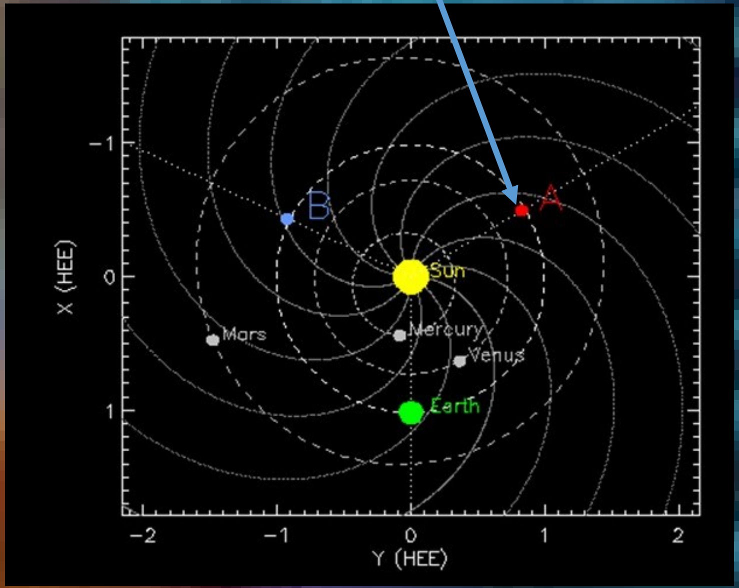
Solar and Heliospheric Observatory (SOHO) coronagraph CCDs affected by radiation storm in October 2003 (followed by largest recorded X-ray flare)



Near Miss – 23rd July 2012



Large CME eruption observed by STEREO-A spacecraft



NB London 2012 Olympics commenced a few days later (could have severely affected satellite TV coverage !!)

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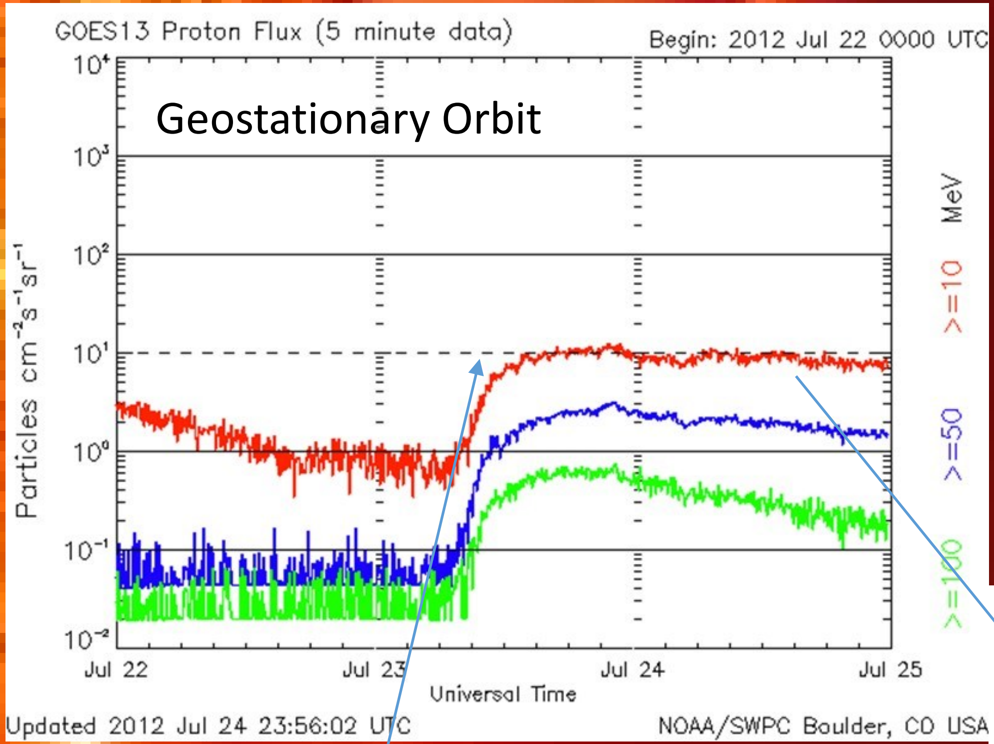
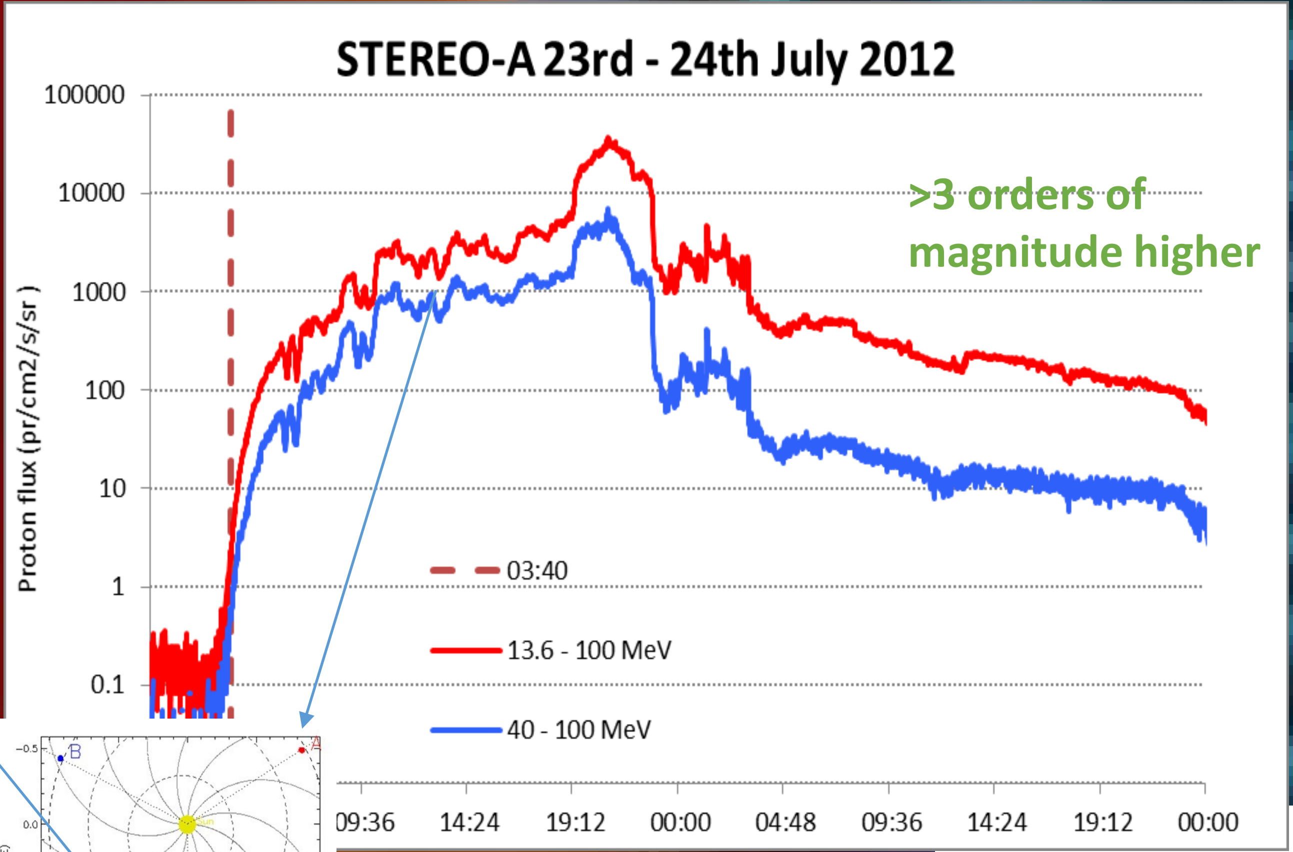
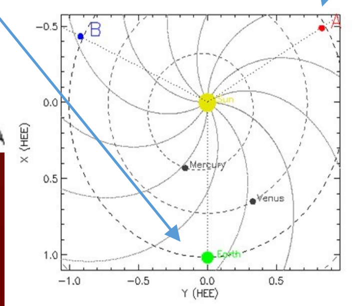
Timing is Everything

Proton flux: Earth vs STEREO-A





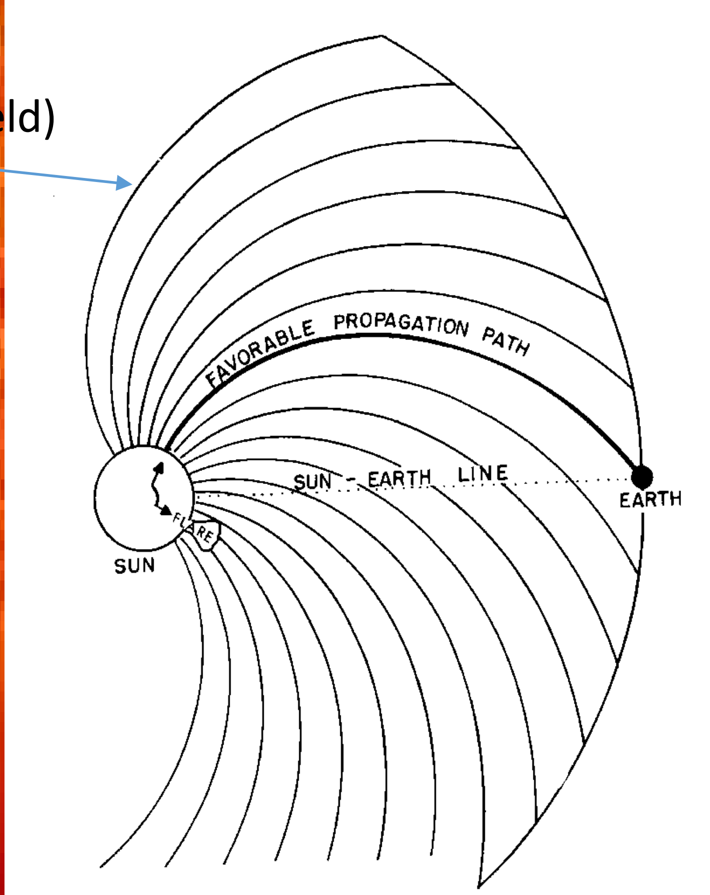


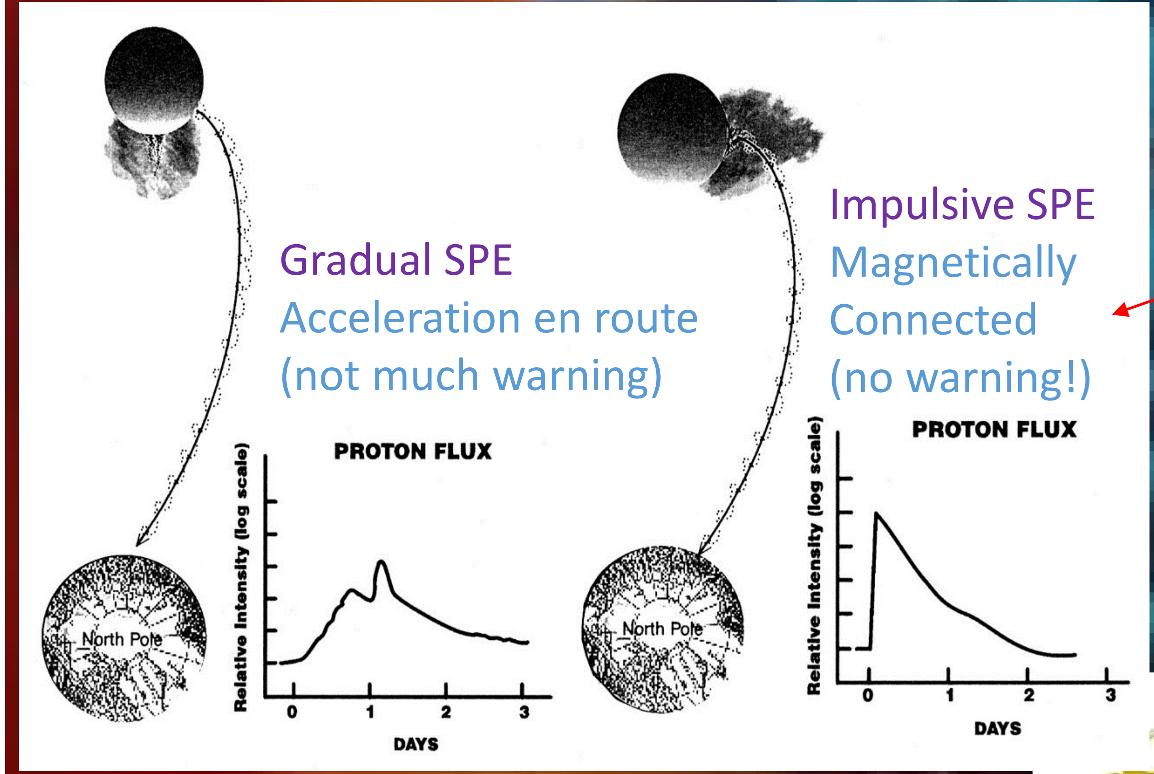
SPE alert level triggered even though active region is not visible from Earth

Two Types of SPE

Particle Flux & Time Profile Depend On Event Location On Sun

Parker Spiral
(magnetic field)



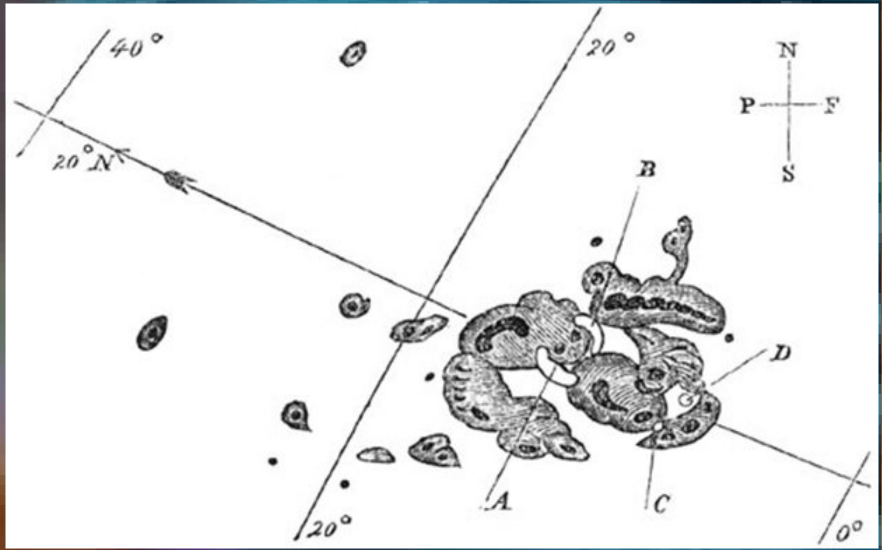


Important (and often ignored) contrast to other SW threats

Worst Case Scenarios

- Engineering design specifications often require ‘worst’ case
- Very difficult to define - different effects have different worst case events
- Most famous general case – Carrington Event:
  - Was part of a sequence of events from an active region which was at 12^{o} W on 1 Sept 1859. (non-optimum position for GLE)
  - There was a preceding storm with aurora observed in Hawaii !
  - Travel time to earth of Coronal Mass Ejection (CME) was a record breaking 17 hours.
  - Estimates for proton fluence based on nitrates in Antarctic ice cores – now discredited (we have no idea how large an SPE this was!)

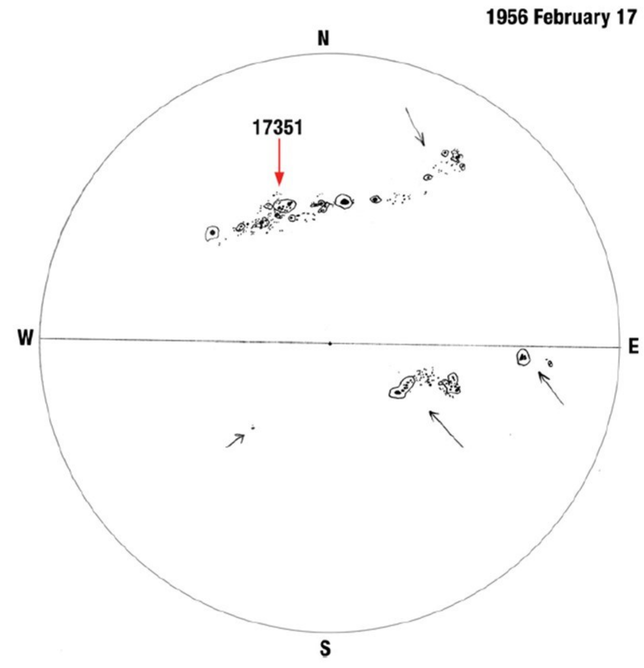
Carrington’s sketch of active region:

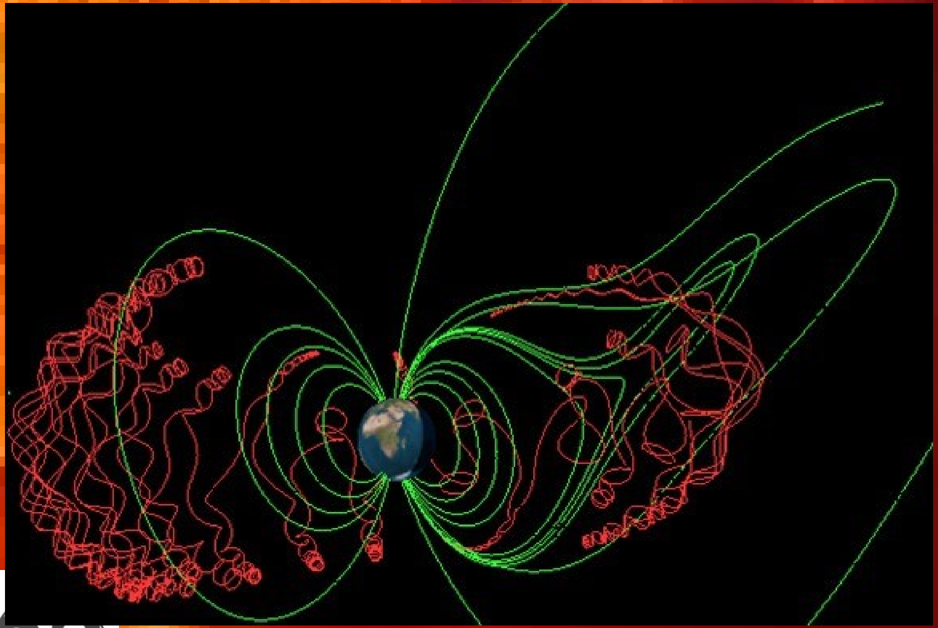


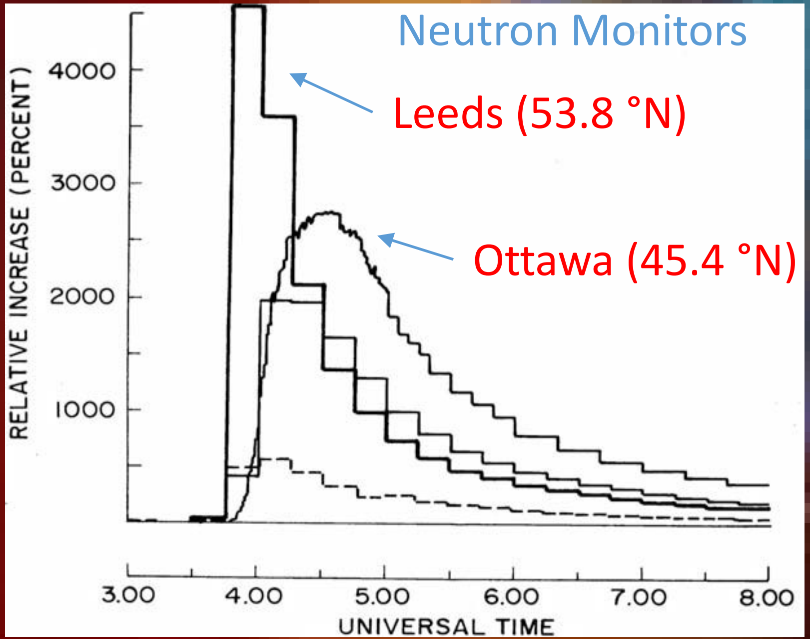
February 1956 Event

- Largest directly measured SPE (by neutron monitors on the ground)
- >4500% ground level increase at Leeds, UK (still a record)
- Highly Anisotropic (no simple latitude correlation)
- Good candidate for 'worst observed case'

Sun spots ~ 1 week before:







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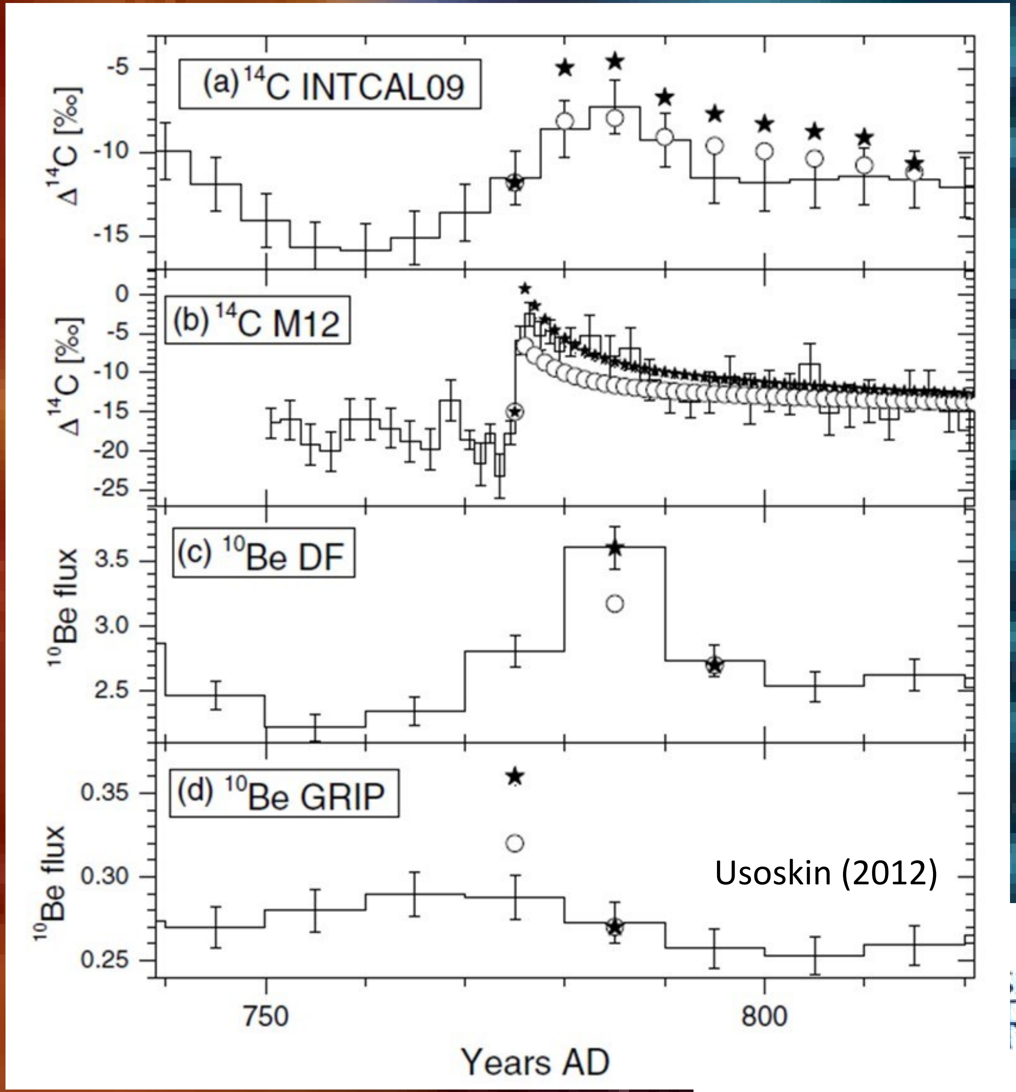
Large events from historical record

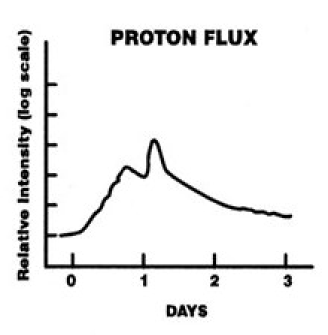
- Much work has been done on cosmogenic isotope analysis to calculate large SPE fluences:
    - Beryllium-10 in ice cores
    - Carbon-14 in tree rings

  (produced by GCR in upper atmosphere)
- E.g. 774/75 AD event
- Proton fluence (not flux) can be inferred by modelling isotope production rates
- Estimated 25 – 50 x Feb '56 fluence (!!)
- Flux depends on light curve assumption (impulsive event? CME driven? Series of events?)
- Time resolution of data inherently poor



10,000 year timescale

- C-14 cosmogenic isotope analysis has been extended to 11,000 BC
- (very) roughly these imply an event of similar magnitude to 774/75 AD occurs once every 1000 years
- Caution: still dealing in fluences, no idea what peak flux was for any of these events (very important for error rates in electronics)



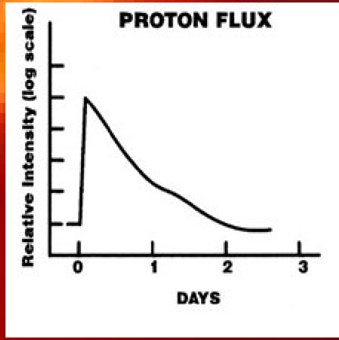


Table 1
Identified SPE Candidates: Approximate Year, Data Set, and Fluence F_{30} (cm^{-2}) Evaluated for the SPE56 Scenario

SPE Year	Series	F_{30} (X_{SPE56})
1460–1462 AD[a]	NGRIP(1460)	1.5×10^{10} (15)
	Dye3 (1462)	9.7×10^{9} (10)
1505 AD	Dye3	1.3×10^{10} (13)
1719 AD	NGRIP	1×10^{10} (10)
1810 AD	NGRIP	1×10^{10} (10)
8910 BC	IntCal09	2.0×10^{10} (20)
8155 BC	IntCal09	1.3×10^{10} (13)
8085 BC	IntCal09	1.5×10^{10} (15)
7930 BC	IntCal09	1.3×10^{10} (13)
7570 BC	IntCal09	2.0×10^{10} (20)
7455 BC	IntCal09	1.5×10^{10} (15)
6940 BC	IntCal09	1.1×10^{10} (11)
6585 BC	IntCal09	1.7×10^{10} (17)
5835 BC	IntCal09	1.5×10^{10} (15)
5165 BC	GRIP	2.4×10^{10} (24)
4680 BC	IntCal09	1.6×10^{10} (16)
3260 BC	IntCal09	2.4×10^{10} (24)
2615 BC	IntCal09	1.2×10^{10} (12)
2225 BC	IntCal09	1.2×10^{10} (12)
1485 BC	IntCal09	2.0×10^{10} (20)
95 AD	GRIP	2.6×10^{10} (26)
265 AD	IntCal09	2.0×10^{10} (20)
780 AD[a]	IntCal09	2.4×10^{10} (24)
	M12	4×10^{10} (40)[b]
	DF	4.5×10^{10} (45)[b]
1455 AD[a]	SP	7×10^{10} (70)

Usoskin (2012)

Numbers in parentheses give estimated ratio to Feb '56

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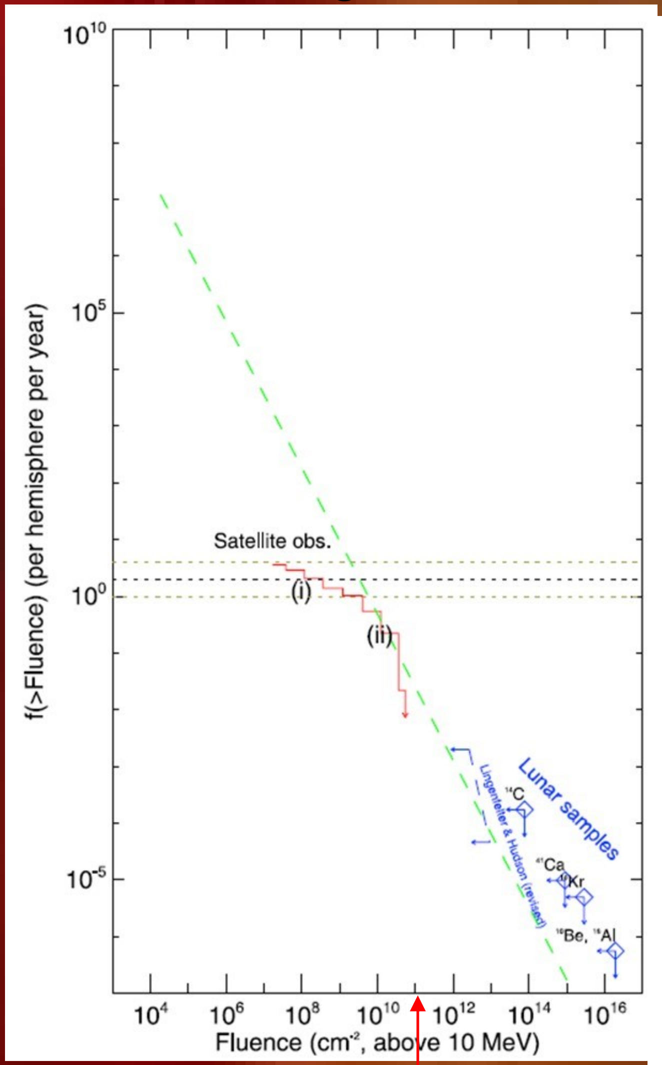
Other Estimates

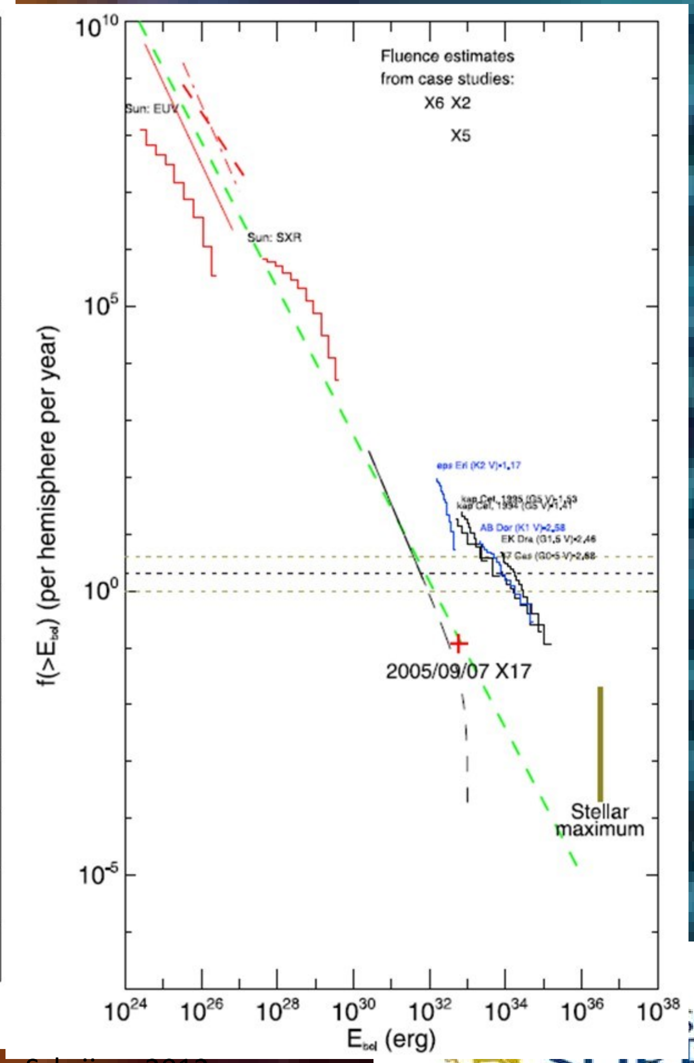
- Extra-terrestrial cosmogenic analysis and astronomical observations of superflaring Sun-like stars can also produce estimates / limits of extreme SPE fluences
- All methods subject to various assumptions and large uncertainties
- Too speculative?

Lunar regolith:



774AD

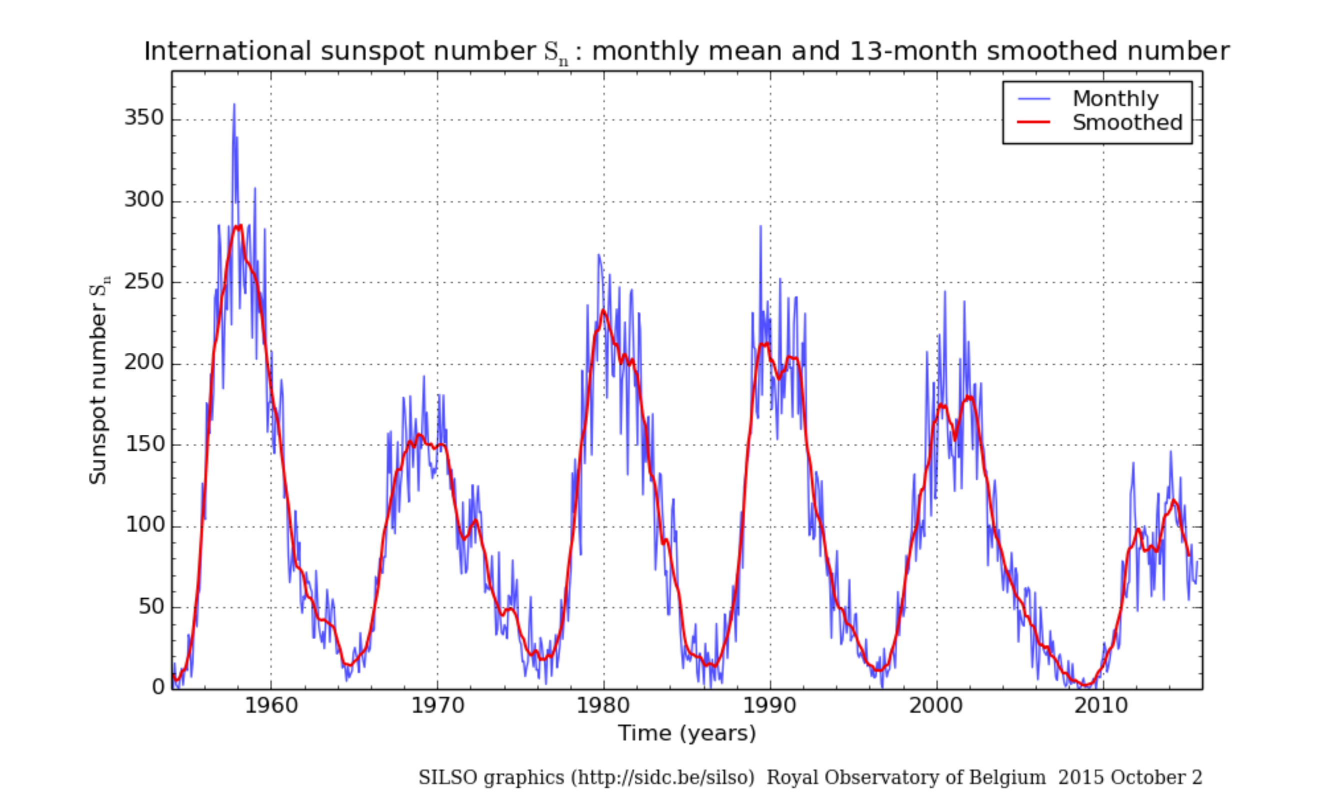
Flaring stars:

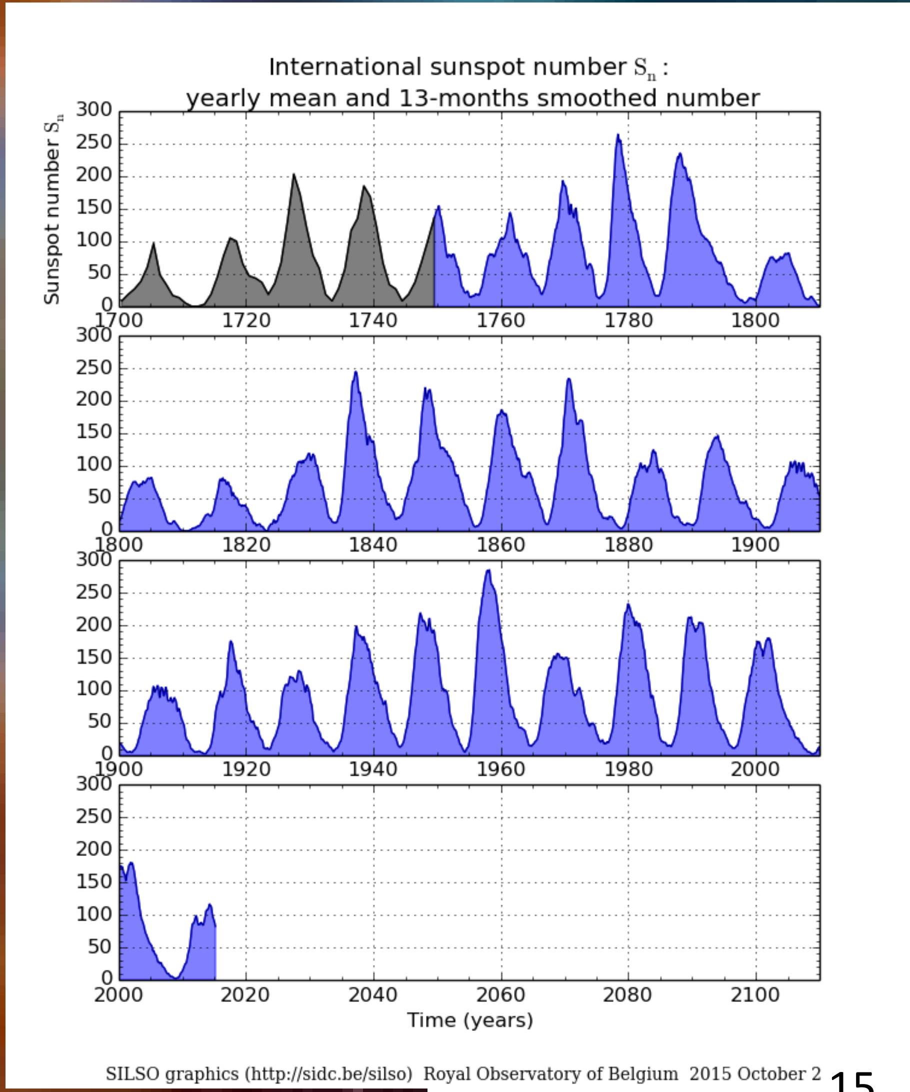


Schrijver 2012

Back to Present Day - Solar Cycle 24

- Lowest number of sun spots for a century:

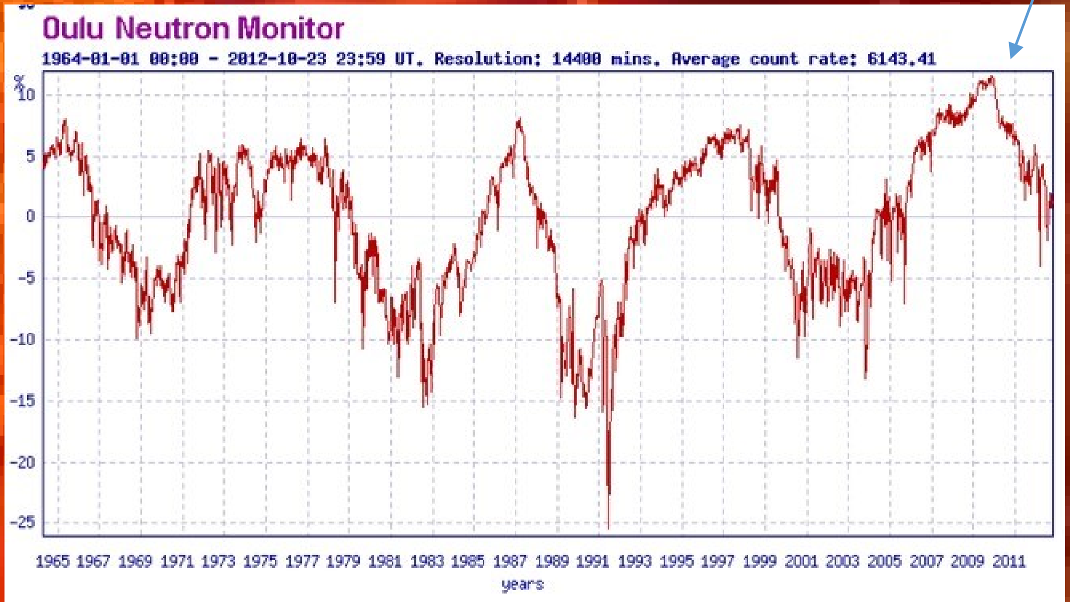


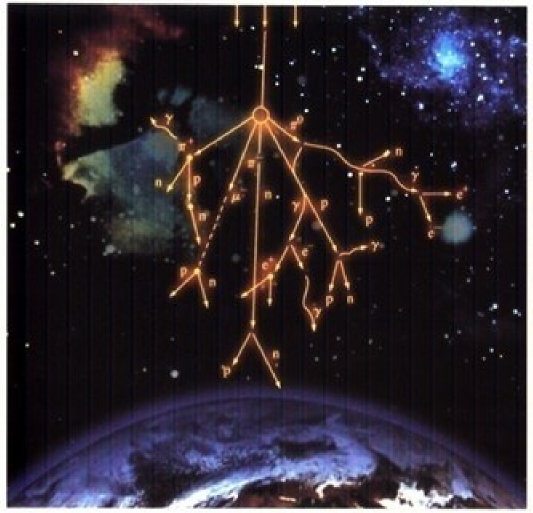


Solar Cycle 24

- However, solar modulation effect means record cosmic ray fluxes

Highest GCR of Space Age





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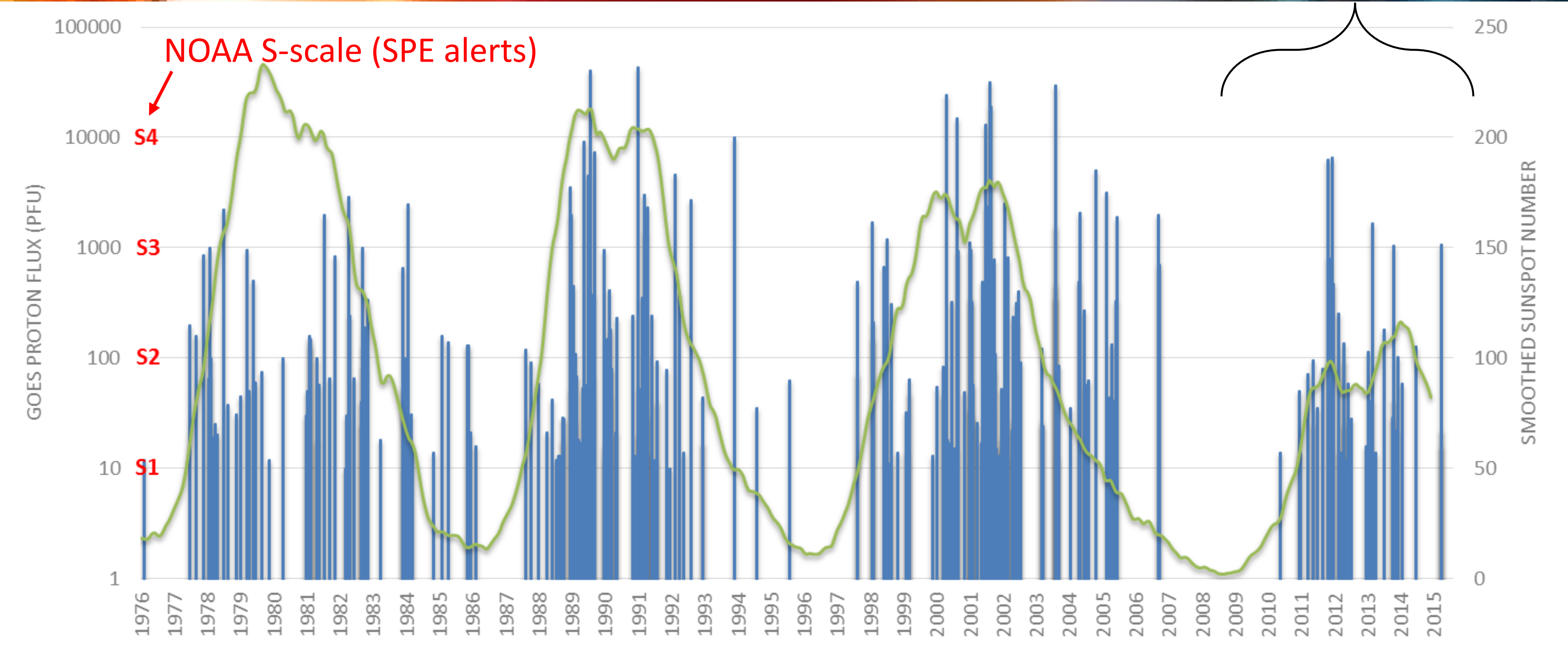
Proton Flux

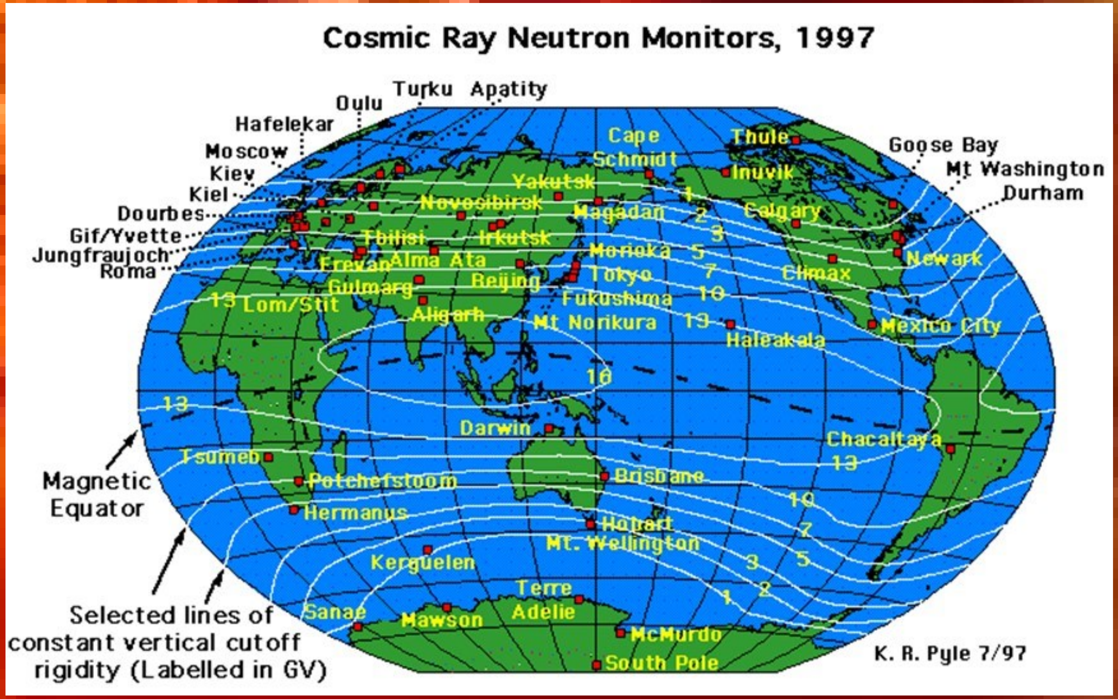
- GOES data since 1976 (>10 MeV):

Cycle 24 has had relatively few SPEs

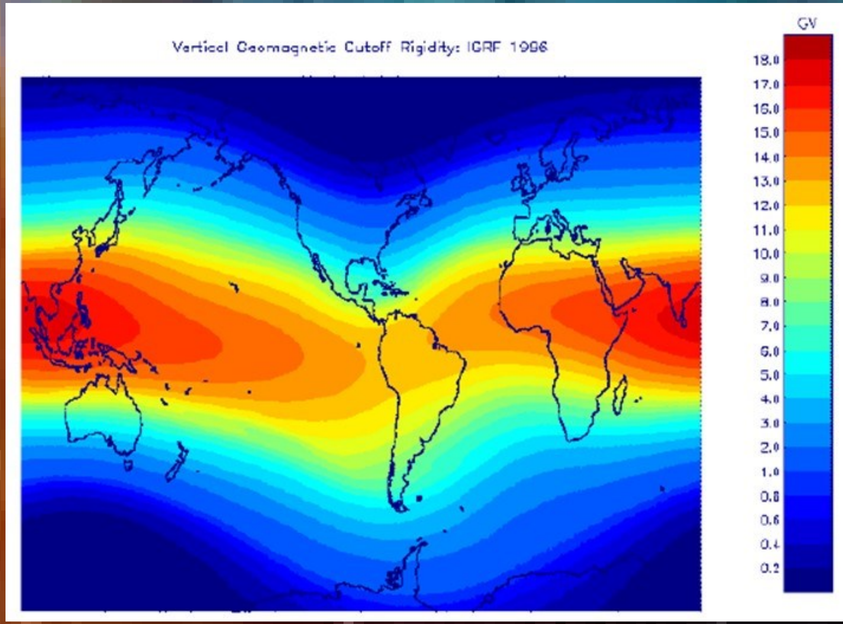


Ground Level Neutron Monitors

- Key ingredient to atmospheric radiation warnings & analysis
- Largest SPEs can cause significant increases in ground level neutron flux
- Neutron Monitors invented in late 1940s, but diminishing global network



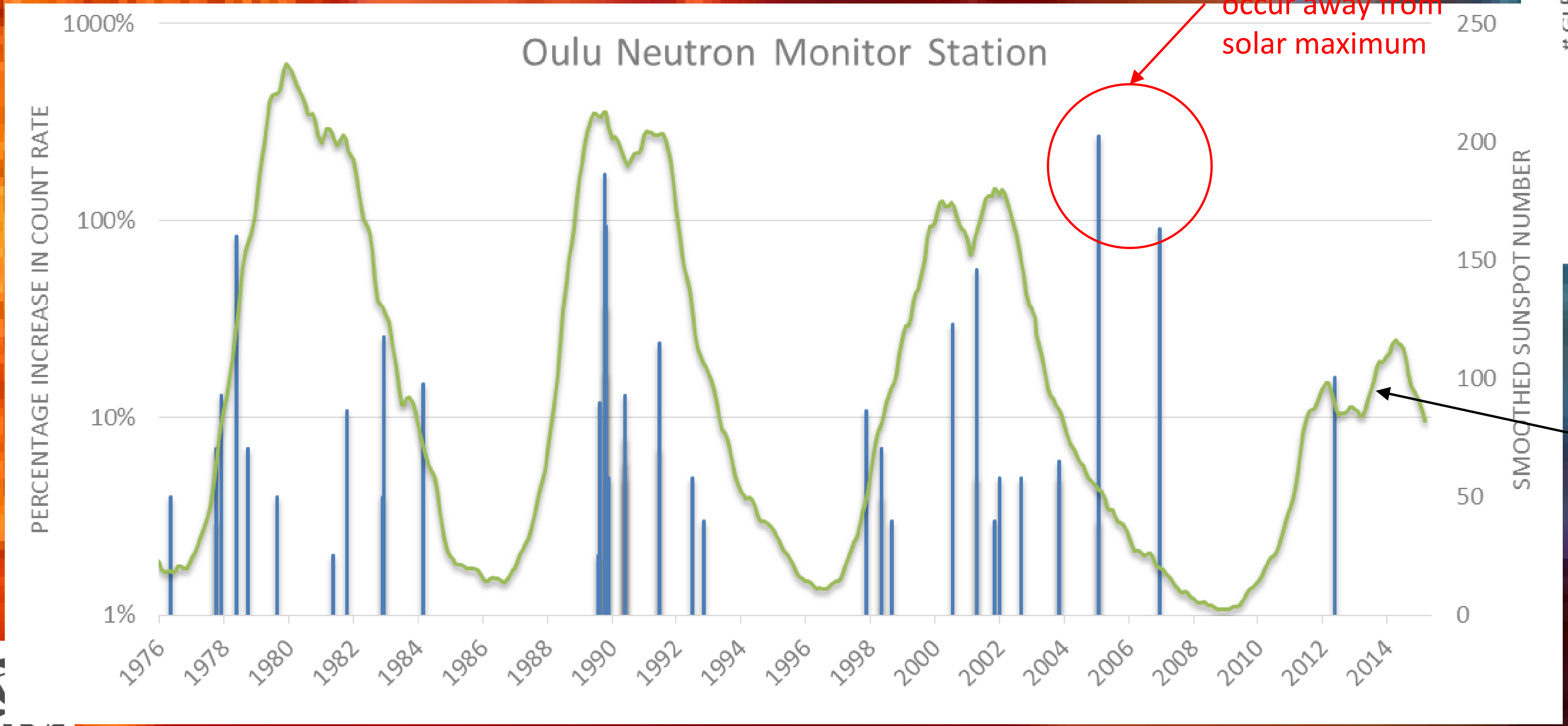
Earth's magnetic field acts like a spectrometer

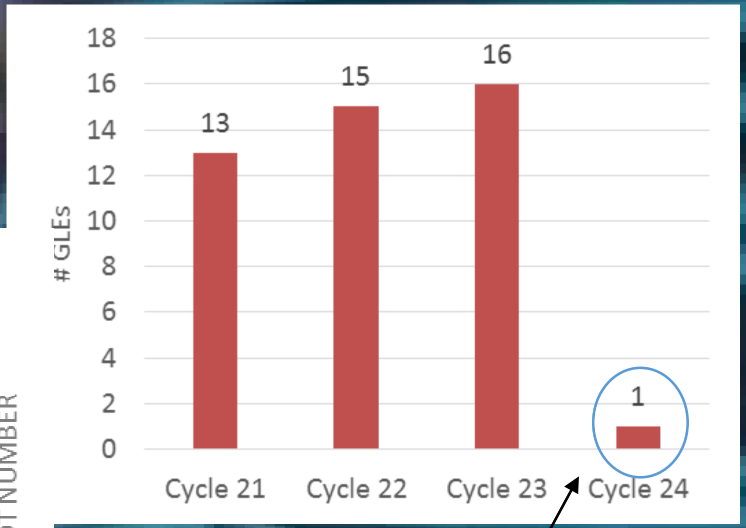


Ground Level Enhancements (GLEs)

- GLEs recorded at Oulu GLNM, Finland

NB Large GLEs can occur away from solar maximum

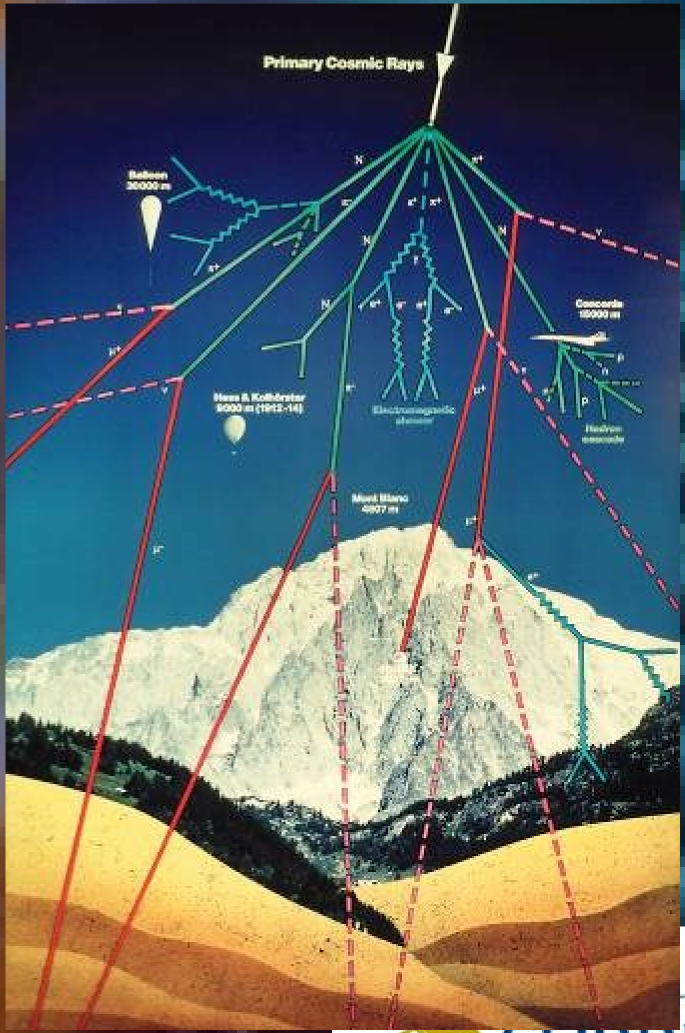




One GLE only (!)
(17th May 2012)

Atmospheric Radiation and Aviation

- Primarily due to Galactic Cosmic Rays (GCR) - composition mainly protons and alpha particles with energies extending up to and beyond 10^{20} eV (cf. LHC ~10^{13} eV)
- Interactions with the atmosphere produce various secondary particles including neutrons across a wide energy range
- Neutron flux builds up to a maximum at 60,000 feet but is reduced by two or three orders of magnitude at sea level
- At aviation altitudes even GCR dose levels can cumulatively be significant for air crew or frequent flyers
- Solar Particle Events (SPEs) can result in doses above GCR levels, potentially exceeding legal annual maximum for pregnant aircrew in a single flight
- SPEs also pose a significant threat to avionics via single event effects (SEE)
- Other effects on aviation exist (largely due to ionospheric disturbances – not discussed here)



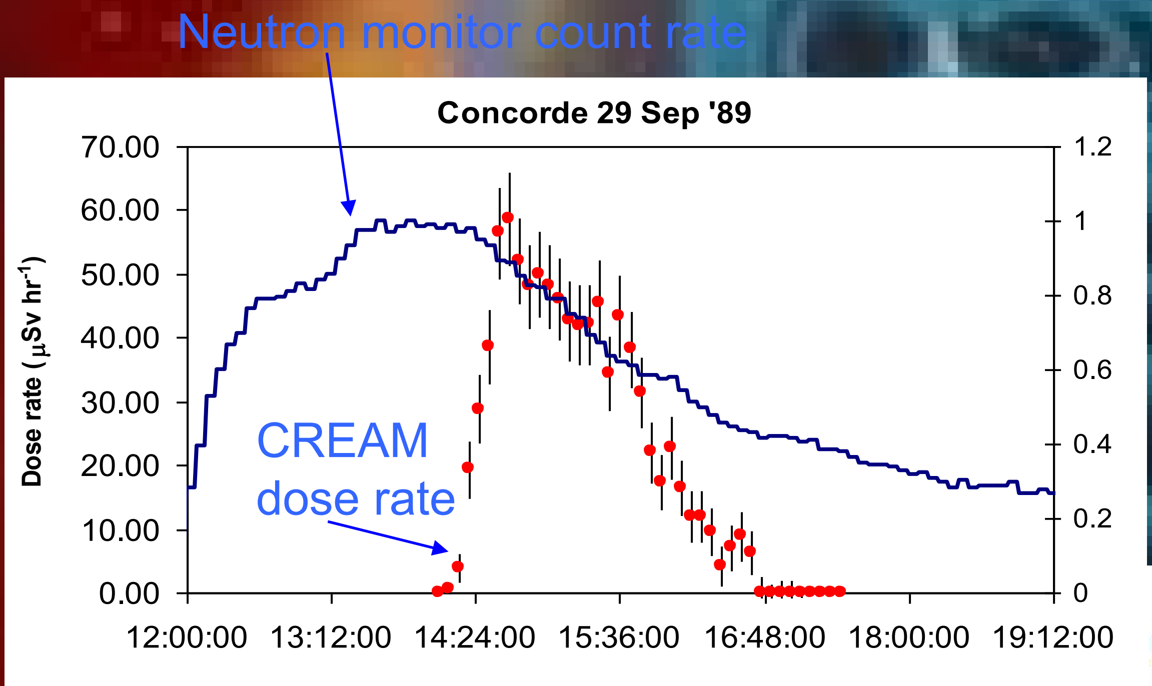
History

- Cosmic Radiation Effects and Activation Monitor (CREAM) designed in 1980s to actively monitor high energy cosmic ray particles in space
- Two Shuttle Activation Monitor (SAM) units built
  - PIN diode array measures charge depositions from directly and indirectly ionising particles in 9 channels
  - Shuttle flight delayed due to Challenger disaster
  - New CREAM unit developed to fly on Concorde

CREAM SAM-1

Concorde Flights

- Special CREAM-C unit flown on trans-Atlantic routes
- ~1000 hours of observation
- Amoung the only in-flight observations of Solar Particle Events (and still the best)



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CREAM in Space

On MIR Space Station (1995-1997)

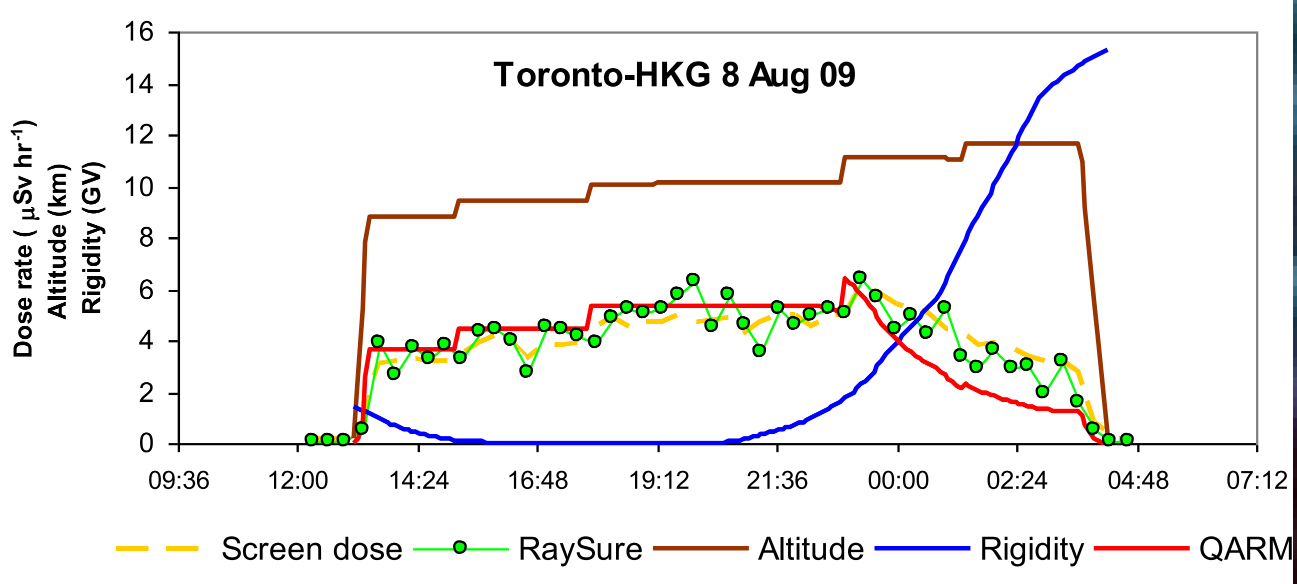
On Space Shuttle (1991-1998)

New Monitor for Flight Dosimetry

- In-flight data are crucial to validate atmospheric models
- RaySure® flight dose monitor developed at QinetiQ
  - (now used under licence by Surrey University)
- Thousands of flight hours accumulated (including data during SPEs, but very few during measurement period)

Live accumulated dose & dose rate readings
(plus alert indicators)

- E.g: Trans-polar flight data:



Typical Dose 50 - 60 µSv
(=several chest X-rays)

Much larger during major SPE !

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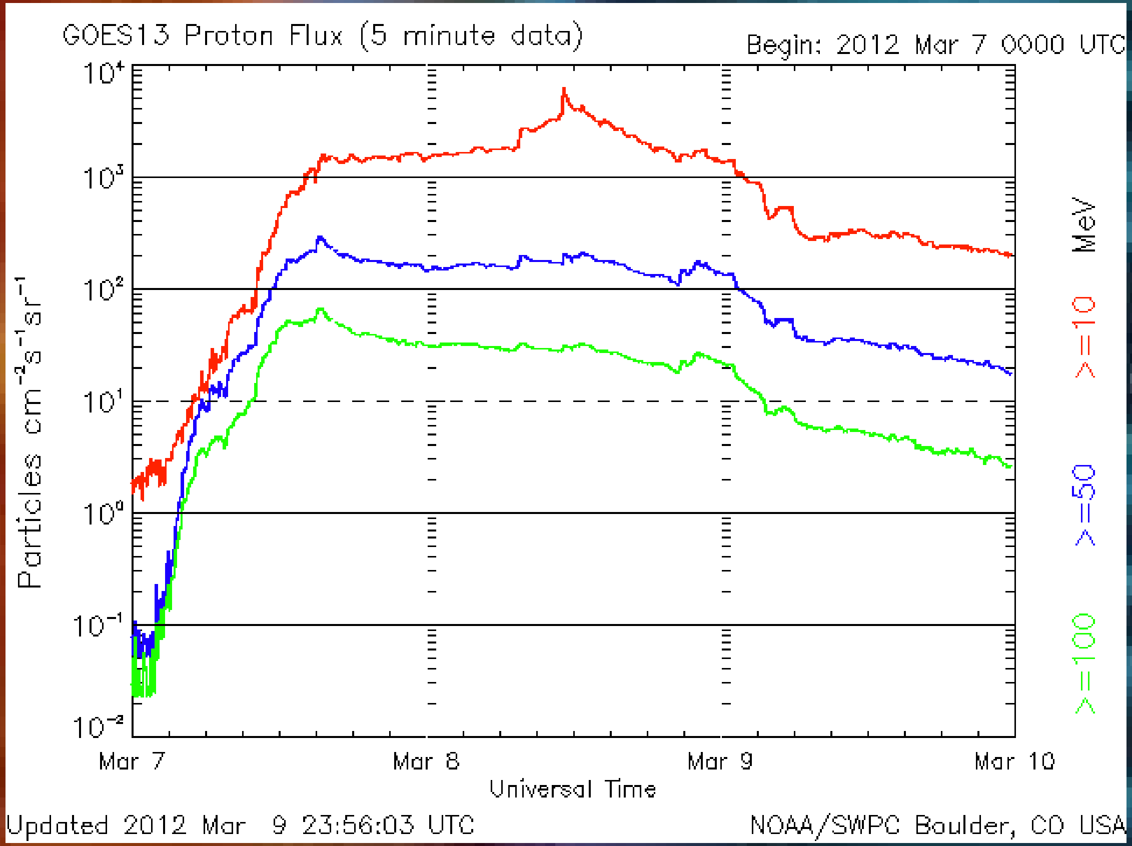
Beware False Alarms

- Very easy to overestimate effect on aviation during "small" events
- Three quick examples:
- 1. March 2012
    - Mid-longitude solar active region
    - S3 on NOAA scale (nearly S4)
    - Largest since 2003 "Halloween" event
    - Large increase in >100 MeV proton flux



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March 2012 Event: Dose Predictions / Now-casting

- NASA's NAIRAS model provided dose rate predictions during event

Effective Dose Rate[1](E) for 2012-03-09 17:00-18:00 GMT

5km (16,000 feet) Radiative Dose Rate (uSv/hr)

lat	90S-60S	60S-40S	40S-20S	20S-0	0-20N	20N-40N	40N-60N	60-90N
avg	3.99	2.89	1.35	0.57	0.50	0.98	2.76	3.95
max	4.57	8.66	8.28	1.06	1.14	8.10	8.65	4.47

11km (35,000 feet) Radiative Dose Rate (uSv/hr)

lat	90S-60S	60S-40S	40S-20S	20S-0	0-20N	20N-40N	40N-60N	60-90N
avg	20.45	12.82	3.89	1.34	1.15	2.69	11.61	21.26
max	21.95	21.29	15.18	2.90	3.28	13.90	22.38	23.01

15km (49,000 feet) Radiative Dose Rate (uSv/hr)

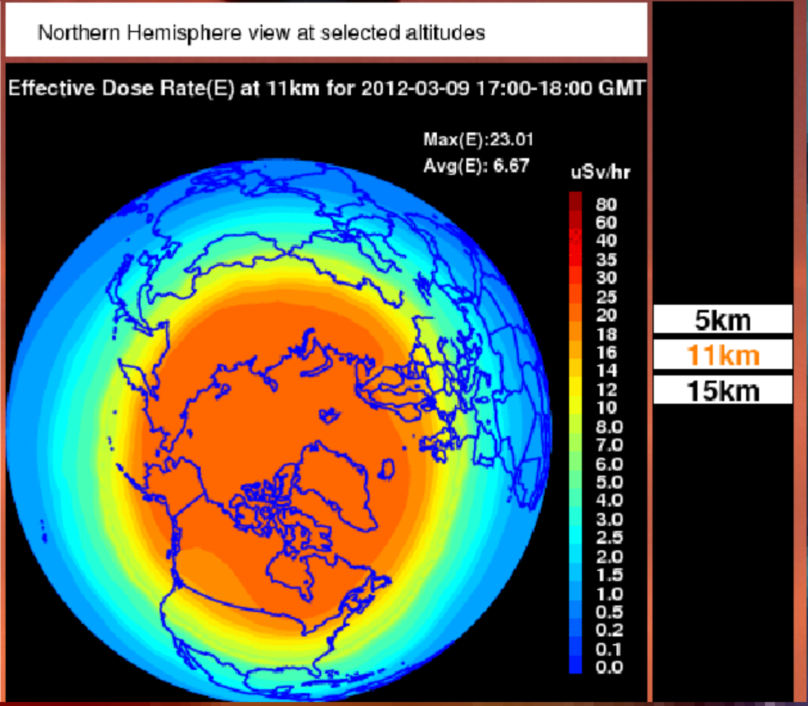
lat	90S-60S	60S-40S	40S-20S	20S-0	0-20N	20N-40N	40N-60N	60-90N
avg	38.00	21.96	4.96	1.54	1.31	3.28	18.81	40.69
max	41.28	40.33	26.17	3.52	4.02	22.16	42.47	43.28

Representative High-Latitude Flights

2012-03-09 17:00-18:00 GMT

Flight Name	Time	Rate[1]	Dose[1]	Safety Signal		
	hours	uSv/hr	mSv	Aircrew[2]	Public[3]	Prenatal[4]
London,GBR - New York,USA	5.50	16.42	0.090			
Chicago,USA - Stockholm,SWE	8.50	20.78	0.177			
Chicago,USA - Munich,DEU	8.50	18.01	0.153			
Chicago,USA - Beijing,CHN	13.50	18.86	0.255			

Signal	Aircrew[5]	Public[6]	Prenatal[6]
	Max_Annual(1000hrs)	one_trip	one_trip
	0-6.0mSv	0-0.330mSv	0-0.167mSv
	6.0-12.0mSv	0.330-0.670mSv	0.167-0.333mSv
	>12.0mSv	>0.670mSv	>0.333mSv

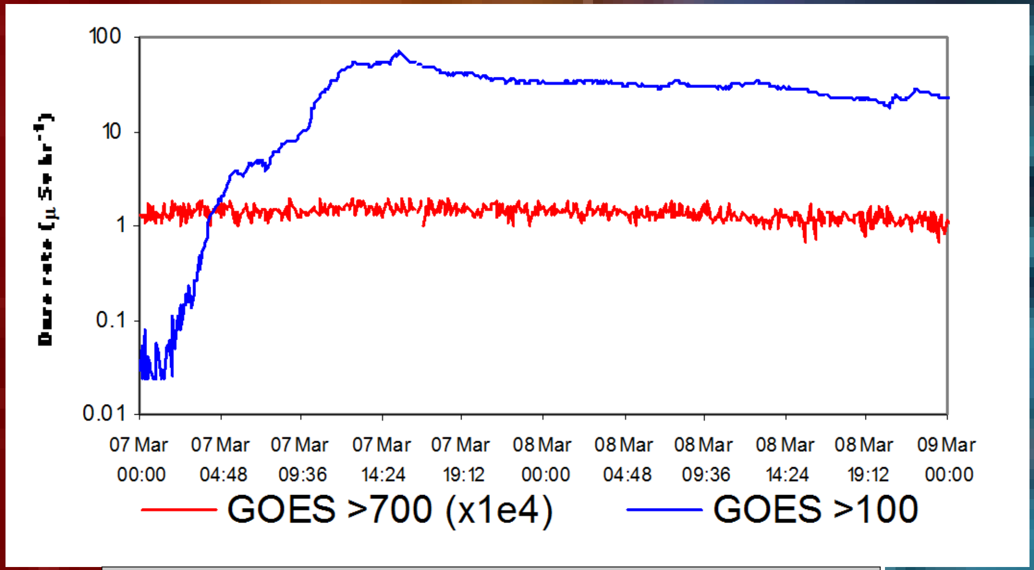


Doses of >20 uSv/hr predicted at high latitude
(2 or 3 times background dose rates)

March 2012 Event

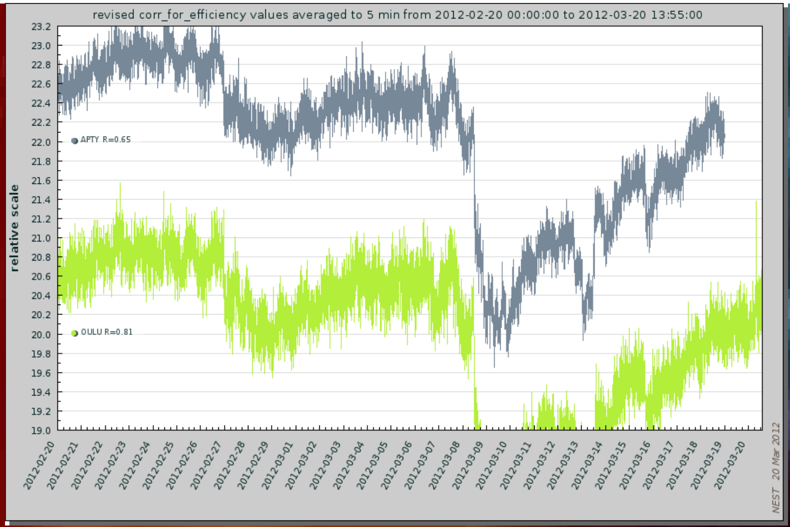
- However… little change in GOES >700 MeV proton flux

(hence no enhancement anticipated at aircraft altitude)



- And…Forbush decrease apparent in ground level neutron monitor data

(hence could expect *decrease* in dose rate)



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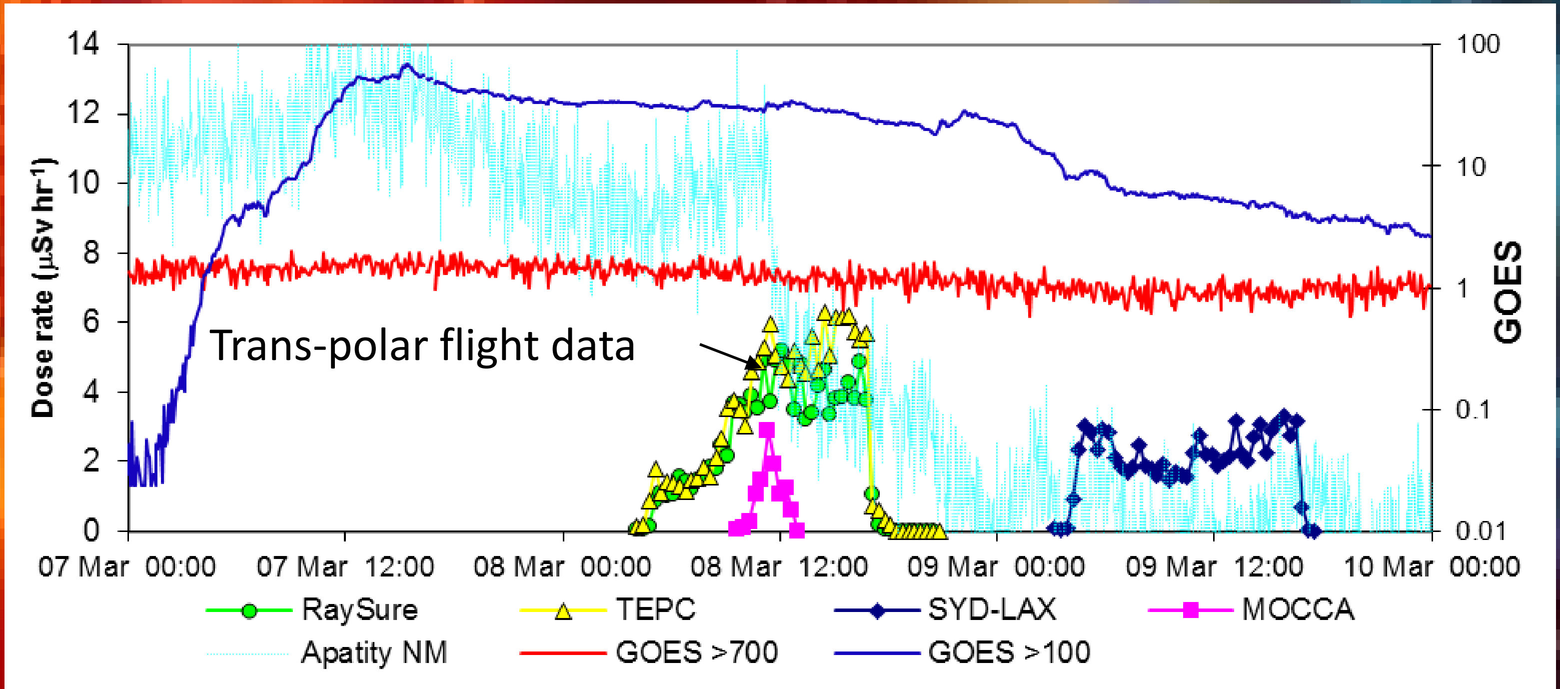
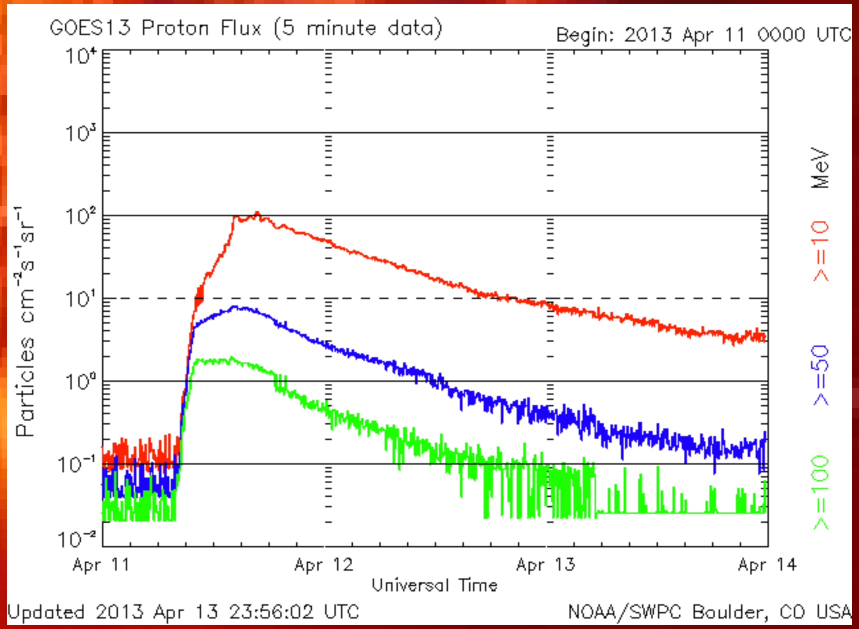
March 2012 Event – RaySure data

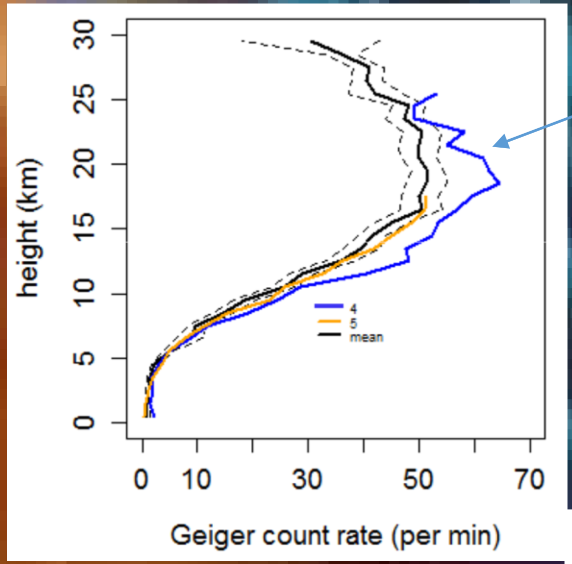
- Three RaySure units recorded data during March SPE
- No evidence of dose enhancement (hint of dose reduction – 38 µSv trans-polar cf. average of 52 µSv)



2. April 2013 Event

- Small S2 event on 11th April 2013
- Higher than average dose rates measured with Geiger counter on balloon flight over UK





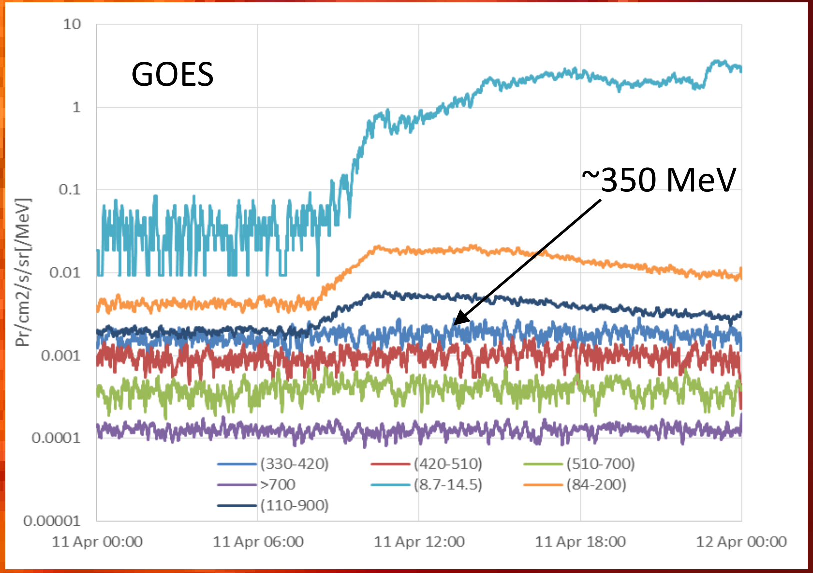
11th April

Nicoll et al. (2014)

However...

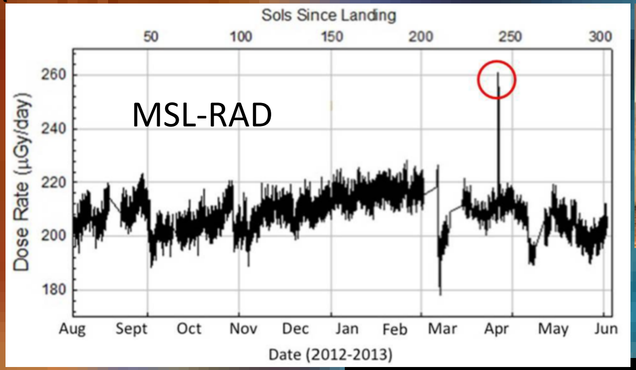
April 2013 Event

- …relatively soft spectrum -> no enhancement in higher energy GOES channels:
- (and no increase in GLNM count rates)

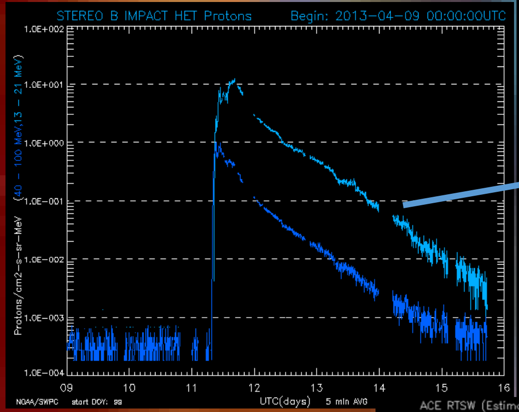


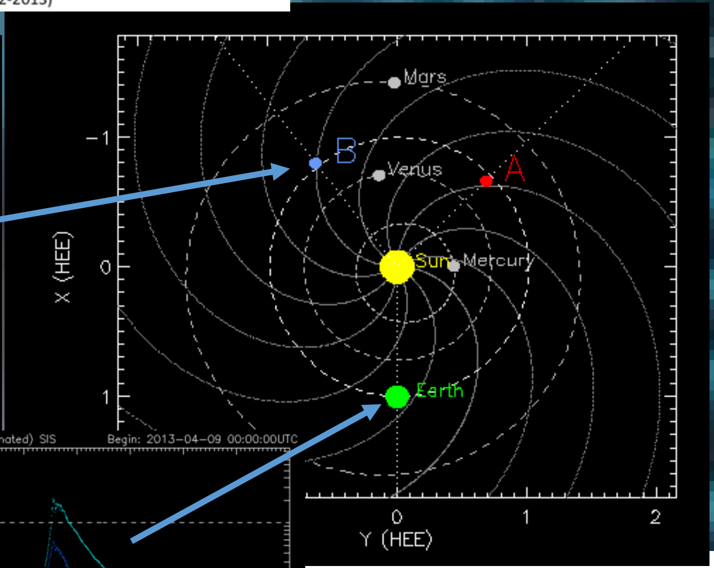
Cf. geomagnetic cut-off energy of measurement location (~2 GeV)
-> dose rates <u>cannot</u> have been due to SPE (rather elevated GCR)

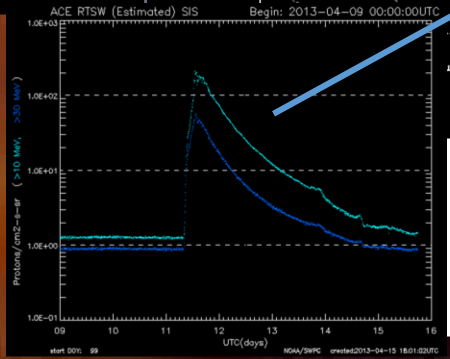
But it was observed on Mars!…
(better connection with event and zero cut-off rigidity)



Hassler et al. (2014)







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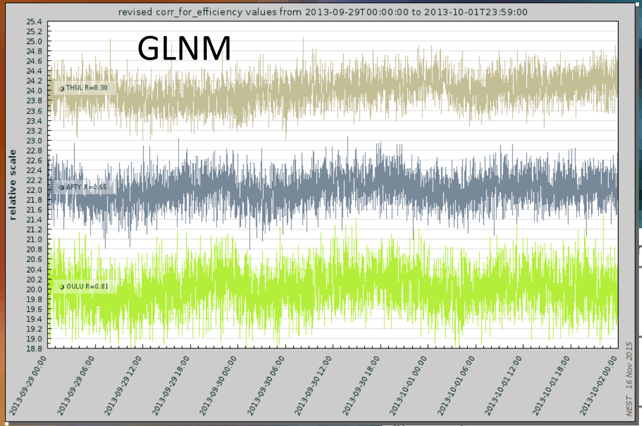
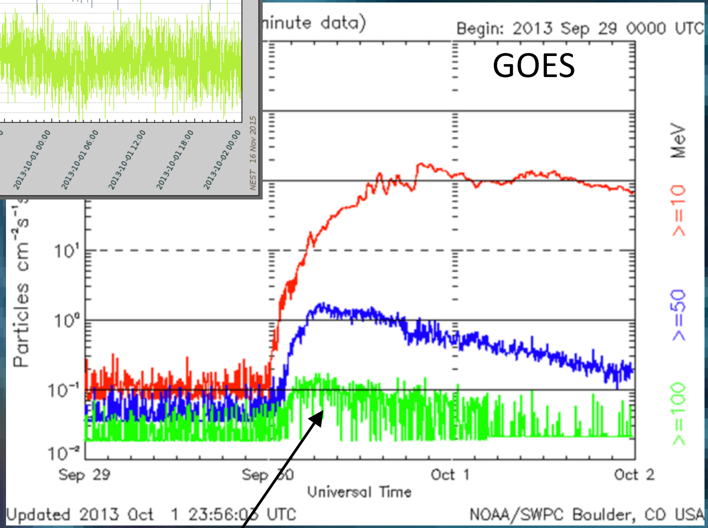
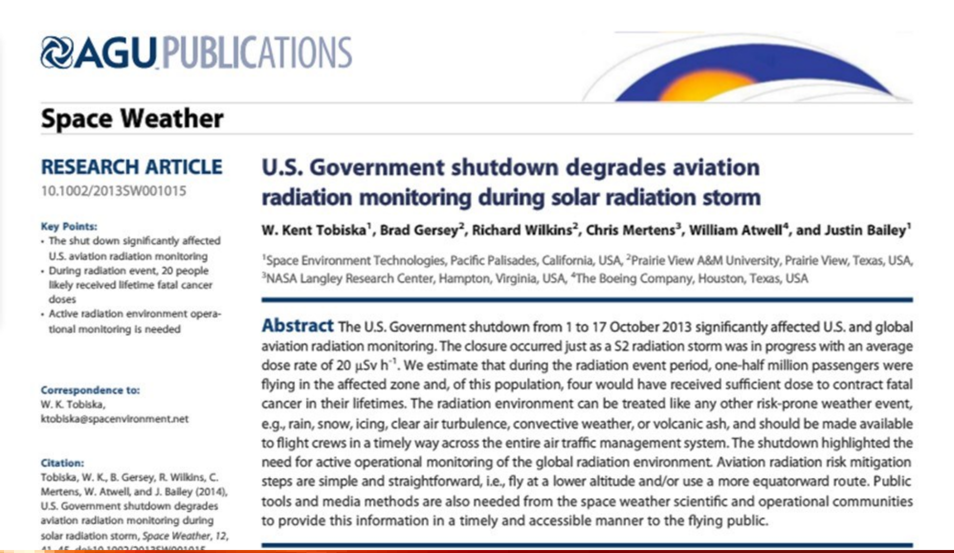
3. September/October 2013 Event

- S2 event on 30th September 2013
- So-called "Government Shutdown event"
- Tobiska et al. (2013) claimed additional dose from event might cause several deaths due to increased exposure for flyers and subsequent cancer risk :







AGU PUBLICATIONS

Space Weather

RESEARCH ARTICLE
10.1002/2013SW001015

Key Points:
- The shut down significantly affected U.S. aviation radiation monitoring
- During radiation event, 20 people likely received lifetime fatal cancer doses
- Active radiation environment operational monitoring is needed

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ktobiska@spacenvironment.net

Citation:
Tobiska, W. K., B. Gersey, R. Wilkins, C. Mertens, W. Atwell, and J. Bailey (2014), U.S. Government shutdown degrades aviation radiation monitoring during solar radiation storm, *Space Weather*, 12,

U.S. Government shutdown degrades aviation radiation monitoring during solar radiation storm

W. Kent Tobiska[1], Brad Gersey[2], Richard Wilkins[2], Chris Mertens[3], William Atwell[4], and Justin Bailey[1]

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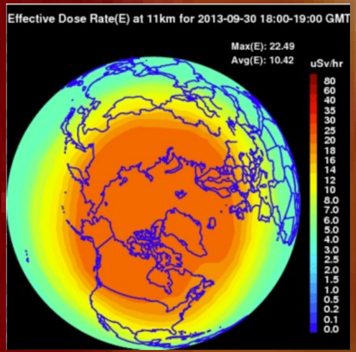
Abstract The U.S. Government shutdown from 1 to 17 October 2013 significantly affected U.S. and global aviation radiation monitoring. The closure occurred just as a S2 radiation storm was in progress with an average dose rate of 20 μSv h⁻¹. We estimate that during the radiation event period, one-half million passengers were flying in the affected zone and, of this population, four would have received sufficient dose to contract fatal cancer in their lifetimes. The radiation environment can be treated like any other risk-prone weather event, e.g., rain, snow, icing, clear air turbulence, convective weather, or volcanic ash, and should be made available to flight crews in a timely way across the entire air traffic management system. The shutdown highlighted the need for active operational monitoring of the global radiation environment. Aviation radiation risk mitigation steps are simple and straightforward, i.e., fly at a lower altitude and/or use a more equatorward route. Public tools and media methods are also needed from the space weather scientific and operational communities to provide this information in a timely and accessible manner to the flying public.

NAIRAS predicted >20 μSv/hr:



However… no significant enhancement in high E protons or GLNM count rates (therefore zero additional dose)

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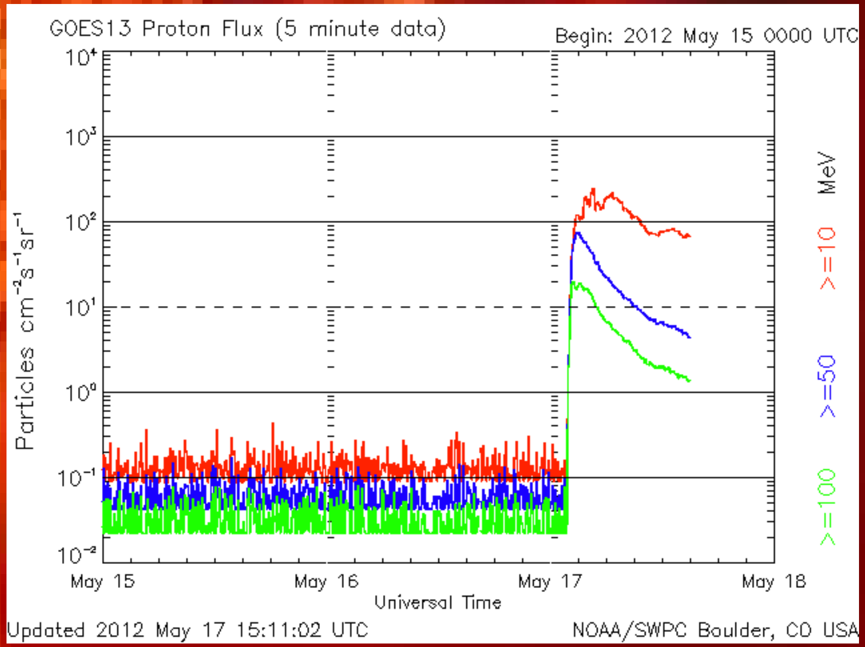
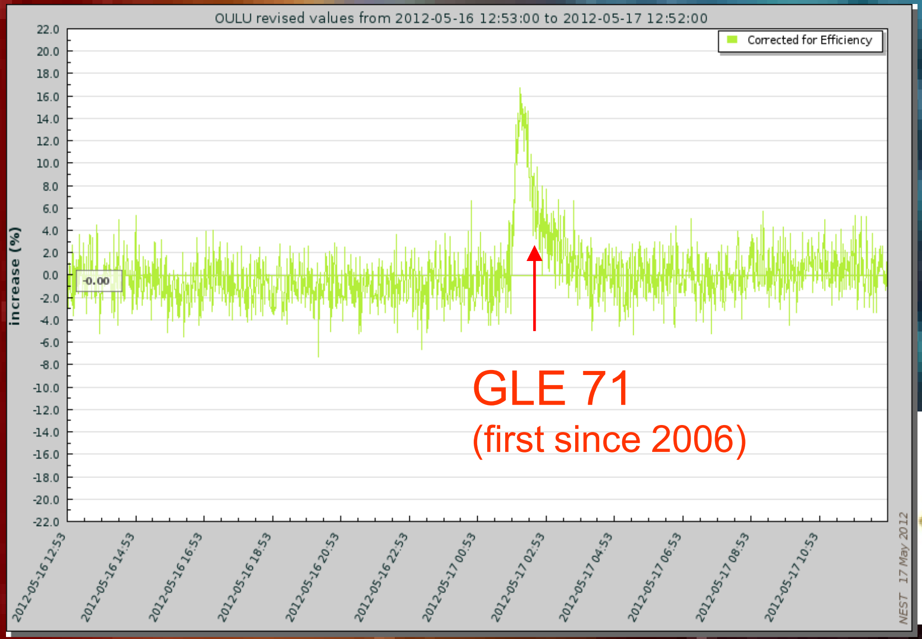
Whereas… May 2012 Event

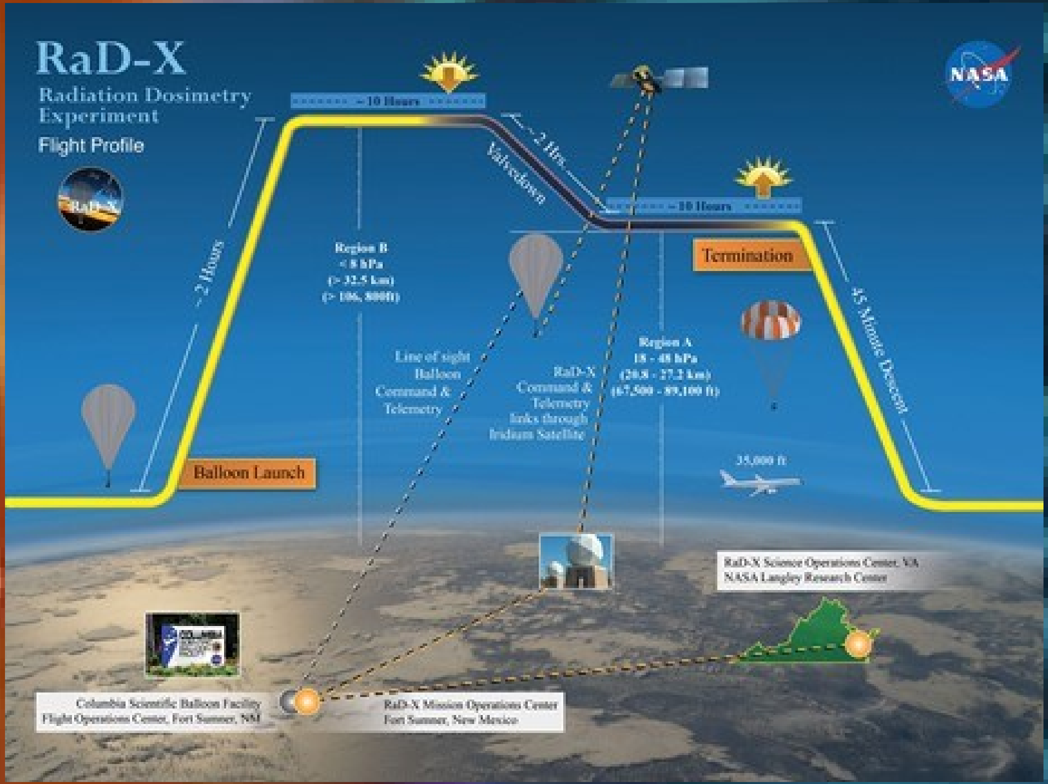
- 'Smaller' than March event in >10 MeV proton flux (SWPC S2 cf. S3)
- Limb event – fast rising, well connected, harder spectrum
- More significant to aviation than March event (but received little press)
- Unfortunately, no RaySure in-flight data



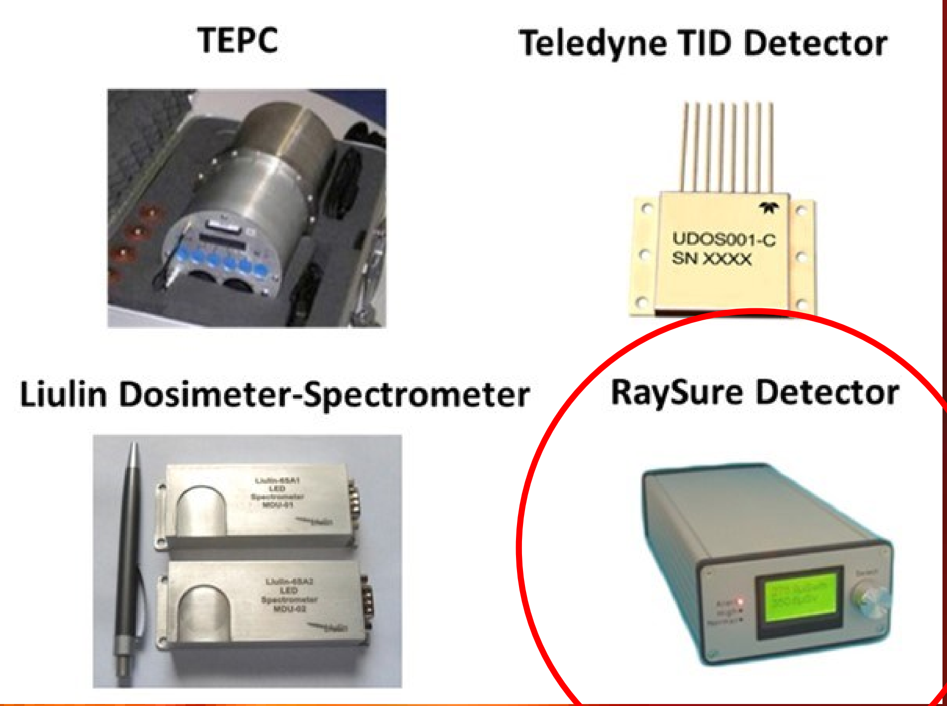


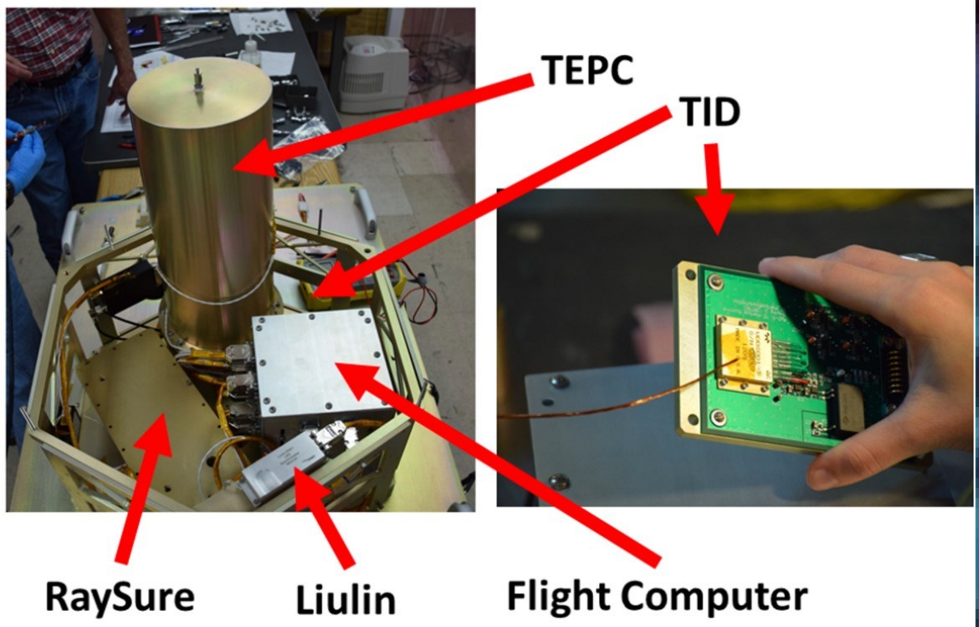
High Altitude Experiments

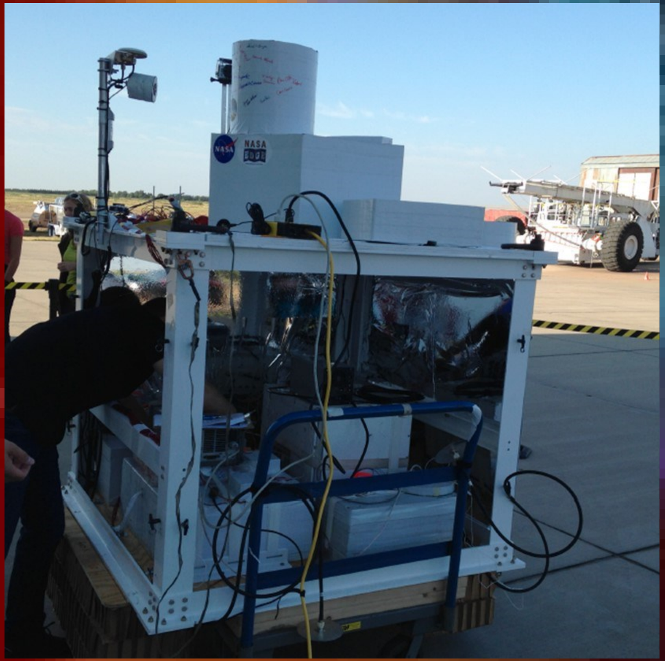
- NASA Radiation Dosimetry Experiment (RaD-X)
- High-altitude balloon carrying four radiation detectors
- Launched September 2015 from Columbia Scientific Balloon Facility, Fort Sumner, NM
- Peak altitude 38 km (125 kft)
  [depth range: >1000 – ~3 g/cm^2]
- Duration ~22 hours



RaD-X Payload







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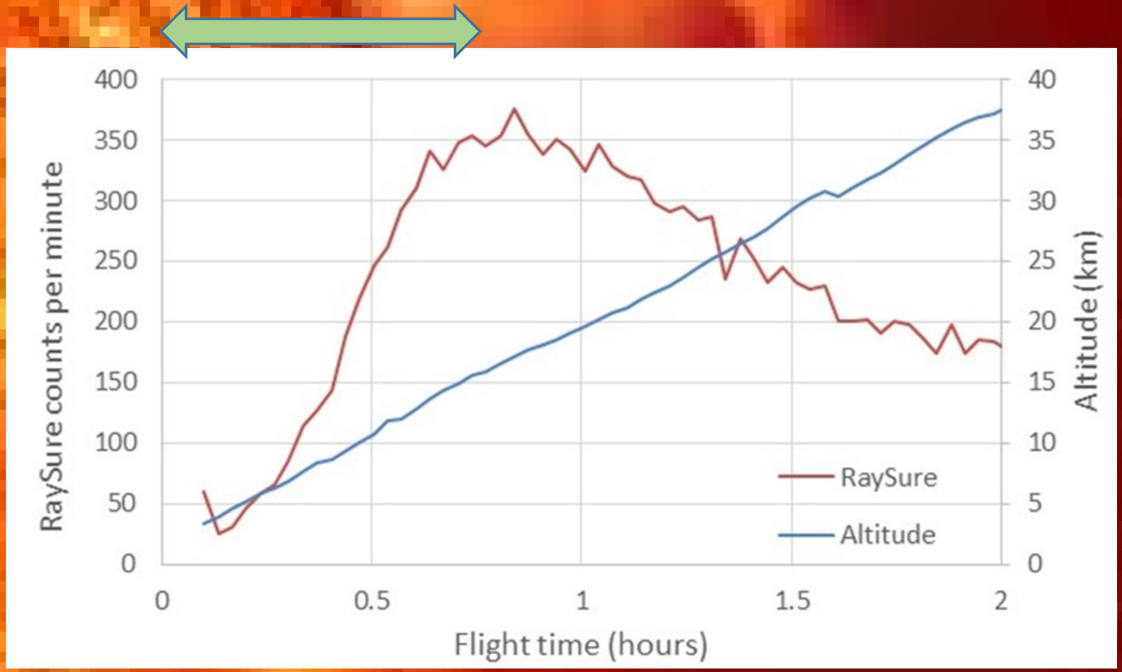
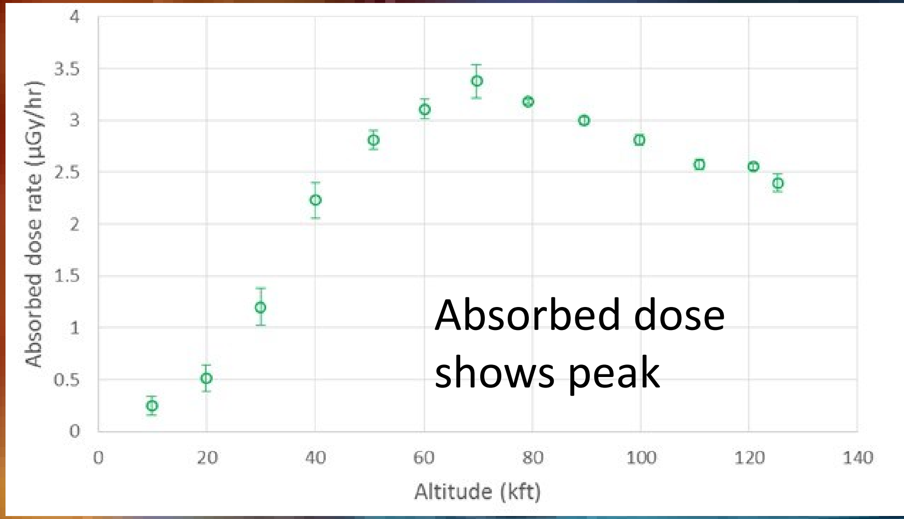
RaD-X Launch

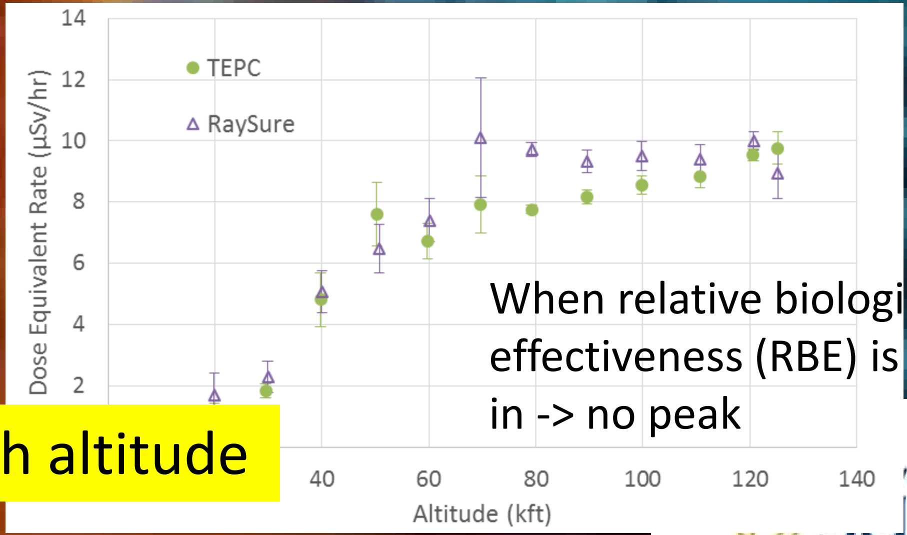
Dose Rate vs Altitude

Total count rate increases with altitude up to ~18 km (60,000 feet), then anti-correlated





Absorbed dose shows peak



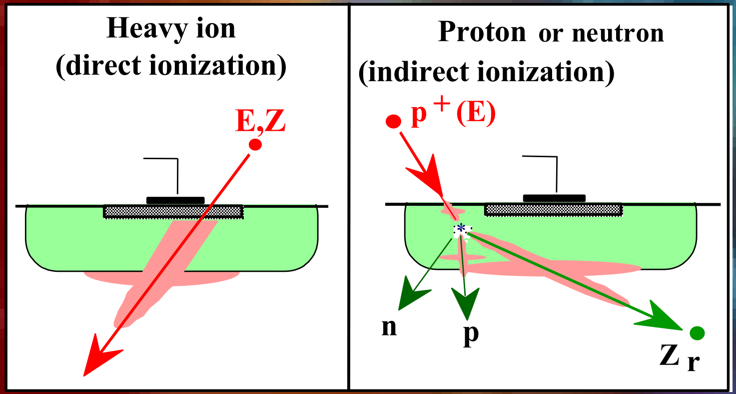
When relative biological effectiveness (RBE) is factored in -> no peak

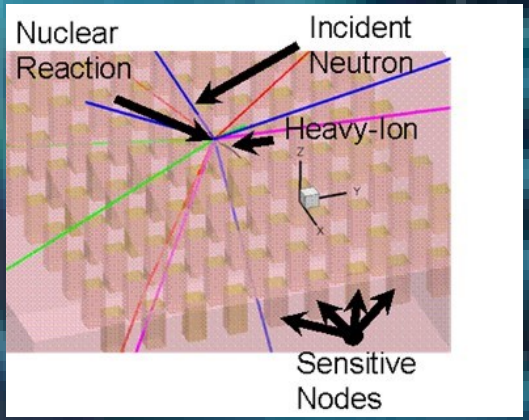
Primary Cosmic Rays matter at high altitude

Single Event Effects (SEE)

- Dose to humans on flights often gets most attention, but threat to avionics is arguably more significant
- Single particles can deposit charge in sensitive volumes of semiconductors, leading to a variety of single event effects:
  - Single Event Upset (SEU)
  - Single Event Latchup (SEL)
  - Single Event Gate Rupture (SEGR)
  - Single Event Burnout (SEB)
  - And an increasing variety of others

SEE basic mechanisms:





Dominant in Space

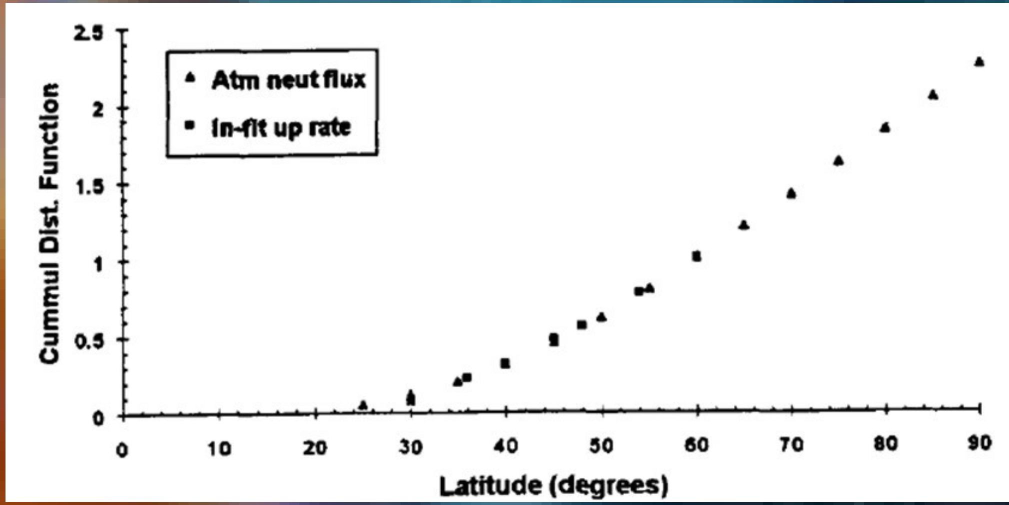
Dominant for aviation
(particularly neutrons)

NB SEE also occur at ground level, e.g. HV diodes in electric trains in 1990s (also concern for civil nuclear industry)

Flight Experience of SEE

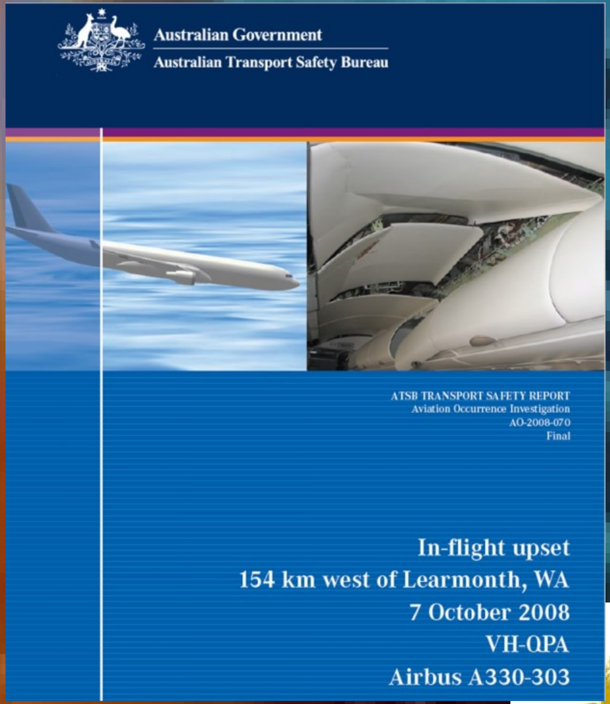
- PERFORM computer withdrawn for tests in 1991 following accumulation of errors in SRAM memory.
- More than one upset per flight in 280 64K SRAMs on Boeing E-3 AWACS and NASA ER-2.
- Autopilot design altered after faults (every 200 flight hours) shown to correlate with altitude and latitude.
- Saab CUTE experiment in 1996 showed upset every 200 flight hours in 4 Mbit SRAM. 2% are multiple-bit upsets.
- At least 3 major equipments with latch-up problem (including burn out)- probable cause of an emergency landing due to smoke in cockpit.

Normand & Baker (1993) observed correlation between SEU rates and neutron flux (latitude)



Example: Qantas Flight 72

- 7th October 2008 QF72 experienced several anomalies in AoA data supplied electronically to the flight computer, leading to pitching manoeuvres that caused serious injuries
- Single event effect identified as plausible cause by process of elimination (but not confirmed)
- Not an ESW-related event, however…
- Investigation revealed neutron-induced susceptibility of air data inertial reference unit (ADIRU)
- “No reference to SEU” during certification of A330/A340 aircraft (SEE in avionics only became apparent in 1990s)
- Airbus amended its standard in 2007 (mentions SEE and references IEC)



Standards

- Various International Standards / Working Groups cover single event effects:
- USA:
  - JEDEC JESD89A "Measurement and reporting of Alpha Particle and Terrestrial Cosmic Ray-Induced Soft errors in Semiconductor Devices "
  - AVSI72 "Mitigating Radiation Effects on Current & future Avionics Systems"
  - SAE ARP4761 "Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment"
  - SAE AIR6219 "Incorporation of Atmospheric Neutron Single Event Effects Analysis into Safety Assessment"
- Other:
  - IEC 62396 "Process Management for Avionics: Atmospheric Radiation Effects"

Only one (yet) to cover ESW

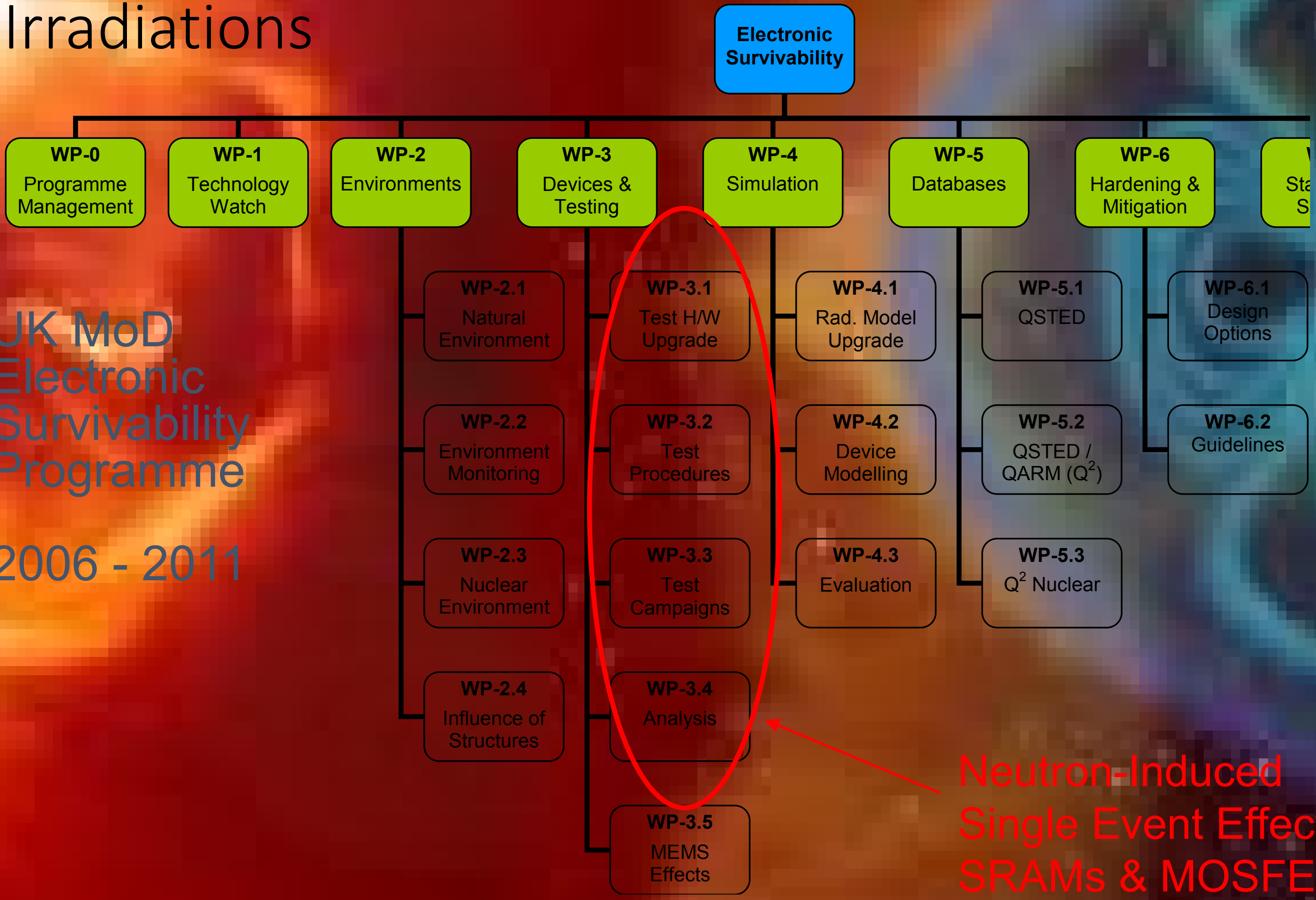
- Also relevant:
  - EASA Proposed CM-AS-004 "Single Event Effects (SEE) Caused by Atmospheric Radiation"

Testing

Component Irradiations

UK MoD Electronic Survivability Programme

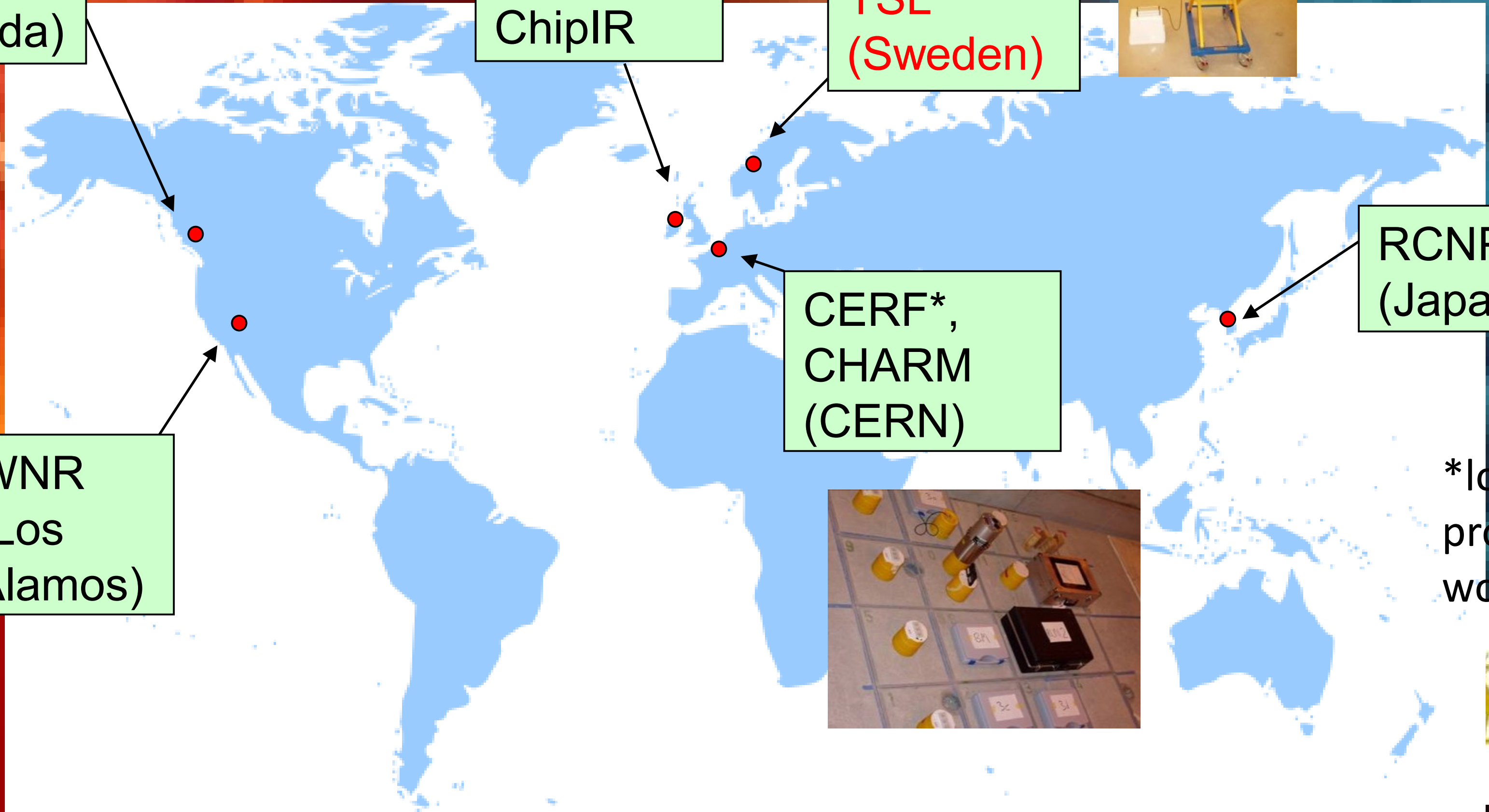
2006 - 2011



Neutron-Induced Single Event Effects in SRAMs & MOSFETs

Test Facilities

- Spallation neutron test facilities needed to recreate atmospheric neutron environment (few available)



*low flux (can't provide 10^5 n/cm^2/s) worst case

Meanwhile, Back in Space

- Spacecraft (and Astronauts) face multiple radiation threats
  - SPEs (as discussed)
  - Background Galactic Cosmic Rays (GCR)
  - Trapped Radiation – Van Allen Belts

- Also, many varieties of radiation effect
  - Single Event Effects (SEE) - electronics
  - Total Ionising Dose (TID) - electronics
  - Displacement Damage Dose (DDD) - mainly solar panels
  - Surface Charging – mainly solar panels
  - Internal charging – dielectric materials and isolated conductors

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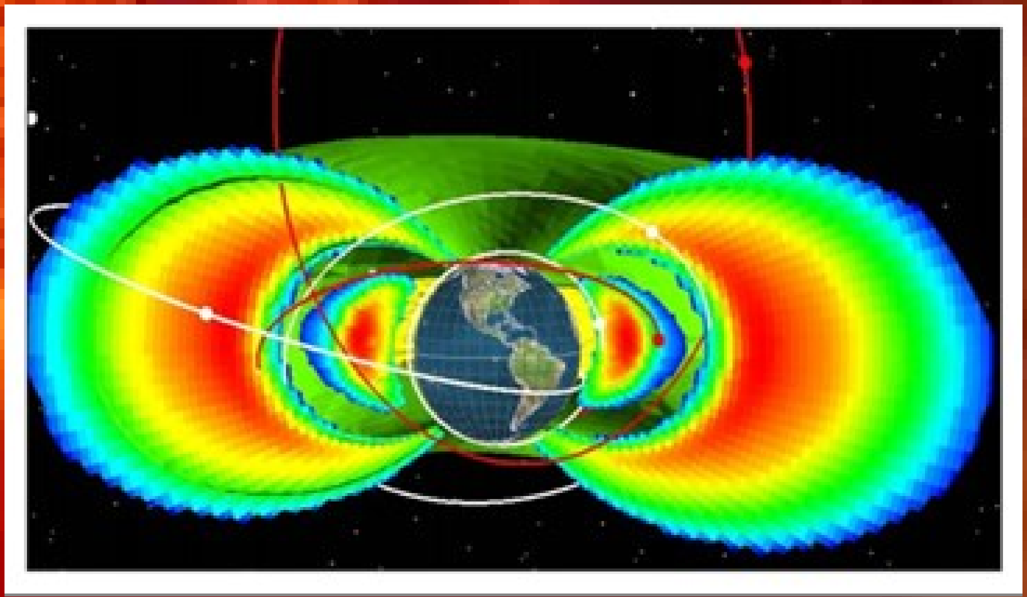
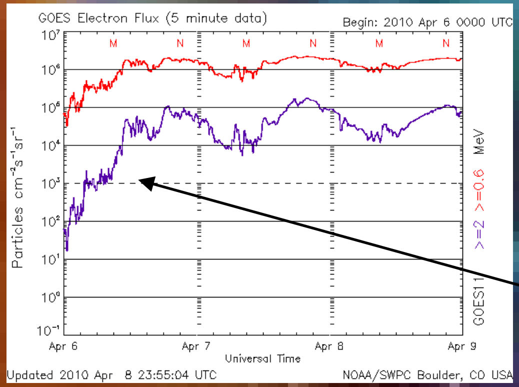
Earth's Radiation Belts

- Van Allen Belts discovered by first US Satellite, Explorer 1, in 1958
- Inner & Outer Electron Belt (energies up to ~10 MeV), single proton belt (10s – 100s MeV)
- Communication and Navigation (GPS) satellites sit right in the heart of outer electron belt
- Solar activity 'pumps' up the radiation belts to greatly enhanced intensities
- Surrey involved with EU-funded (☹ !!!) Spacestorm project, studying extreme storms



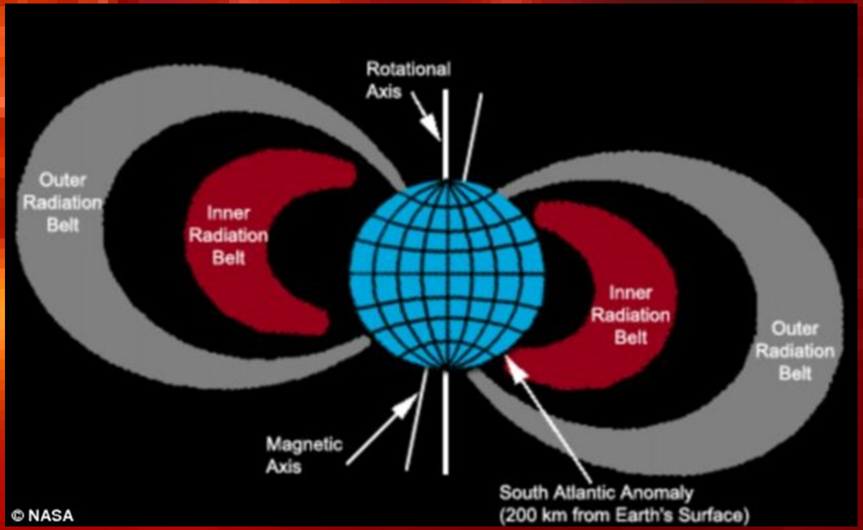


e.g. April 2010:

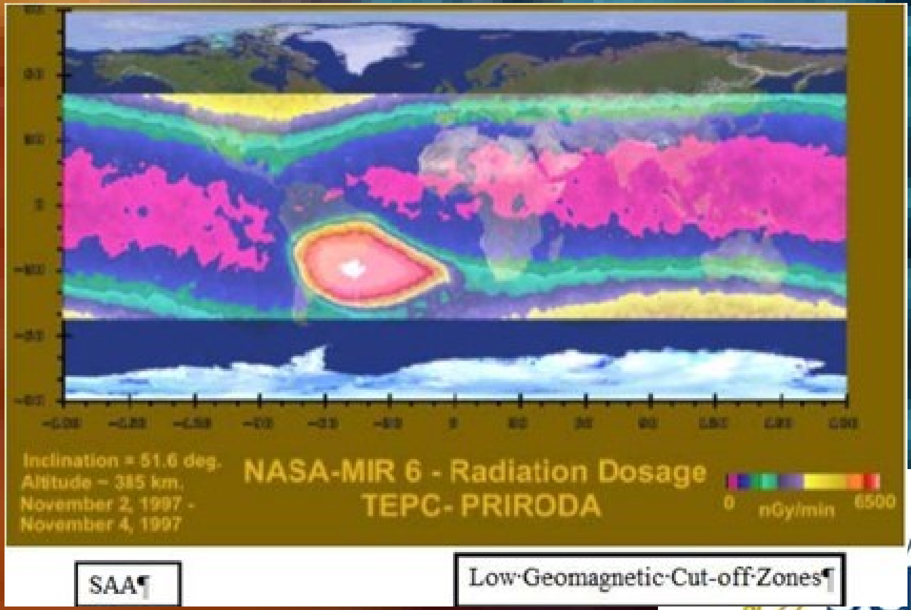
>2 MeV flux at GEO increases by ~4 orders of magnitude in a few hours!

South Atlantic Anomaly (SAA)

- Foremost risk to low Earth orbit (LEO) satellites, and astronauts on ISS is SAA
- SAA occurs due to offset between Earth's rotational and magnetic dipole axes
- Increased SEE occurrence in SAA
- Astronauts avoid EVAs during passage (!)

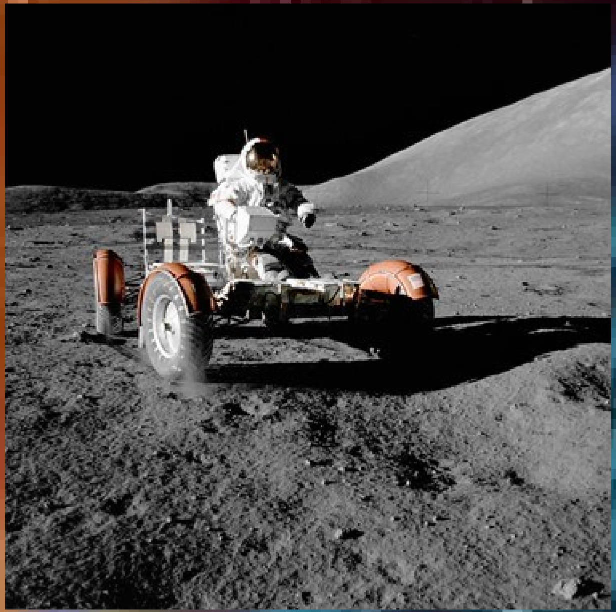


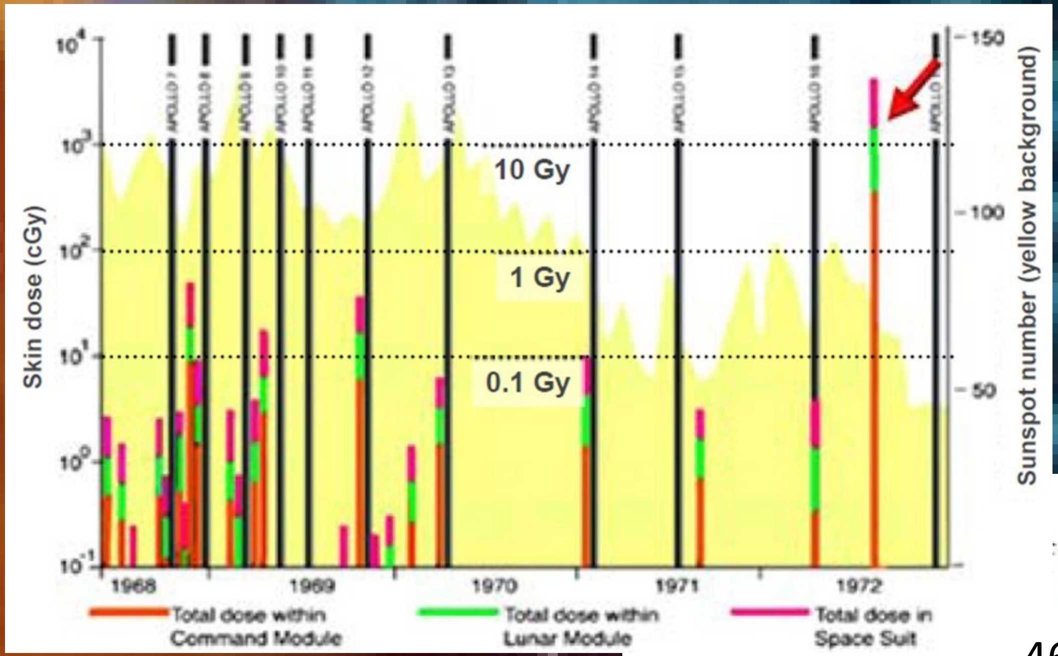
Dose measured on MIR:



Near Miss II (Apollo)

- Large SPE occurred in August 1972
- In between Apollo 16 (April 1972) and Apollo 17 (December 1972)
- No protection from magnetosphere
- Dose estimates vary but could have been lethal, especially for EVA
- A warning for future Moon or Mars manned missions

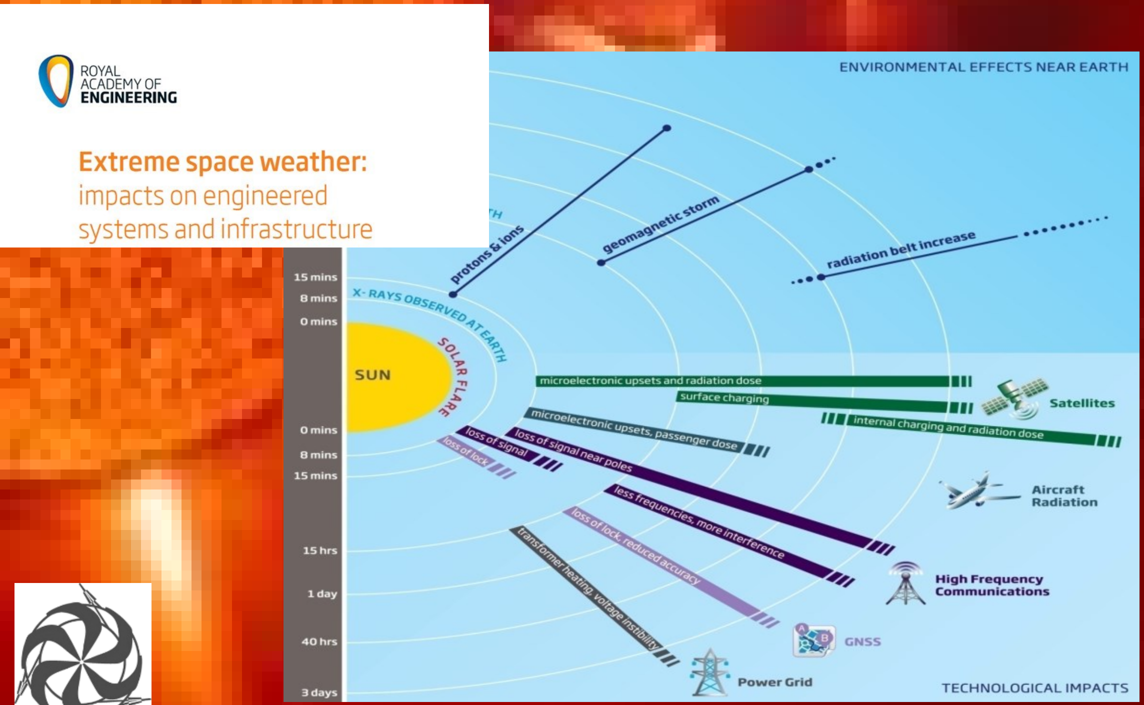




Hellweg (2013)

Recent UK Activity on Space Weather

- Royal Academy of Engineering (RAE) Study, 2013
- Considered multiple aspects of extreme space weather on infrastructure
- Extreme Space Weather added to National Risk Register



Impact					
Catastrophic (5)				Pandemic influenza	
Severe (4)			Coastal flooding Widespread electricity failure		
Moderate (3)		Major transport accidents Major industrial accidents	Effusive volcanic eruption Emerging infectious diseases Inland flooding	*Severe space weather* Low temperatures and heavy snow Heatwaves Poor air quality events	
Minor (2)		Public disorder Severe wildfires	Animal diseases Drought	Explosive volcanic eruption Storms and gales	
Limited (1)			Disruptive industrial action		
Probability in next 5 yrs	1-in-20000 to 1-in-2000	1-in-2000 to 1-in-200	1-in-200 to 1-in-20	1-in-20 to 1-in-2	> 1-in-2

Volcano Analogy

- 2010 Eruption of Eyjafjallajökull in Iceland grounded flights for ~ 1 week
- Largely unnecessarily – poor understanding of ash effects on aircraft, poor preparedness
- UK MET Office now has bespoke aircraft with monitoring equipment (they also have a RaySure detector!)
- We are lobbying Government to fund research to improve preparedness for extreme SPE
- Effects on Aviation very uncertain (SEE likely to be more significant than dose to passengers)
- "If you think ~~education~~ research is expensive, try ignorance!"

My Own View (literally)

Peaceful isn't it?

Eyjafjallajökull, May 2016

Let’s not make the same mistake – we should all care about Space Weather!