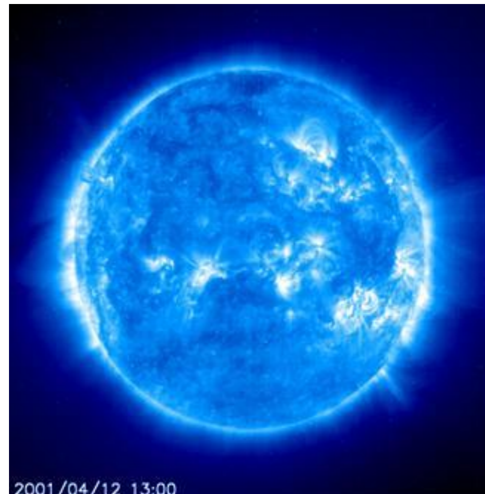
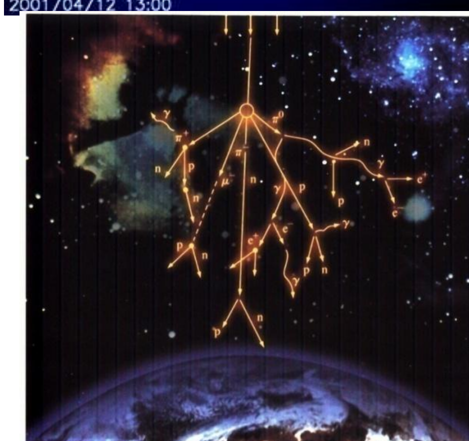
High Energy Radiation Impacts on Ground Level, Aircraft and Space Electronics The Need for an L5 Measurement Package

11-14 May 2015
L5 Consortium Meeting
London

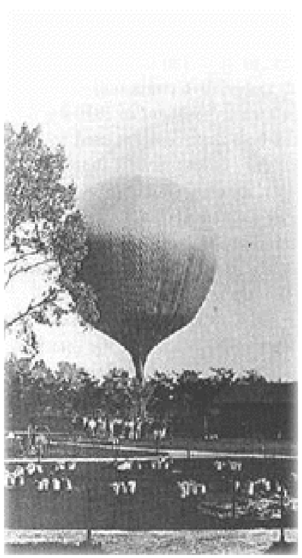



K A Ryden
Prof. C. S Dyer*
University of Surrey (Space Centre)
*** and CSDRadConsultancy Ltd**

“Sic Itur Ad Astra.”

Cosmic Rays



Hess balloon flight in 1912 showed atmospheric ionisation increased with altitude.

In 1936 Pfotzer showed this reached a maximum at about 60,000 feet due to build up of secondaries.

High altitude balloons and spaceflight showed primaries to be very energetic ions (GeV to 10^{12} GeV) of all the elements (85% protons, 14% helium, 1% heavier. e.g. C.N,O, Fe).

Originate in supernova and travel the galaxy for ten million years on average before intersecting the earth.

Intensity varies by about a factor of three in antiphase with the eleven year solar cycle. Increasing solar activity keeps the lower energy cosmic rays out of the heliosphere.

Sporadic solar particle increases occur around solar maximum. First discovered by ground level ionisation chambers in 1942 to 1946 and associated with solar flares by Forbush i.e. space weather issue.

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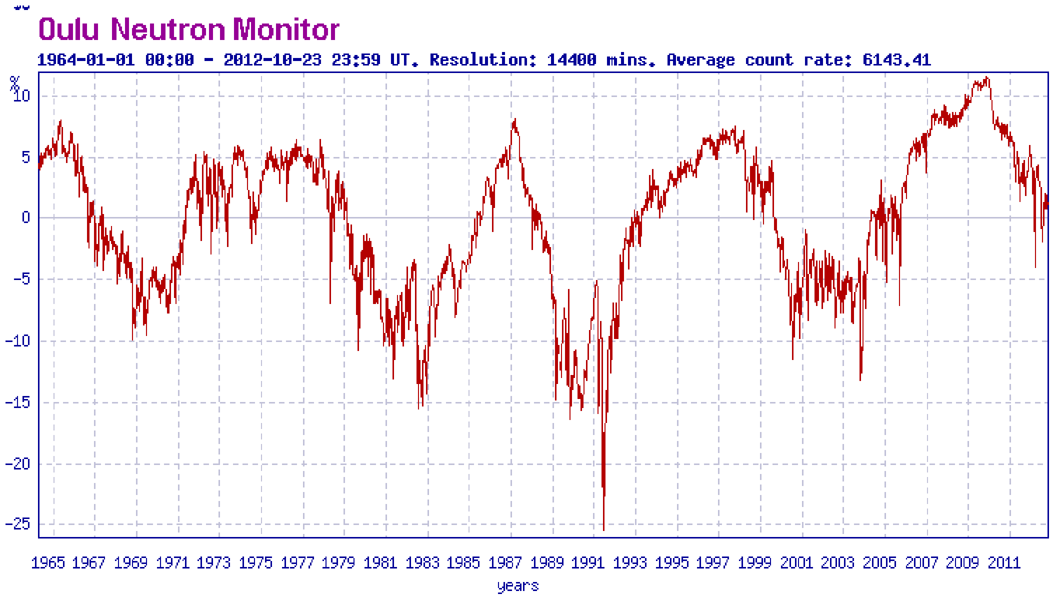
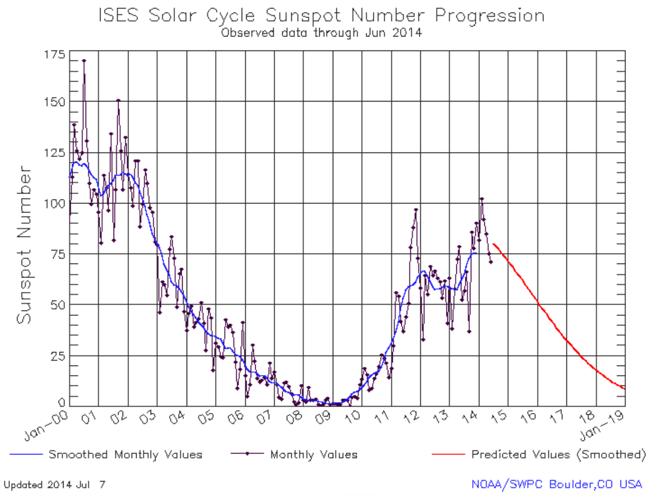
Atmospheric Neutrons Are Produced By Cosmic Ray Showers

The Recent Deep Solar Minimum Gave High Cosmic Ray Fluxes





Ground level ionisation chambers (from 1942) & neutron monitors (from 1948) also showed solar particle increases.

71 ‘Ground level Enhancements’ (GLEs) to date. Last was 17 May 2012. On average ~1 per year.

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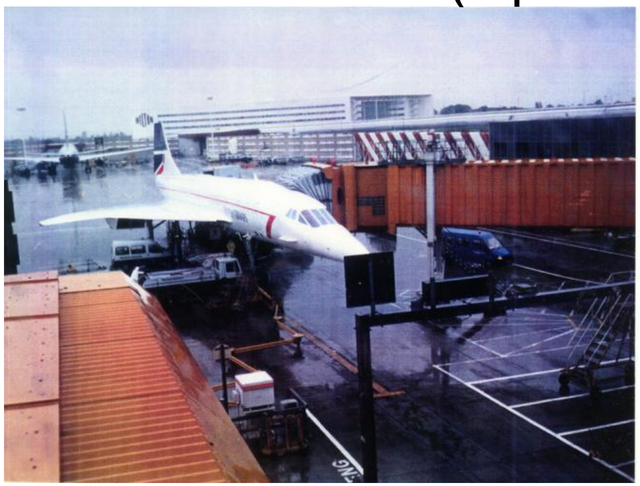
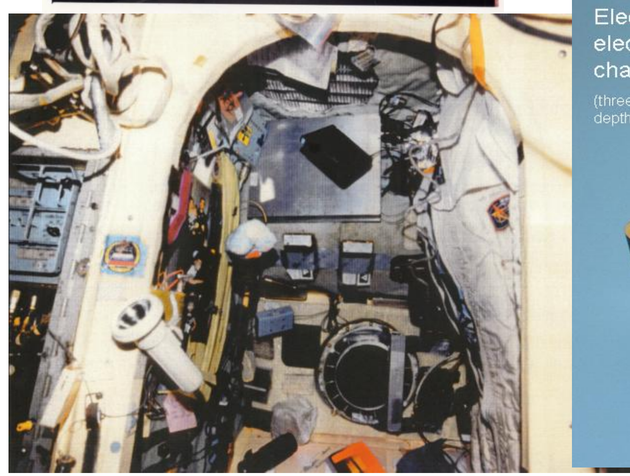
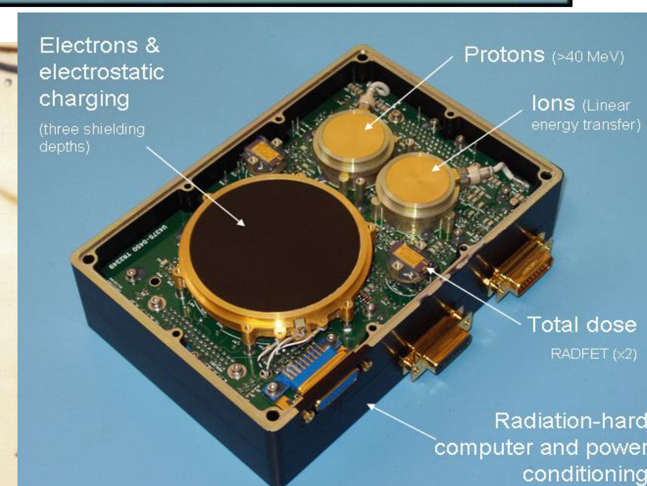
UK pioneering research

CREAM on Concorde 1988-1992 , many subsonic flights, Shuttle & Mir 1989-1998, CREDO on UoSat-3, Apex, STRV, MPTB, Merlin/CREDANCE on GIOVE-A , future LWS/SET (Farnborough research team now at University of Surrey) .

S24 on HEOS 1968-70 (Imperial College)







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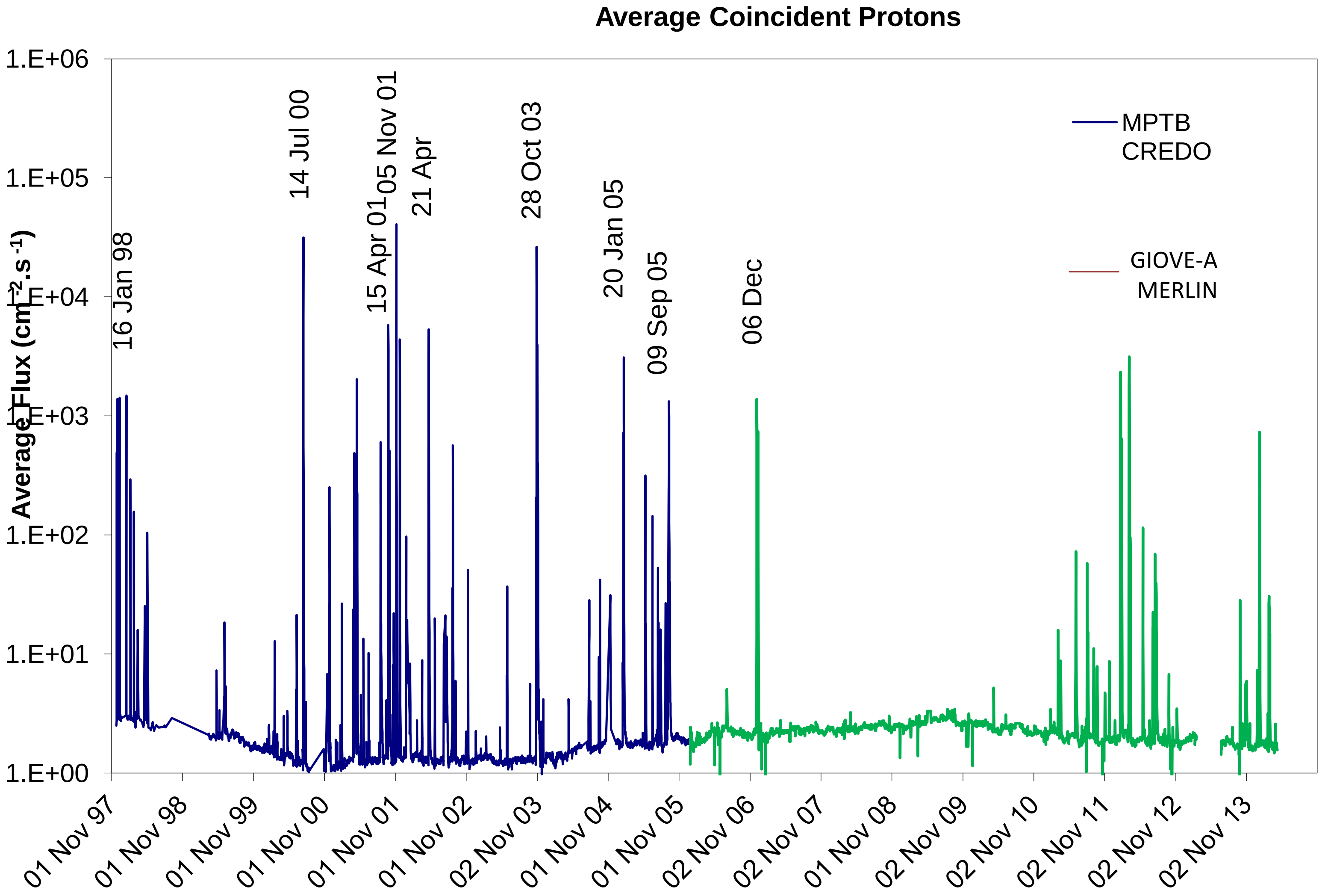
Recent Cosmic Ray & Solar Particle Fluxes (>38 MeV) As Measured By UK Monitors CREDO on MPTB and Merlin on GIOVE-A



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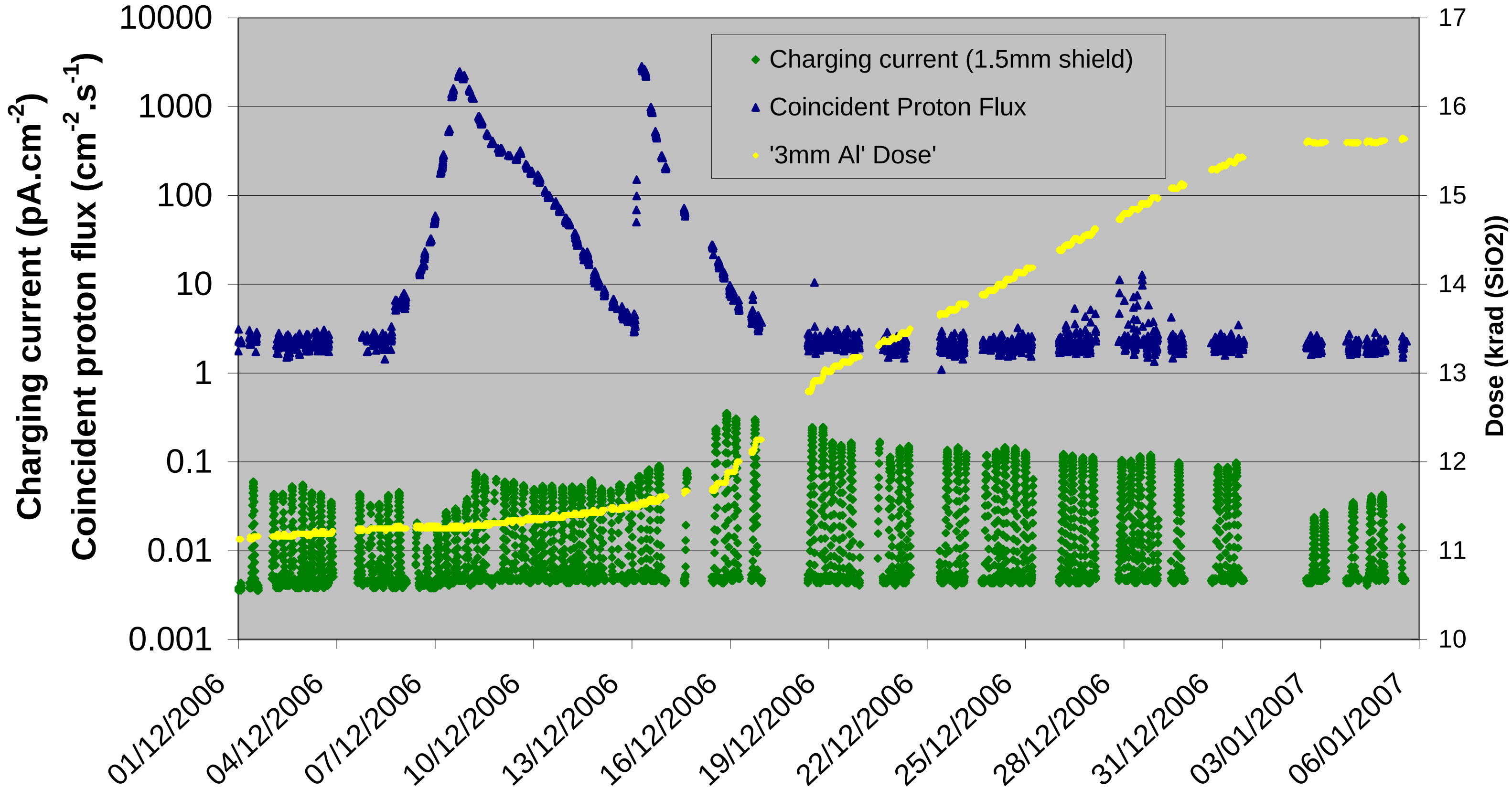
December 2006 SEP Event & Electron Enhancement from Merlin on GIOVE-A



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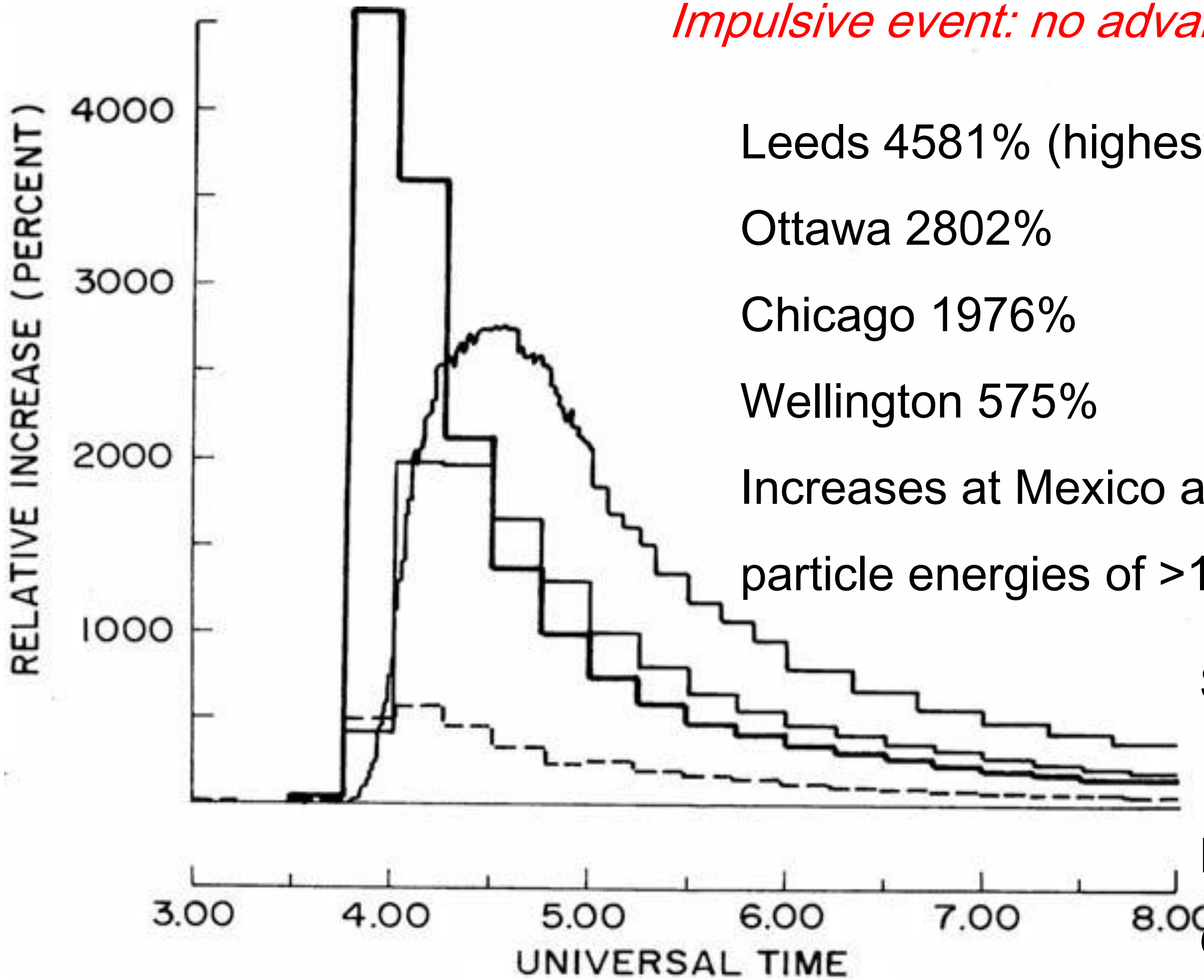
Ground level neutron increases for 23 February 1956



Impulsive event: no advance warning!

Leeds 4581% (highest on record)

Ottawa 2802%

Chicago 1976%

Wellington 575%

Increases at Mexico and Peru indicated

particle energies of >14 GeV

Solar flare 0334-0340 UT

at 85W.

Particle onset 0345 UT but

Only 15 min resolution.

Particle max 0345-0400 UT

From Rishbeth, Shea and Smart, Adv Sp Res 2009

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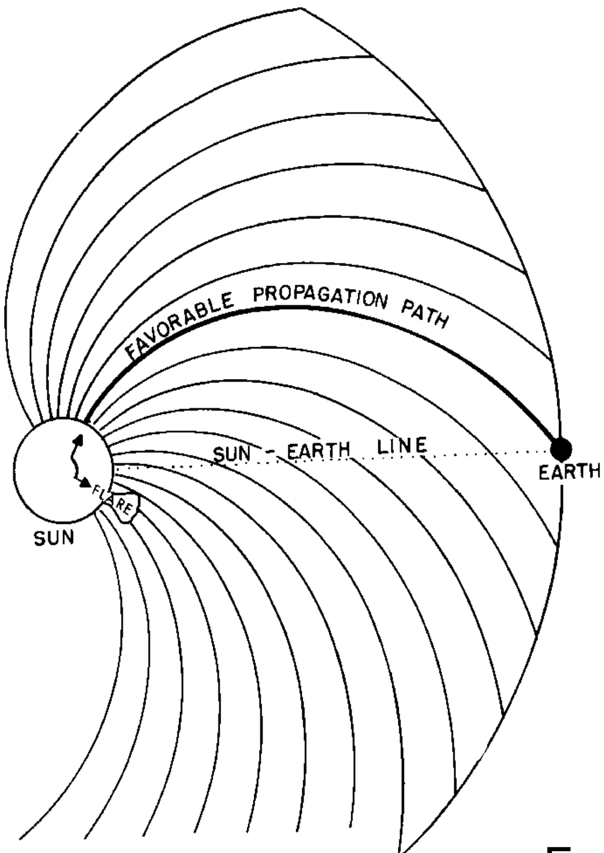
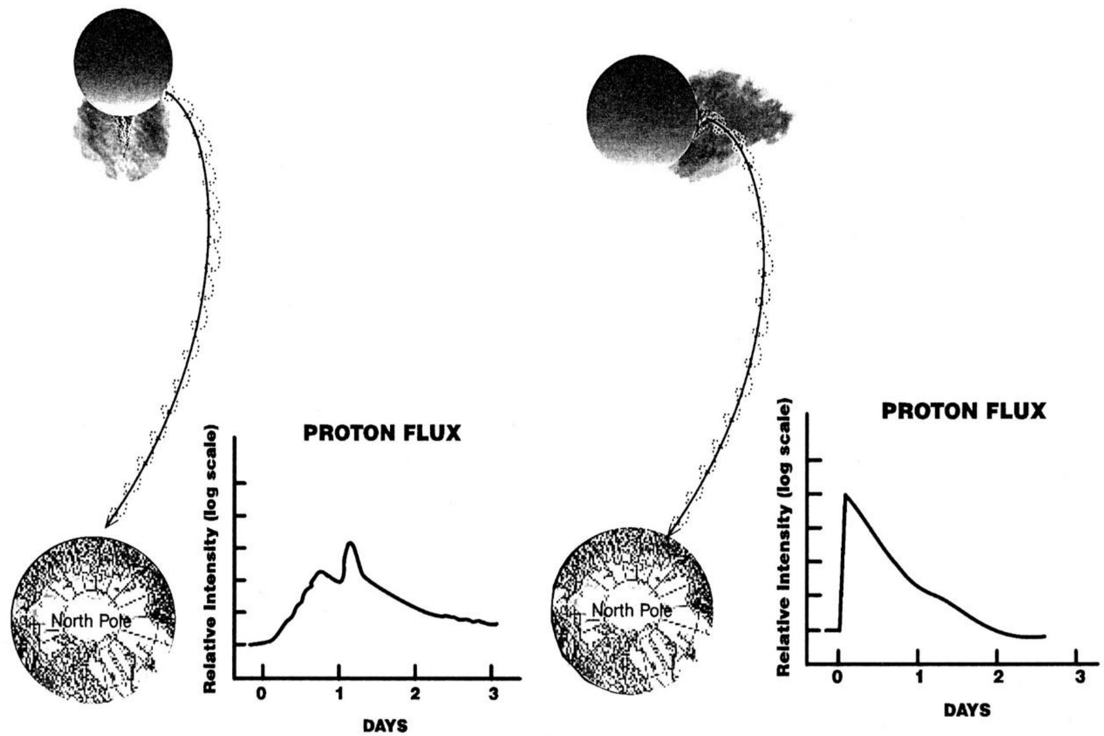
Particle Flux & Time Profile Depend On Event Location On Sun





From Shea and Smart

First evidence for Parker spiral

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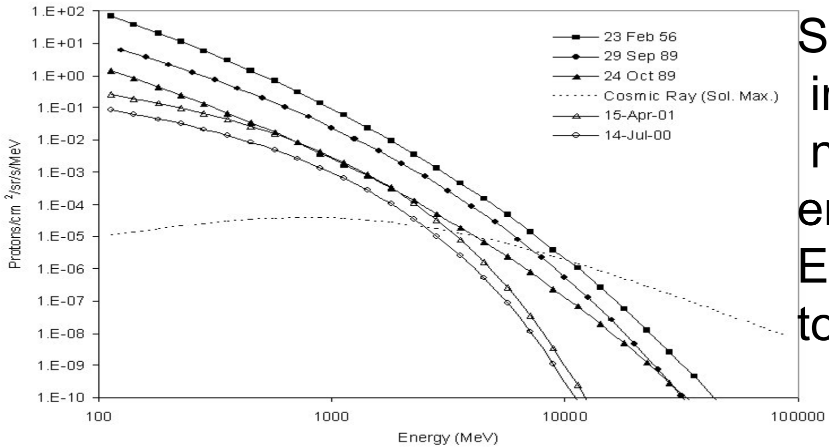
High Energy Particle Events

- Events with particles above 300 MeV are important for GLEs, aircraft and spacecraft .
- We need to better understand their production and propagation
- McCracken, Moraal, Shea (Ap.J., Dec 2012) using database of 71 GLEs from 1942 to 2012 showed importance of Impulsive Ground Level Enhancements
  - 9 largest GLEs originate from > 24W;
  - Most show initial anisotropic, impulsive event rising in 3 to 7 minutes and falling in similar timescale;
  - Often these are followed by a slower, more isotropic phase lasting hours.
  - Events include Feb 56 (85W), Sept 89 (105W), Oct 89 (57W), Apr 01(85W), Jan 05(58W), Dec 06 (24W).



Spectra inferred using satellite detectors in conjunction with ground level neutron monitors. Difficult without high energy channels on spacecraft. Extrapolation beyond 300 MeV is subject to huge errors.

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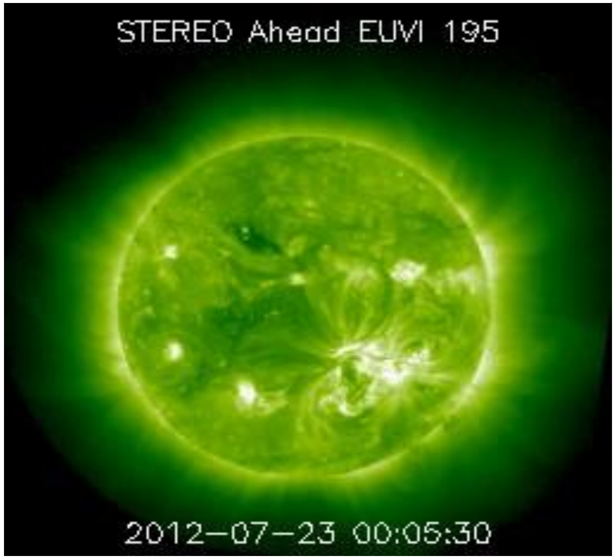
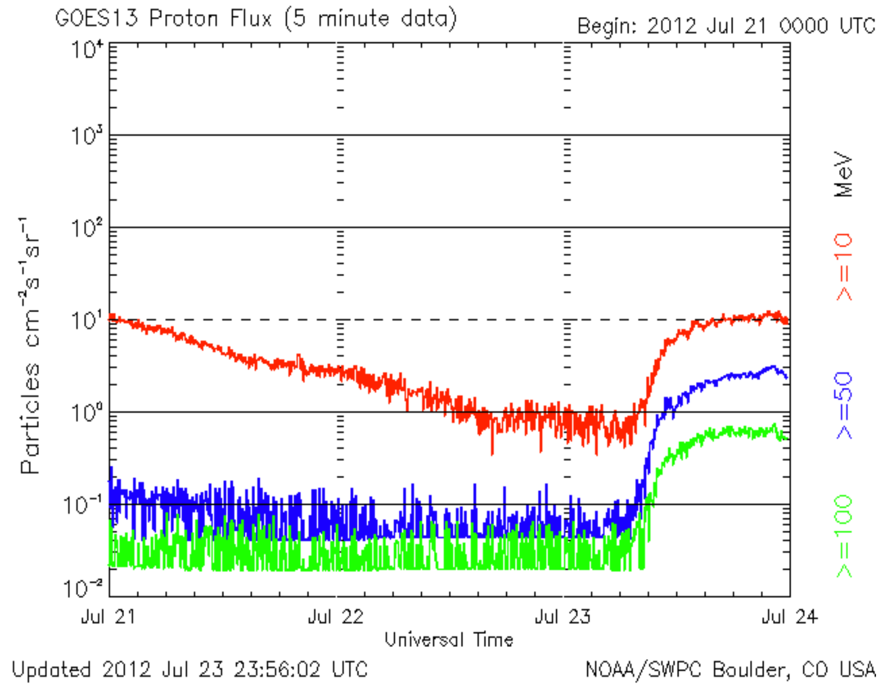
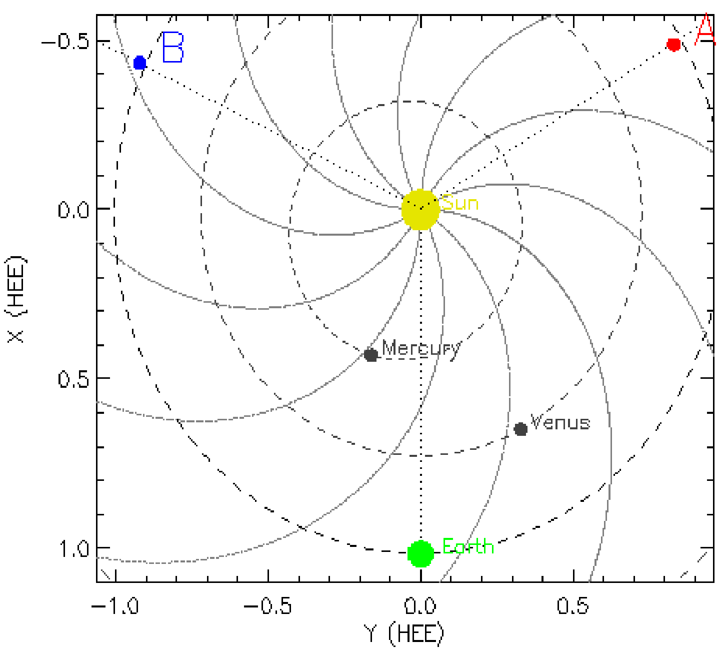
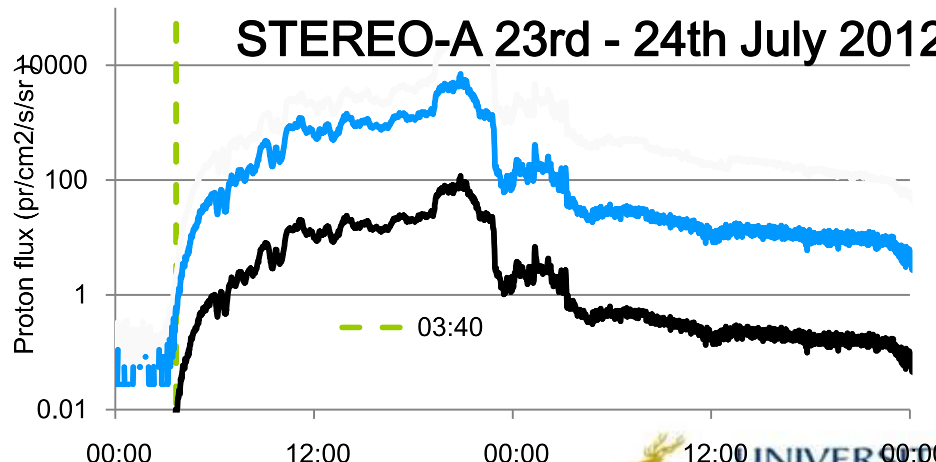
23 July 2012 SPE from STEREO & GOES









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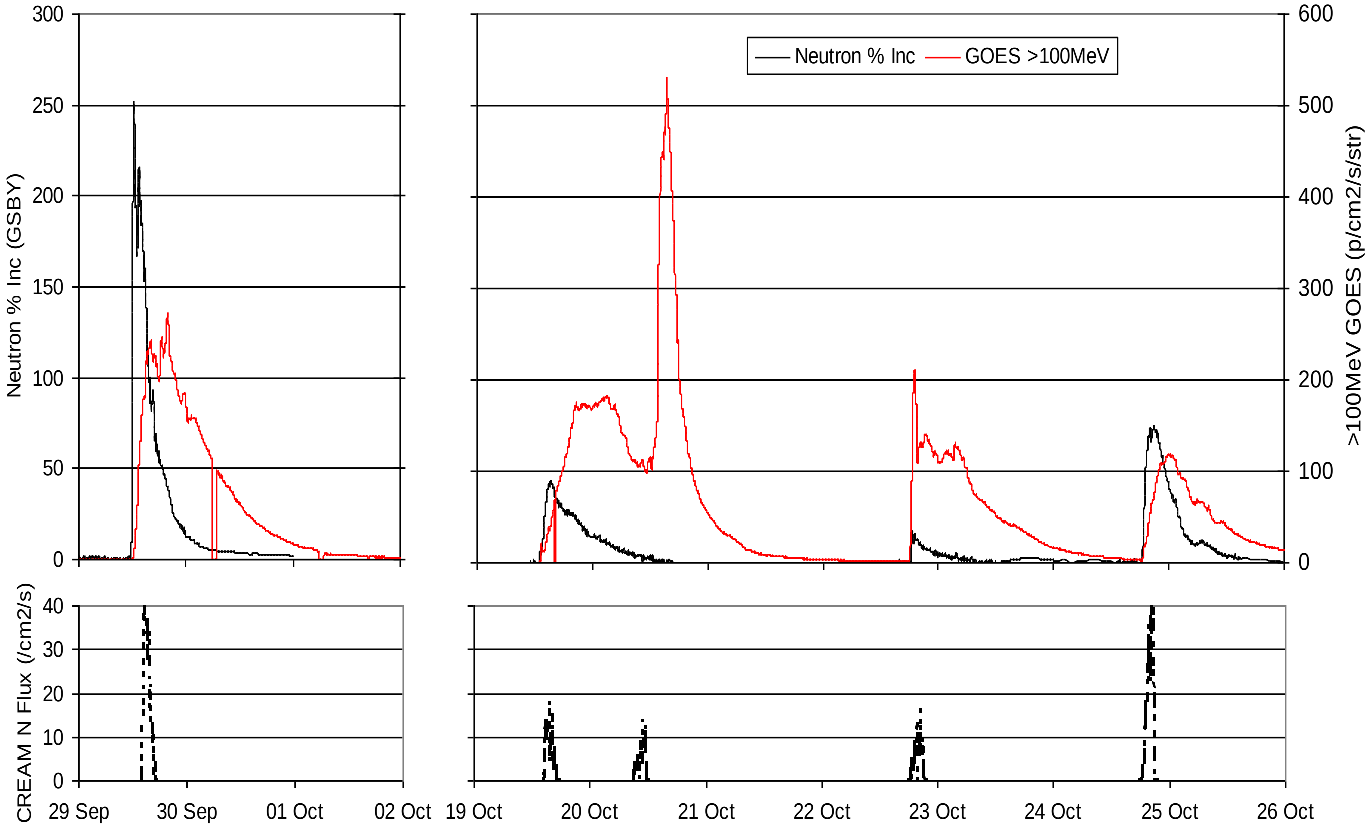
Neutron Fluxes Measured on Concorde (CREAM) cf Ground Level Neutrons & Space Protons during Major Solar Particle Events of 1989



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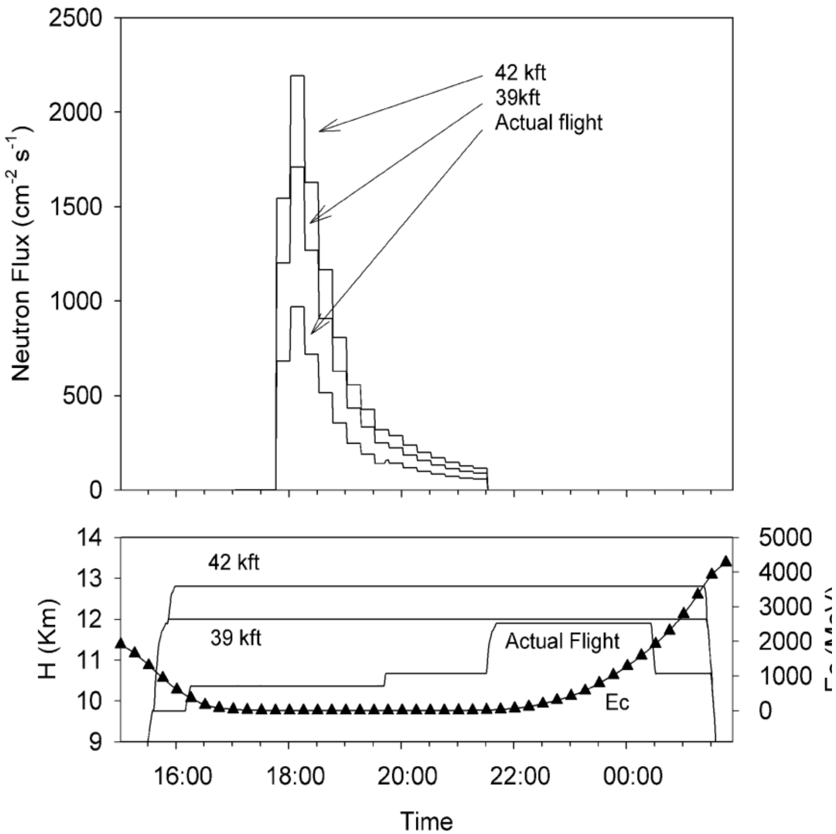
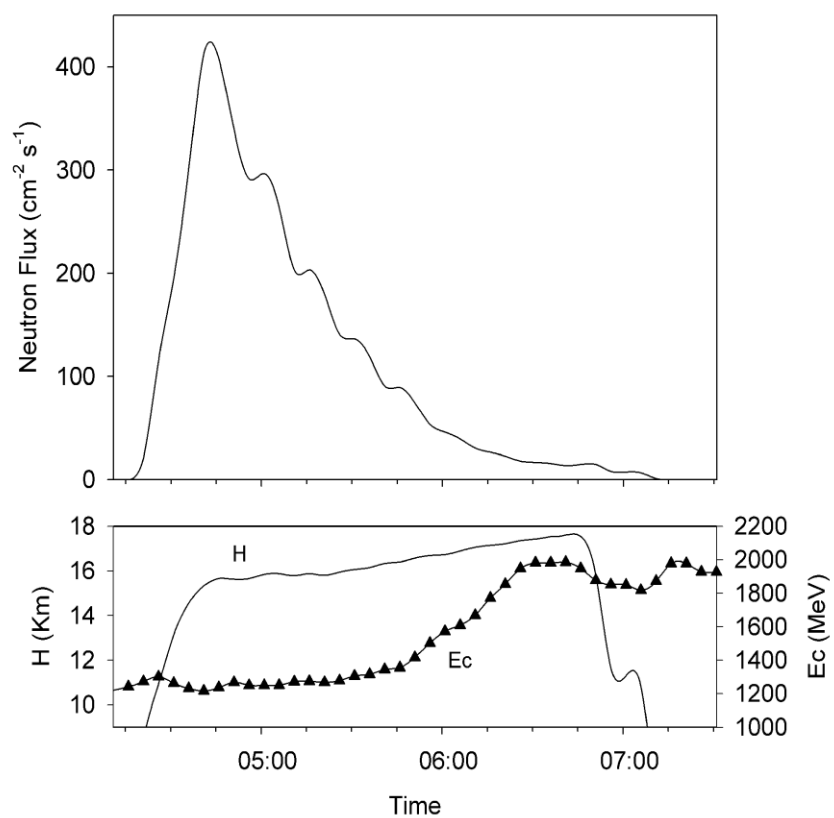
Calculated Neutron Fluxes for Feb 56 Event: London-Los Angeles Routes(left) cf New York- London on Concorde Route(right)





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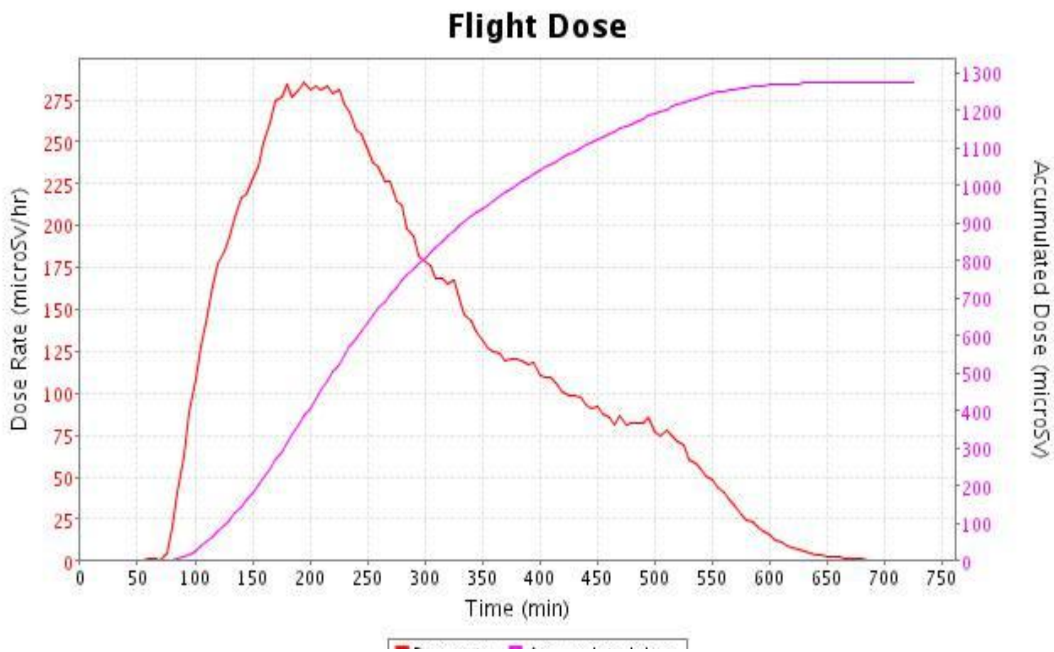
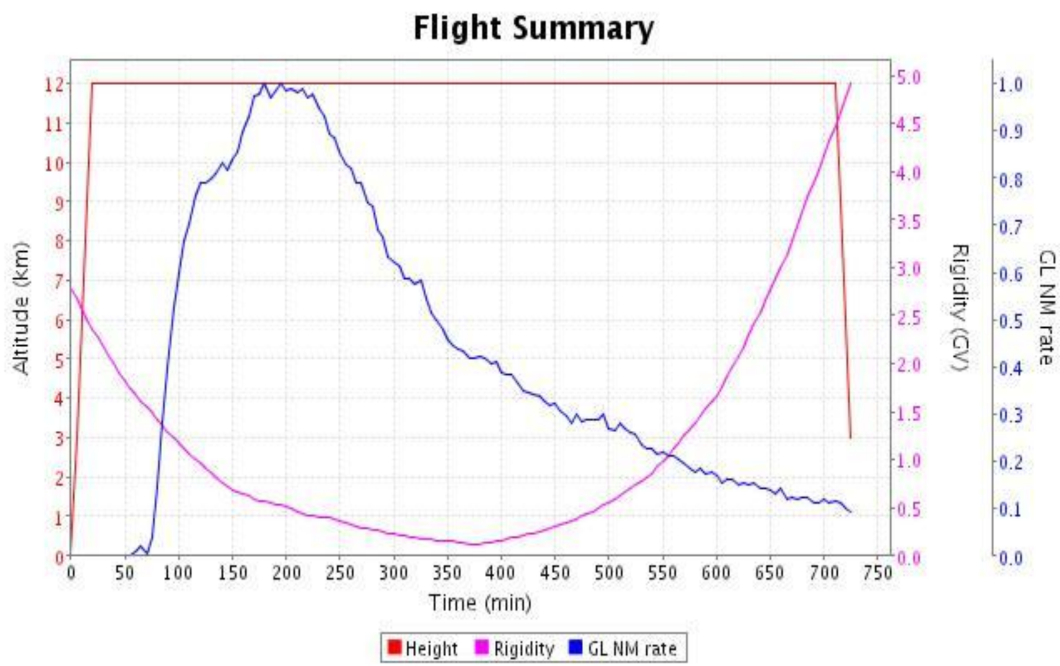
29 September 1989 Event





Calculated influence of Solar Particle Event of 29 Sept 1989 on LHR-LAX Flight; Kp=0

This was beyond Western limb (~105W) and less well connected cf Feb56 giving longer timescale.

Calculations validated against Concorde data but note that rates are higher due to steep latitude dependence.

Event profile obtained from ground level neutron monitor at Goose Bay.

Worst case event start is 1 hour after take-off

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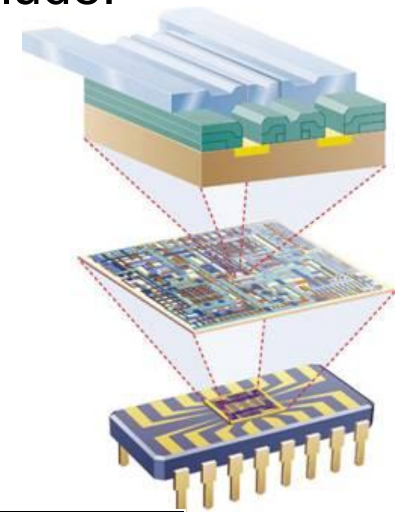
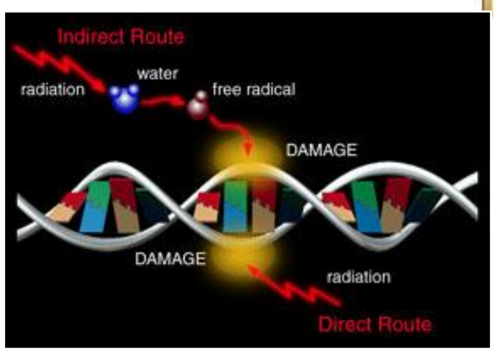
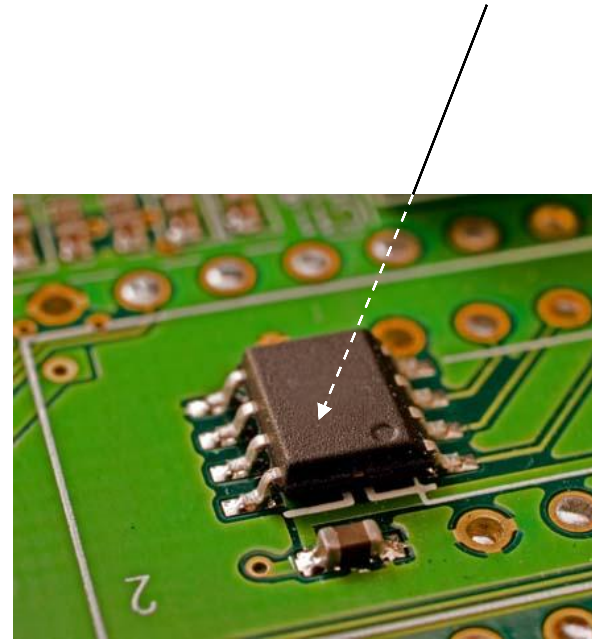
Single event effects

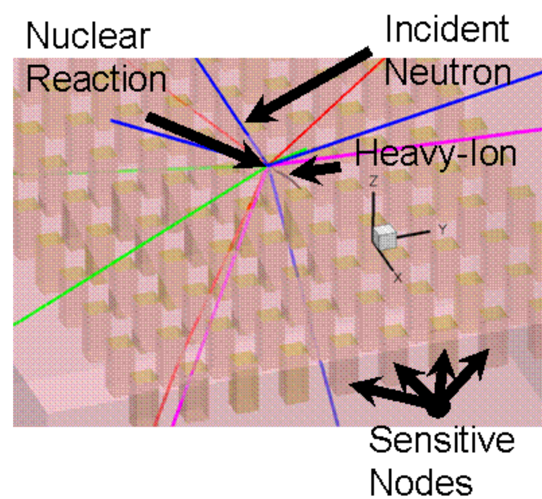
Single event effects (SEE) result from single particles by direct ionisation or nuclear reactions and include:



- Upsets (bit-flips)
- **Multiple cell upsets**
- Transients
- **Functional Interrupts**
- Latch-up
- **Burn-out**
- Gate rupture,
- Dielectric failure
- DNA rupture







NB: Single events can cause multiple effects!

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SEE History

- Limits reliability of even sea level electronics – predicted in 1960s.
- In <u>space</u>:
  - First observed in space in 1970s and major problem realised in 1984 when TDRS-1 attitude control memory (several upsets per day background, 100s during solar event)
  - Latch-up failure of ERS-1 PRARE instrument after 5 days of operation in July 1991 (in heart of South Atlantic Anomaly).
  - Remains a major source of anomalies in space systems, e.g. WMAP in Nov 2001.
- At <u>ground level</u>:
  - Typically one upset per month per 256 MB SRAM
  - Burnout of high voltage diodes on French trains.
  - SUN server problems led to major financial losses
  - Now considered in accident investigations (Toyota accelerator issue) and safety-critical infrastructure e.g. nuclear power station controls

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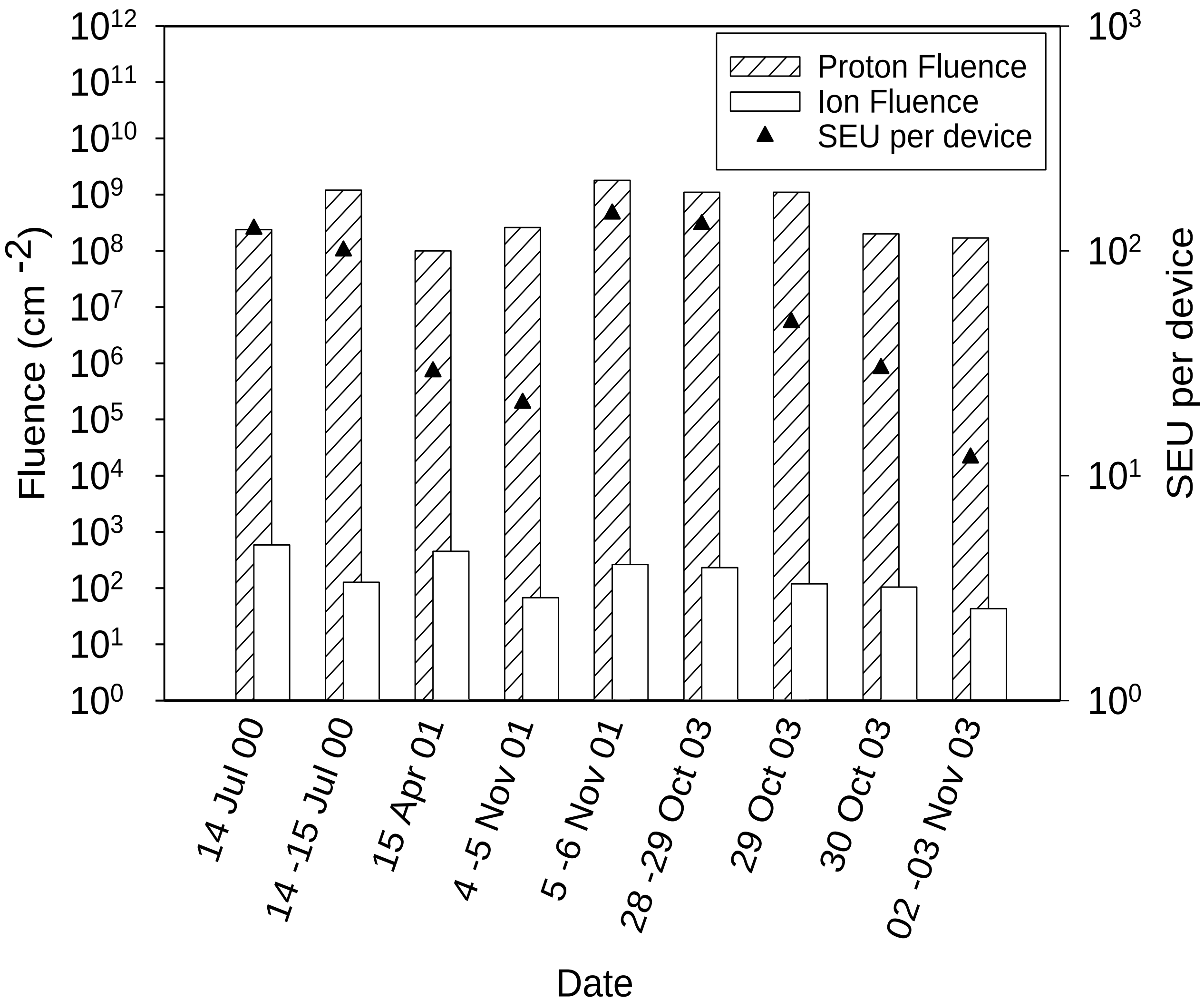
Proton and ion fluences per 12-hour orbit from CREDO-3 on MPTB compared with SEUs per 16-Mbit DRAM.



Airflight Experience of SEE

- Cosmic Radiation Effects & Activation Monitor flown on Concorde between 1988 & 1992, and on SAS in 1993.
5 solar particle increases seen.
- 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).
- Possibly implicated in QF72 accident in October 2008 when aircraft twice dropped several hundred feet.

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Consequences of an Extreme Event at 12 km (39kft) Altitude

- Based on 4 x Feb56 average at high latitude and further factor 4 spike for well connected area (such as Leeds UK in February 56)
- Effective Dose **20 mSv to 50 mSv**.
  - Compares to **1mSv** limit for general public and pregnant aircrew (“normal “ transAtlantic flight 0.05 mSV)
- Unexpected behaviour: risk of increased pilot workload
  - 1 Gbyte of average SRAM would suffer 8000 to 24000 upsets with peak rate 2 to 5 per sec. Worst case SRAMs 10x worse.
  - Hitachi-B 4 Mbit SRAM would have 3 to 10% latch-up failure probability (device is used in avionics)
  - Typical power MOSFETS could show 100% failures if not adequately de-rated.
  - The problem autopilot would have upset every 4.5 to 1.5 mins.

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Ground level neutron fluxes

- Based on statistical study plus modelling of recent events such as 23 Feb 1956 using Atmospheric Radiation Model.
- Effective time of event considered to be 74 mins (but note there might be an initial spike lasting few mins).
- Some evidence for 100 and 1000 yr (tree rings, Be-10 ice cores and superflares on similar stars)
- E.g. 100 year case gives x400 compared to background 1 hour fluence
  - i.e. 1 year’s worth in one hour.
- For SRAM worst case cross-section would give (for 1 in 100yr, 1000yr, 10,000y scenarios) 37, 520, 4000 upsets in 1 Gbyte
- MOSFET with typical burn-out cross-section all would be expected to fail in 1 in 10,000yr event.
  - Even in the 1 in 100 year case, 1% of power MOSFETSs would be expected to fail

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Carrington Event in Perspective

Was part of a sequence of events from an active region which was at 12º W on 1 Sept 1859.

There was a preceding storm and low latitude aurorae on 28 August produced when region was less favourably connected at 50º E - or was this from different region?

Travel time to earth of CME was a record breaking 17 hours.

Estimated to be four to ten times larger than events of the space age; e.g 4 Aug 72, 13 March 89,19 Oct 89, 14 July 00, 28 Oct 03, although debatable basis for particle flux estimates (use of nitrates in ice cores discredited?)

Recently revisited by Cliver and Dietrich. Best estimate for particle fluence 2x Aug72 but 1-Sigma 20x Aug72!

Considered to be worst case in 100-200 years but evidence from C14 in tree rings (AD774/5) and superflares on Sun-like stars suggests could get 10 to 100 x worse on 1000 year timescales.

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Some Suggestions

Scenarios are most likely to be multiple event.

Maybe use Oct 2003 as model scenario but scaled to Carrington (factor 7?); 5 energetic particle events from 2 regions (38W) and (08E, 02W, 56W, 83W).

Events on East hemisphere can be warning but currently there will be many false alarms if particles not measured.

Note that the region giving event of 23 July 2012 at Stereo did not get much attention at the time when facing earth (small events on 12, 15, 17 July).

Events that are most important for Space are not always the same as those affecting aircraft and ground. The latter are more impulsive and anisotropic.

We still understand very little of acceleration and propagation and have seen only a selective sample, since 1942 on ground and since 1958 in Space.

3D observations such as L5, L1, GEO, aircraft, ground are essential to furthering understanding and developing adequate warning systems.

Operationally from L5 we can identify approaching region giving intense, high energy events but will they repeat when better connected?

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Suggestions (continued)

In space we must have reliable high energy channels (>300 MeV/nucleon)

Cerenkov detectors are ideal and UK has experience (S24B telescope on HEOS-1, 1968-70, apogee 222,300 km).

- Observed 2 solar proton events at > 360 MeV from same active region in Feb-March 1969
- 25 Feb 1969 event was well connected at 37W and showed sharp rise within 8 mins of X-ray maximum. Anisotropy was 40% (1st harmonic amplitude) in first hour falling to 4% after 6 hrs.
- 30 March 1969 event was poorly connected at 110W and showed slow rise and decay with anisotropy < 10 % throughout. Note that this was probably the first ever event detected on an aircraft (Wilson et al, NASA Langley).

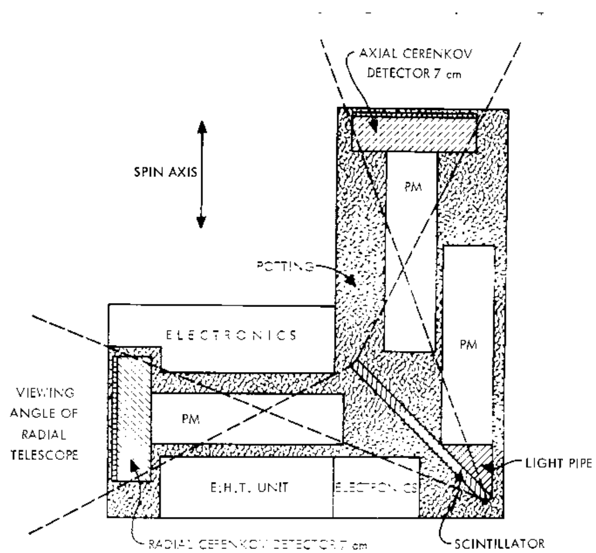
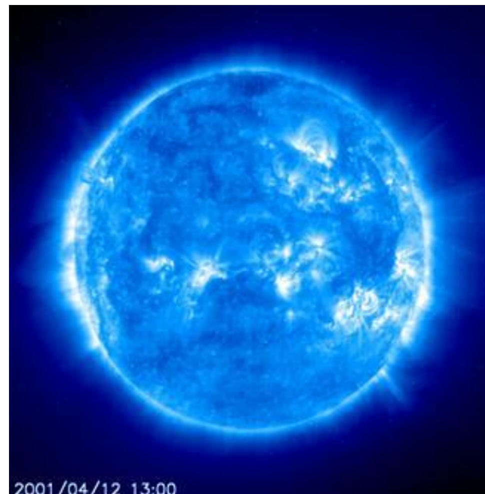


Fig. 1. The high energy proton telescope on HEOS-1.

High Energy Radiation Impacts on Ground Level, Aircraft and Space Electronics
The Need for an L5 Measurement Package



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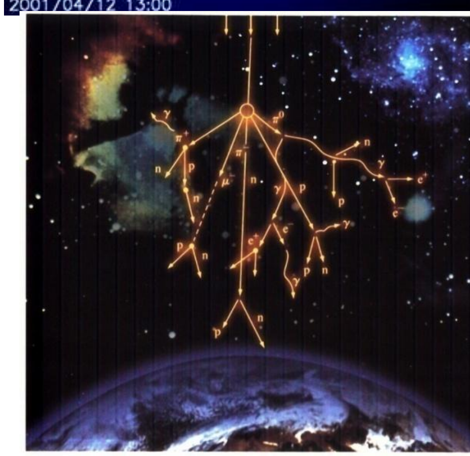

"Sic Itur Ad Astra."

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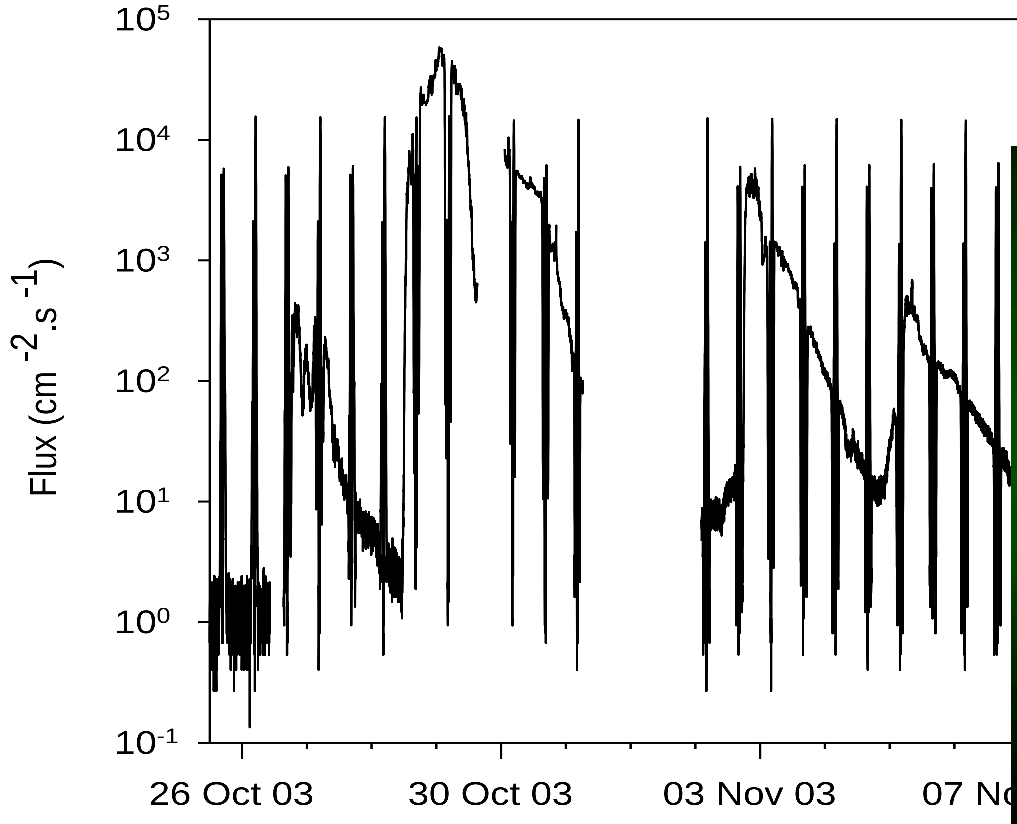
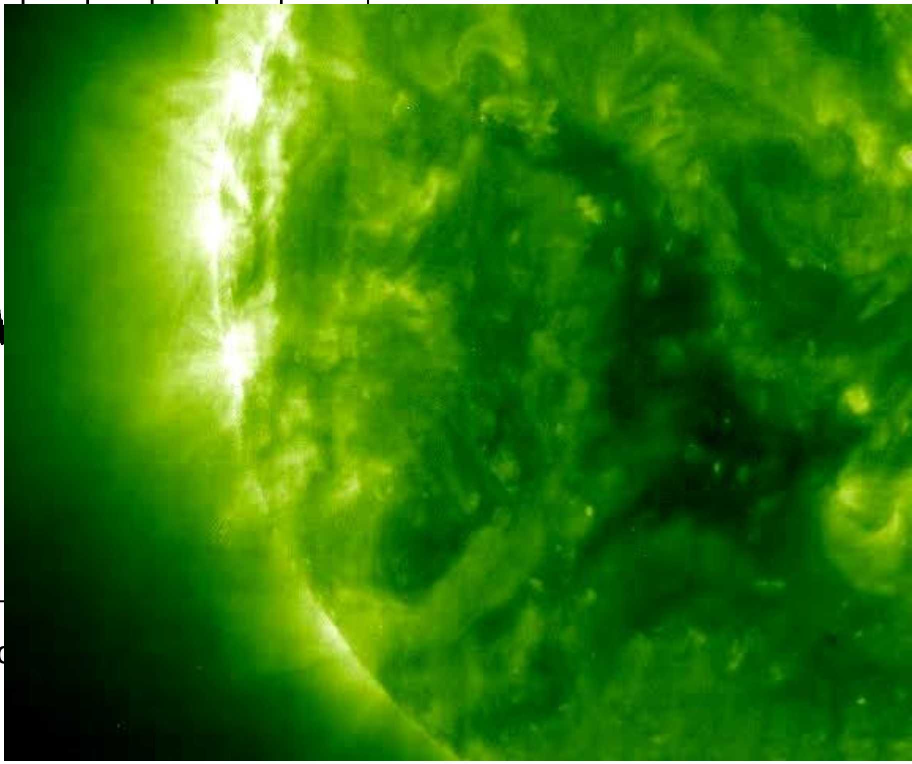
Proton fluxes from CREDO on MPTB during Halloween Events





Major Events of The Space Age

4 Aug 72 between Apollos 16 and 17 and at E09 solar longitude

- Sequence of events (2-7 Aug) gave proton fluence 5.0E9 cm^{-2} > 30 MeV
- Used for EUROSTAR/SK5 specs &CREME86

19 Oct 89

- Sequence of events (19, 22, 24 Oct at E10, W31, W55) gave proton fluence 4.3E9 cm^{-2} > 30 MeV
- Used for most modern spacecraft and CREME96
- Notable for TDRS anomalies in AOCS

28 Oct 2003 (19 Oct to 5 Nov, particles 26 Oct to 5 Nov))

- Sequence of events from 2 regions(W38) and (E08, W02, W56, W83) gave proton fluence 3.3E9 cm^{-2} > 30 MeV

Comparable events were 11 Jul 59, 12 Nov 60, 14 Jul 2000, 9 Nov 2000, 4 Nov 2001.

Recent events of 2012 July 12 (E06), July 17 (W64), July 19 (W89) and July 23 (W141) from same active region. First 3 were weak but from Stereo observations last was Carrington level. Hence Olympics OC on 27 July had near miss!

- More work needed on particle fluxes

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Headline News

Washington Post: Extreme space weather threatens to leave the US in the dark

The Washington Post

First Published Aug 10 2014 01:47 pm • Last Updated Aug 10 2014 01:48 pm

Mail Online

From blackouts to transport chaos: Solar superstorms pose a 'catastrophic' threat to life on Earth, warns scientist

- Huge storms are caused by violent eruptions on the surface of the sun
- They can induce surges of electrical currents in the ground on Earth
- A storm can also affect overhead transmission lines causing a black out
- Warning comes from, Ashley Dale, a member of the Solarmax task force
- Solarmax was set up to find out how to reduce the impact of solar storms
- Mr Dale says it is only a 'matter of time' before an exceptionally violent solar storm is propelled towards Earth

By Ellie Zolfagharifard

Published: 00:56, 1 August 2014 | Updated: 15:54, 1 August 2014

Mail Online

Solar flare almost blasted Earth back to the dark ages two years ago, NASA scientists reveal

- Plasma cloud or 'CME' rocketed away from the sun as fast as 3000 km/s on July 23, 2012
- Had the eruption occurred just one week earlier, the blast site would have been facing Earth
- Direct hit could cause widespread power blackouts, disabling everything that plugs into a wall socket.
- Total economic impact could have exceeded $2 trillion or 20 times greater than the costs of a Hurricane Katrina

By Mark Prigg

Published: 20:30, 24 July 2014 | Updated: 05:23, 25 July 2014

EXPRESS Home of the Daily and Sunday Express

Apocalypse NOW: Killer solar superstorm could destroy Earth at ANY MOMENT, scientists warn

VIOLENT solar superstorms could destroy life as we know it at ANY MOMENT, shocked scientists have warned today.

ROYAL ACADEMY OF ENGINEERING

Extreme space weather: impacts on engineered systems and infrastructure

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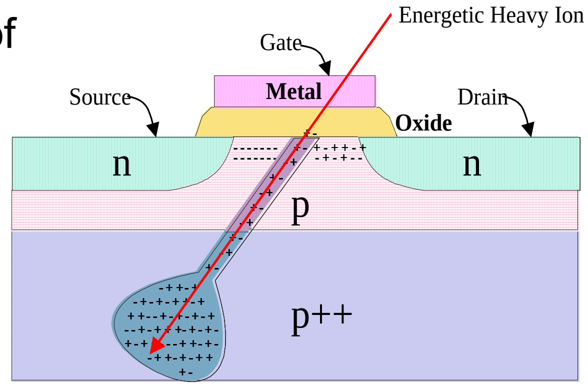
Single Event Effects

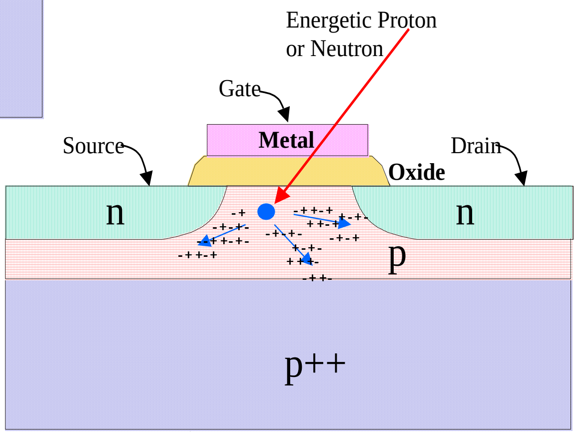
SEE result from charge depositions of individual particles and include:

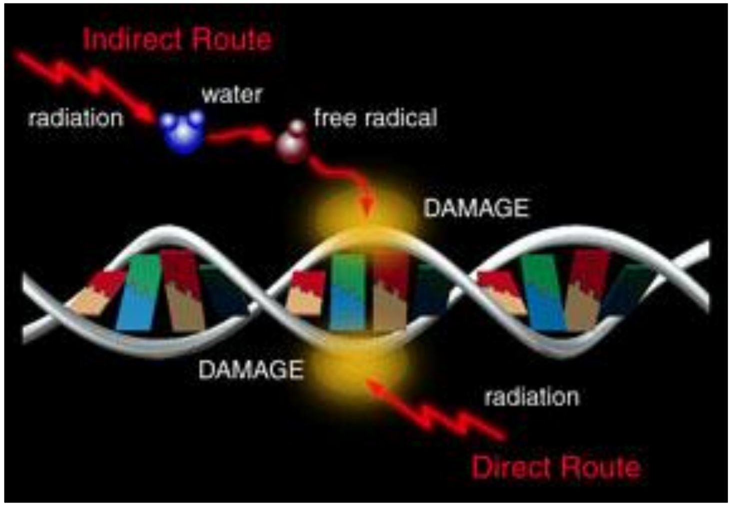
- Upsets (bit-flips),
- Multiple bit upsets
- Transients
- Functional Interrupts,
- Latchup,
- Burnout,
- Gate rupture,
- Dielectric failure,
- DNA rupture



Direct Ionization

Nuclear Reactions





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Consequences of Extreme Event on Avionics

- Unexpected behaviour: risk of increased pilot workload
  - 1 Gbyte of average SRAM would suffer 8000 to 24000 upsets with peak rate 2 to 5 per sec. Worst case SRAMs 10x worse.
  - Hitachi-B 4 Mbit SRAM would have 3 to 10% latch-up failure probability (device is used in avionics)
  - Typical power MOSFETS could show 100% failures if not adequately de-rated.
  - The problem autopilot would have upset every 4.5 to 1.5 mins.
- Actual effect on aircraft not necessarily predictable in advance: need to prepare for the unexpected
- Develop ‘GLE’ alerts e.g. to a) enable seat belts to be fastened, b) potentially delay take-offs.
- Need to include atmospheric radiation within meteorological services for aviation

Note: multiple cell upsets, functional interrupts and burn-outs are hard to mitigate

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Aircraft Memory Upset Rates in 1 Gbyte of Typical SRAM (calculated)

Event	Neutron Flux ($/cm^2/s$)	Upset Rate (/hr)	MTBU (sec)
1GV - 17km			
23 Feb-56	2893	582	6.2
29 Sep-89	487	98	37
24 Oct-89	80	16	224
GCR	9.3	1.8	2005
1GV - 12km			
23 Feb-56	1113	247	14.6
29 Sep-89	191	42	85.0
24 Oct-89	31	7.0	517
GCR	5.8	1.2	2935

Cross-Section of $5x10^{-14}$ cm^2 per bit. Note that many SRAMs are 10x worse . Extreme event could be 4 to 10x worse

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Research at Surrey Space Centre

Monitors on various aircraft e.g.

- with SolarMetrics (Virgin Atlantic)
- US polar routes
- Qantas
- Met Office (MOCCA aircraft)

Smart-phone linked monitoring project

Neutron flux measurements on balloons e.g NASA Rad-X project in US

Rapid response balloon project

Atmospheric radiation model (developing)

SEE research (adapt from space activities)

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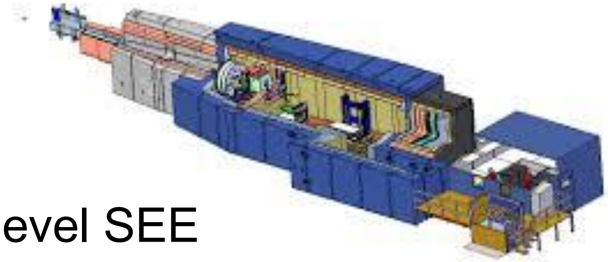
What do we need to do?



1. Engineering research into component and system-level SEE risk and mitigations for critical aviation and ground systems
   - Use of UK's new ChipIR facility
   - Future technologies: provide advice to improve safety standards (e.g. IEC TS62396)
   - Collaborate with space programmes and methods
   - The influence of shielding for GLE spectra should be studied (for ground systems).
   - Particles other than neutrons should also be studied,
2. Develop reliable atmospheric radiation measurement <u>network</u> (aircraft, balloons and ground level)
3. Develop atmospheric radiation models (including interfaces for engineering effects for calculations)
   - To include worst case event assessments
4. Develop improved alert and operational responses
   - e.g. current SWPC alerts unsuitable for radiation impact
   - More meteorological approach to information supply

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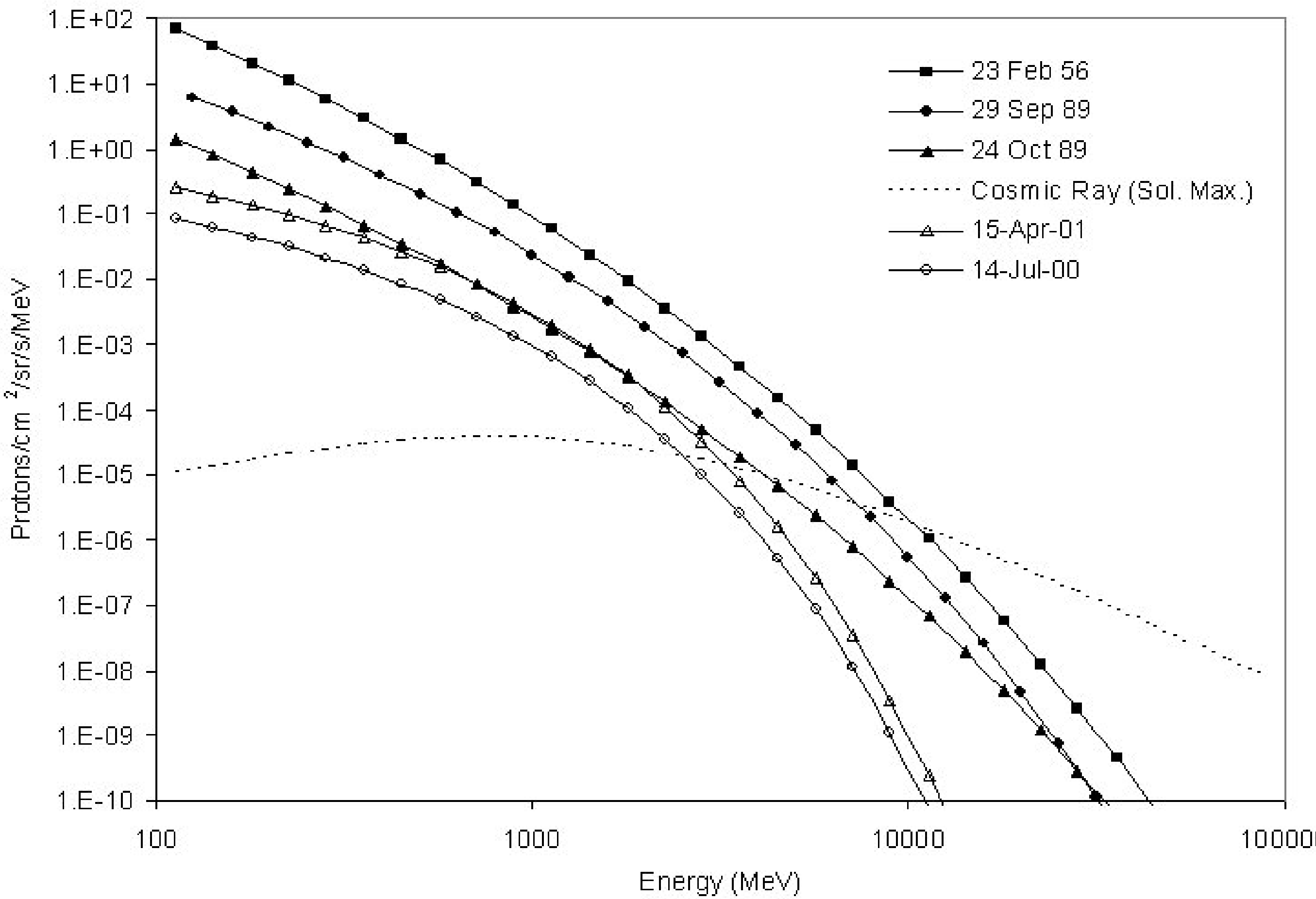
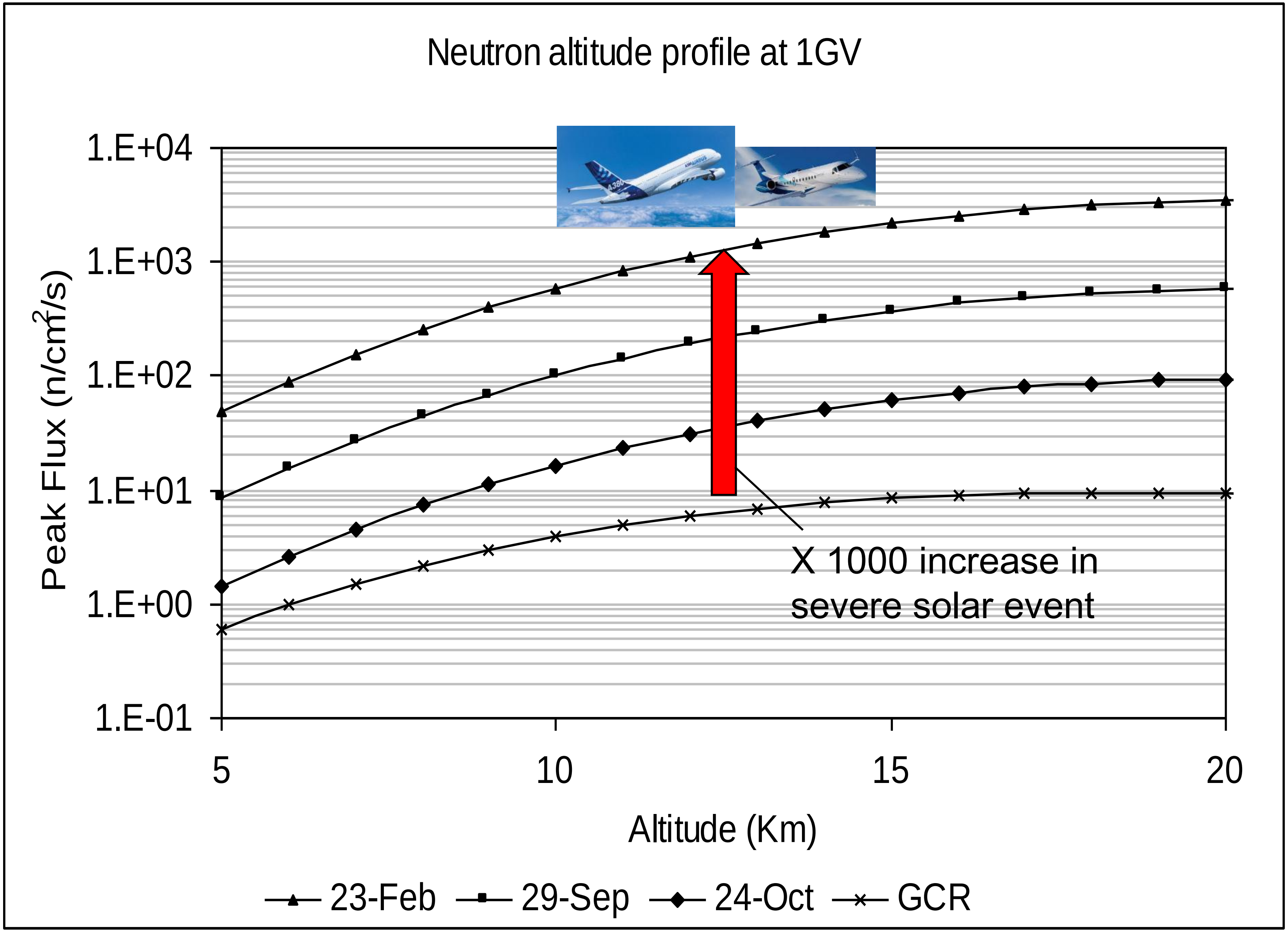
Calculated spectra of large solar particle events cf cosmic rays

These had hard spectra and were ground level events

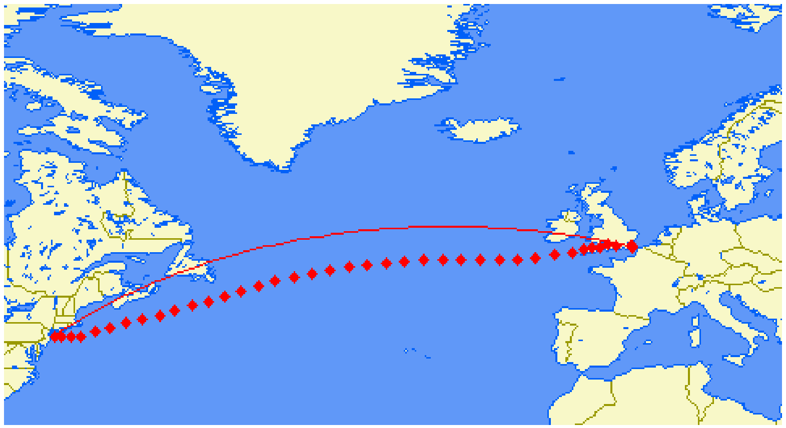



Neutron altitude profile at 1GV
Peak Flux (n/cm2/s)
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
5
10
15
20
Altitude (Km)
X 1000 increase in severe solar event
23-Feb
29-Sep
24-Oct
GCR

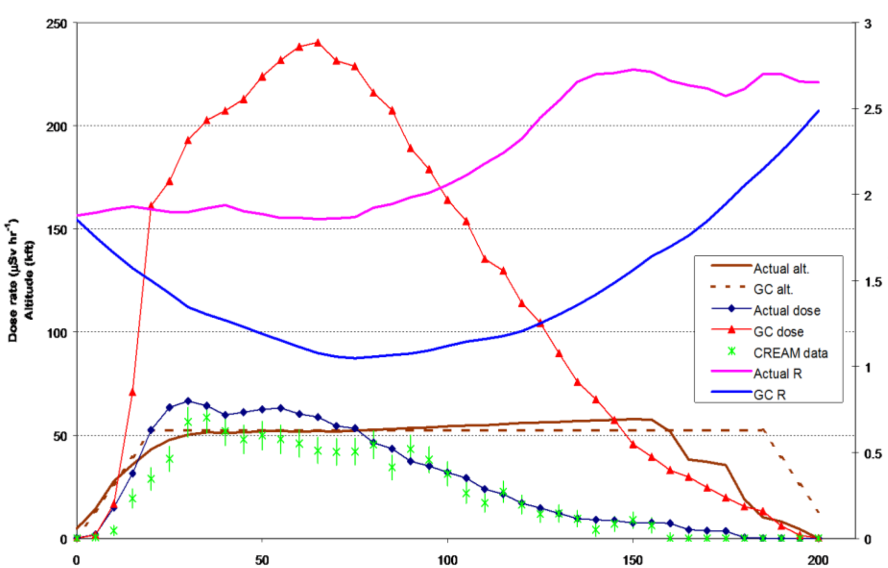
GLE42 (Kp =2): JKF-LHR on 29 September 1989

Great Circle vs. Actual Flight Path

JFK-LHR 29 September 1989



JFK-LHR 29/09/89



Concorde route during event of 29 September 1989 (Kp = 2). Data from CREAM.

Peak dose rate on great circle route (solid line) would have been factor 5 higher cf actual route (dotted).

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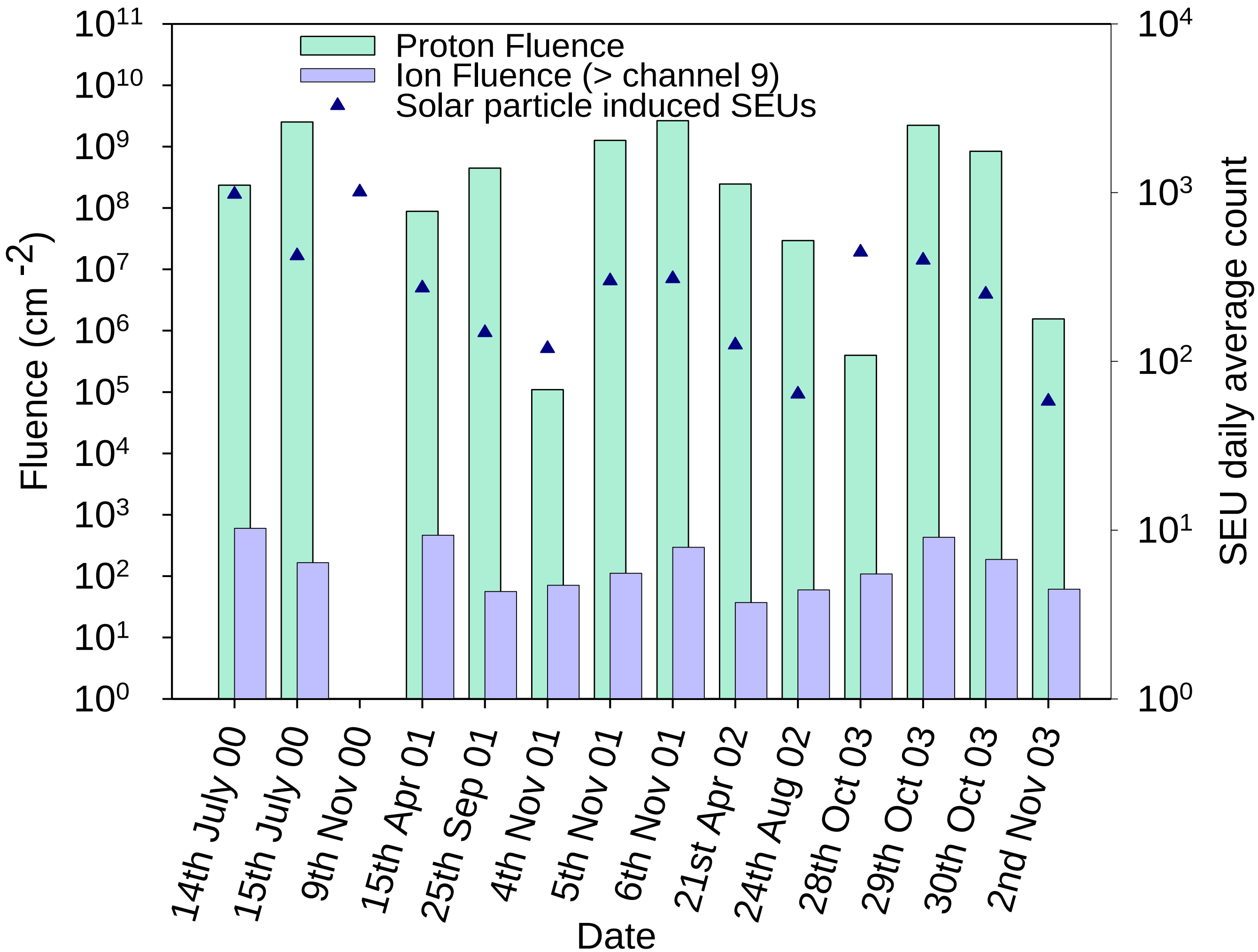
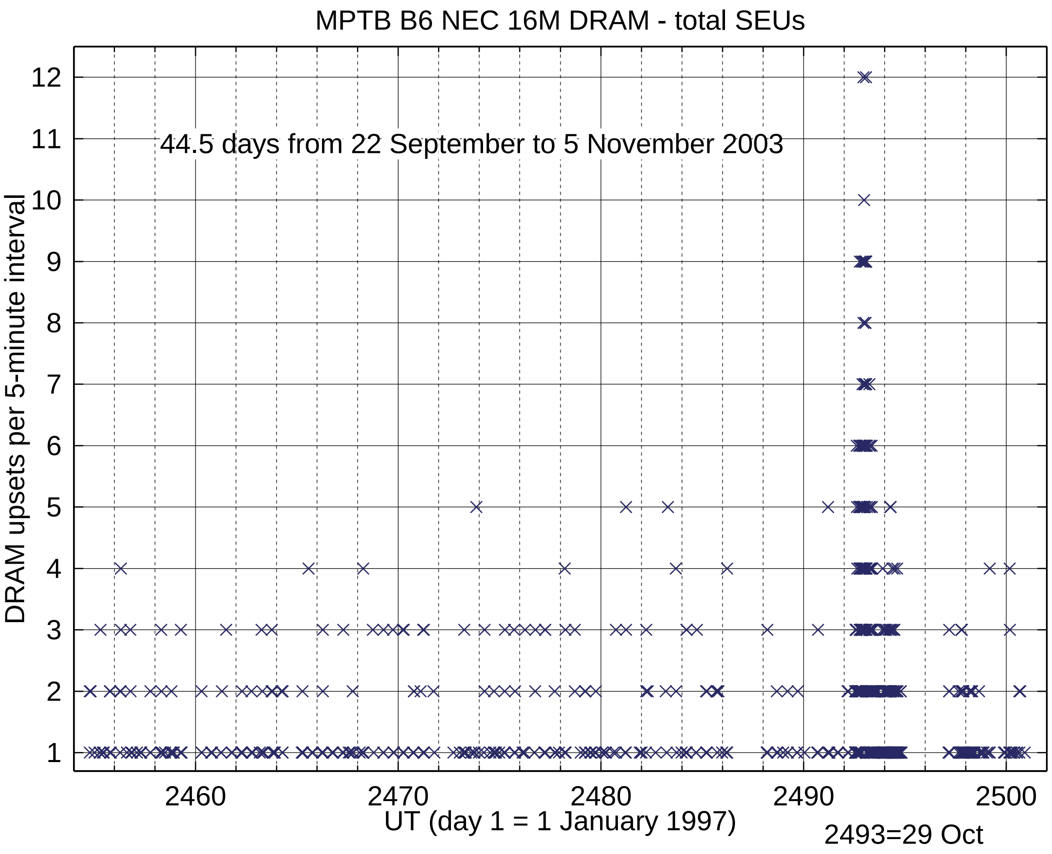
SEUs in Orbview-2 SSDR (512 MB of DRAM)* cf Solar Proton & Ion Fluences

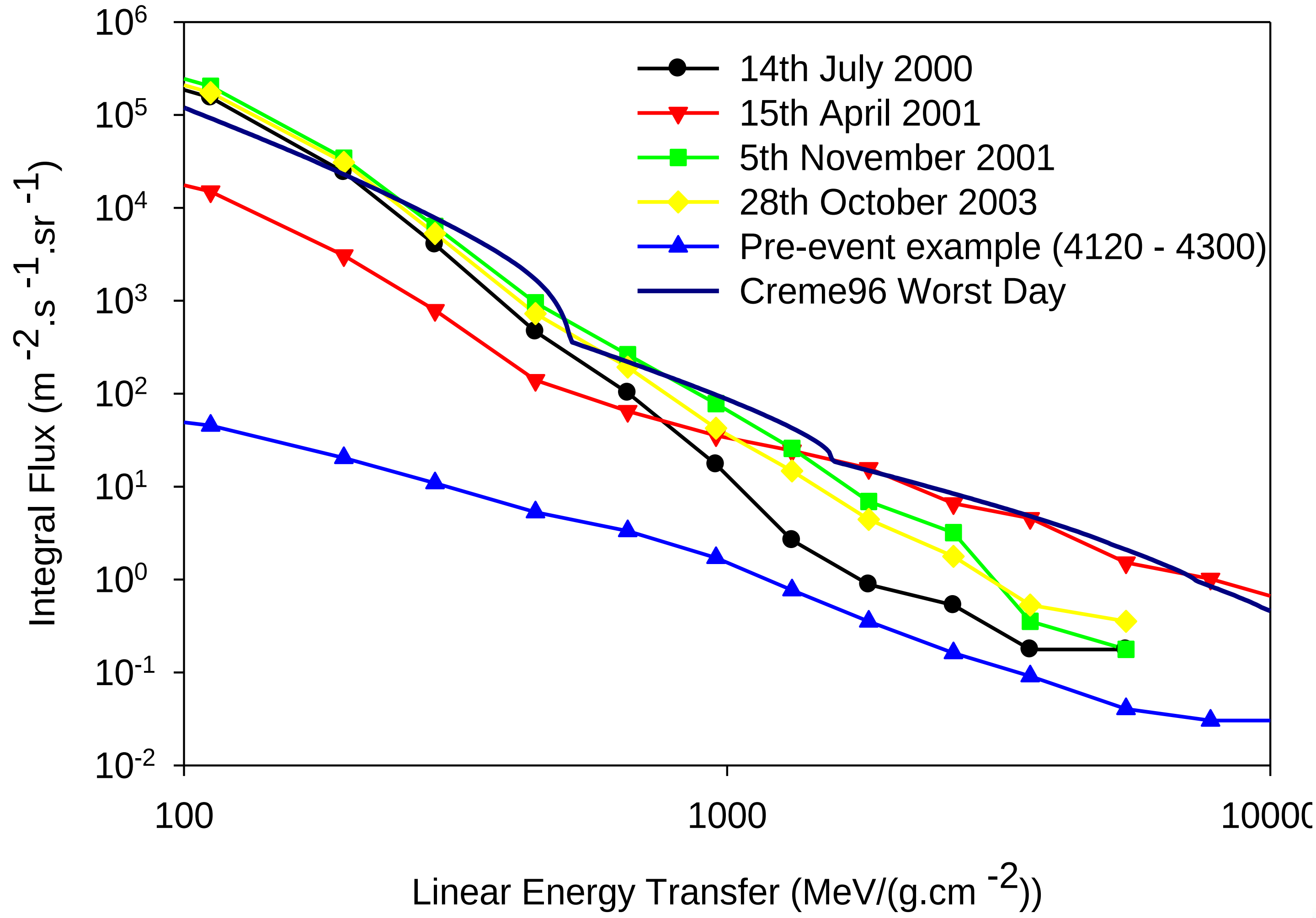


*Courtesy C Poivey et al

Upset rates in four 16-Mbit DRAMs on MPTB for the time period 22 September to 5 November 2003 showing the increases from the Halloween events.



LET Spectra for Major Events Compared to CREME96 Worst Day Model



Solar Proton Fluences > 38 MeV Measured by CREDO-3 on MPTB cf Model

Event/Model	Worst Day Fluence cm^{-2}	Worst Week Fluence cm^{-2}
CREME96	$1.48x10^9$	$2.66x10^9$
14-20 July 00	$2.53x10^9$	$2.80x10^9$
15-21 April 01	$1.03x10^8$	$1.33x10^8$
5-11 Nov 01	$2.77x10^9$	$3.94x10^9$
28 Oct-3 Nov 03	$2.22x10^9$	$3.33x10^9$

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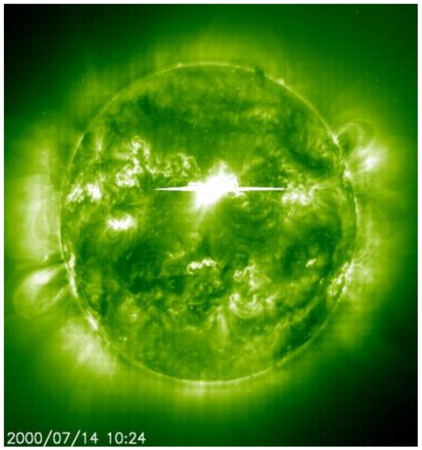
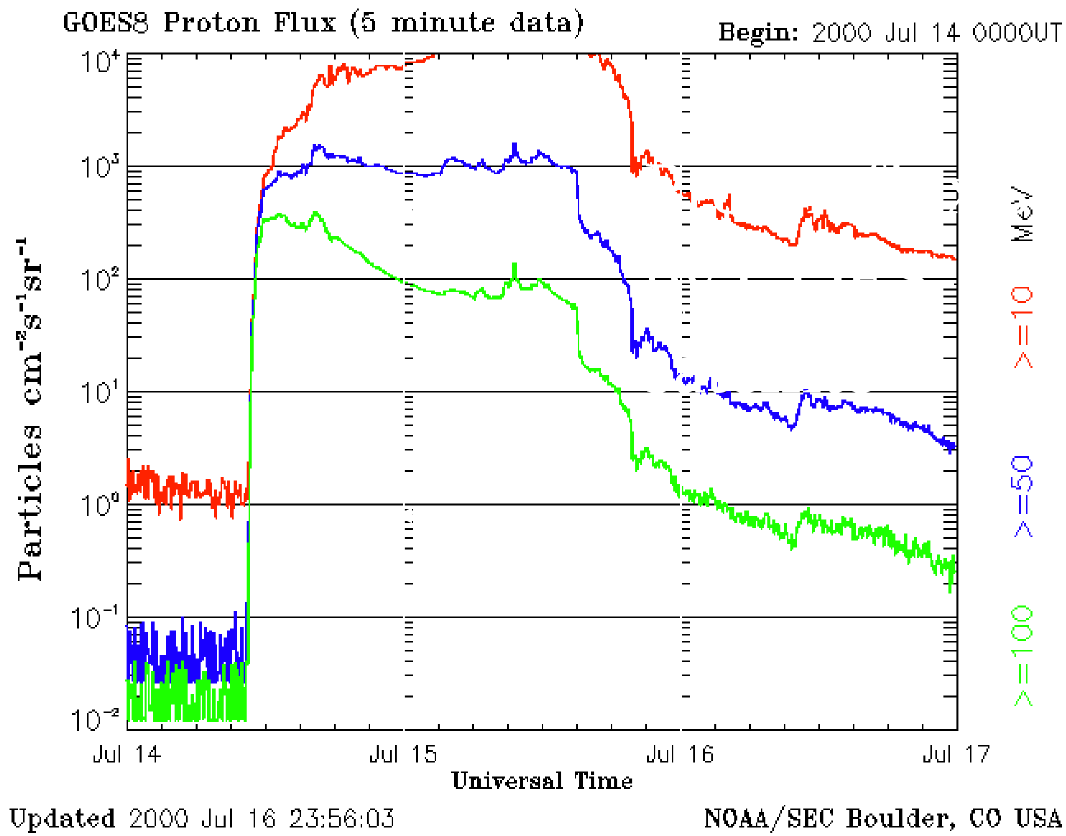
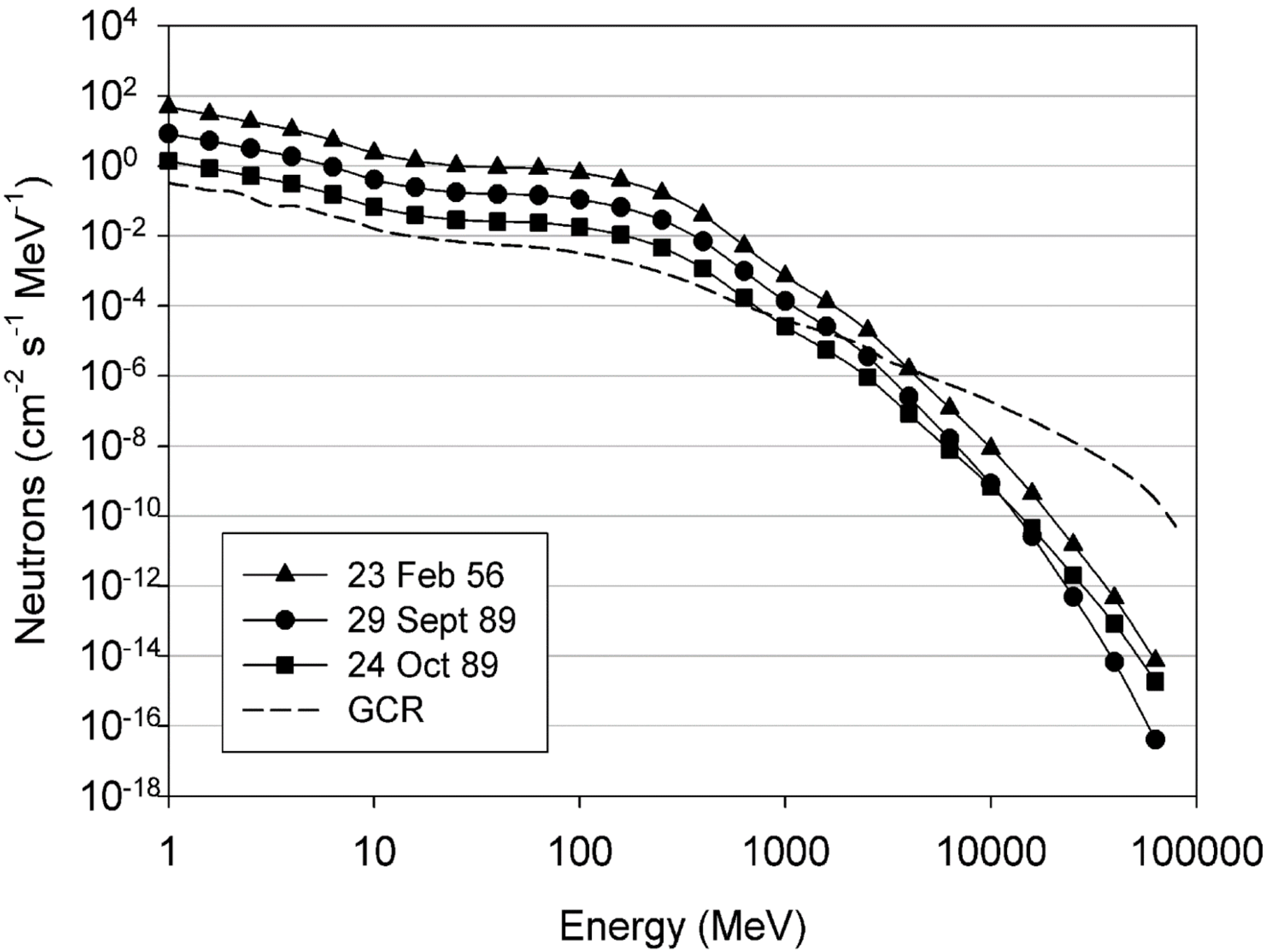
Solar Particle Events
Bastille Day Event at GEO





Secondary neutron spectra at 10 km altitude from major GLEs cf from Galactic Cosmic Rays



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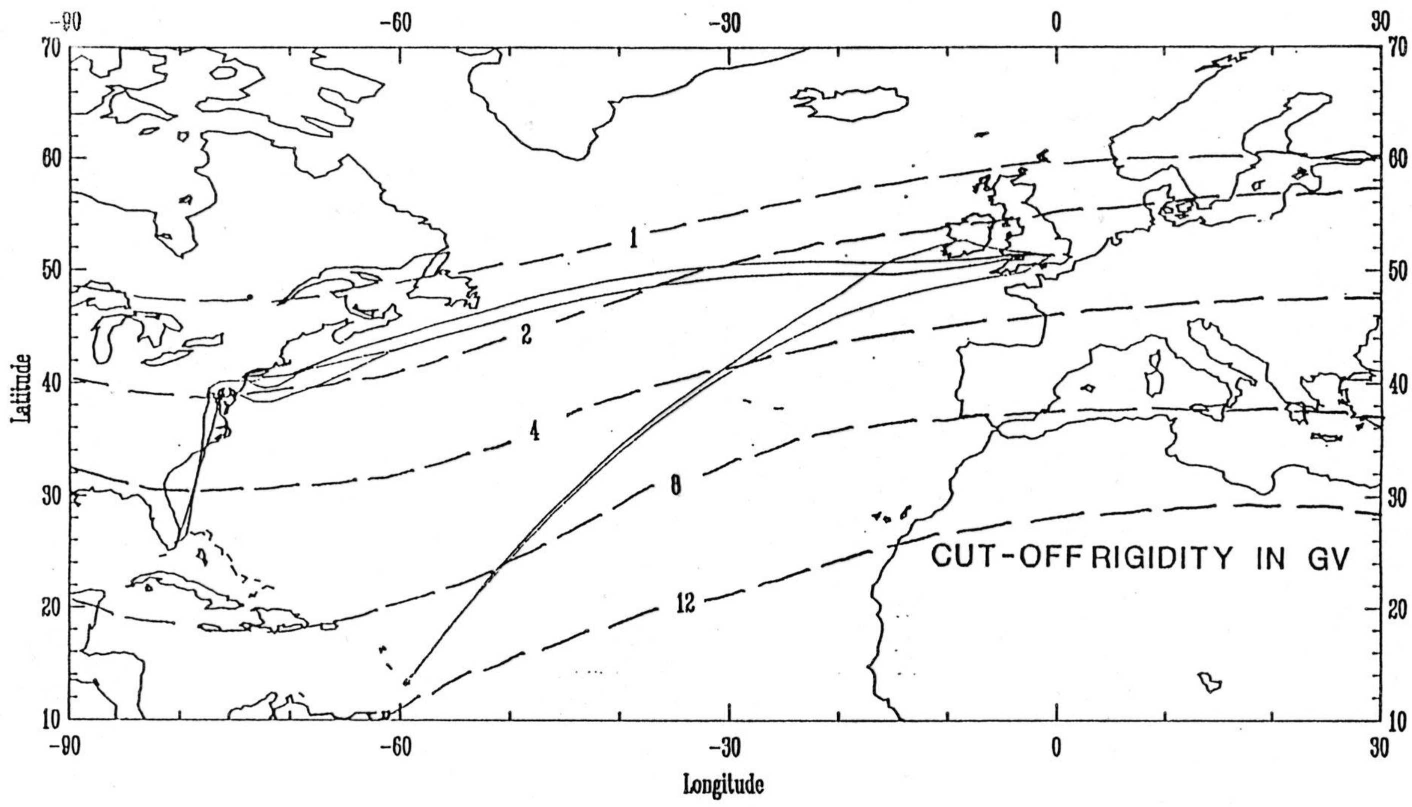
Rigidity (momentum to charge ratio)
is resistance to bending in magnetic field.
Penetration easiest at magnetic poles.
Concorde routes were actually well protected cf LHR-LAX etc



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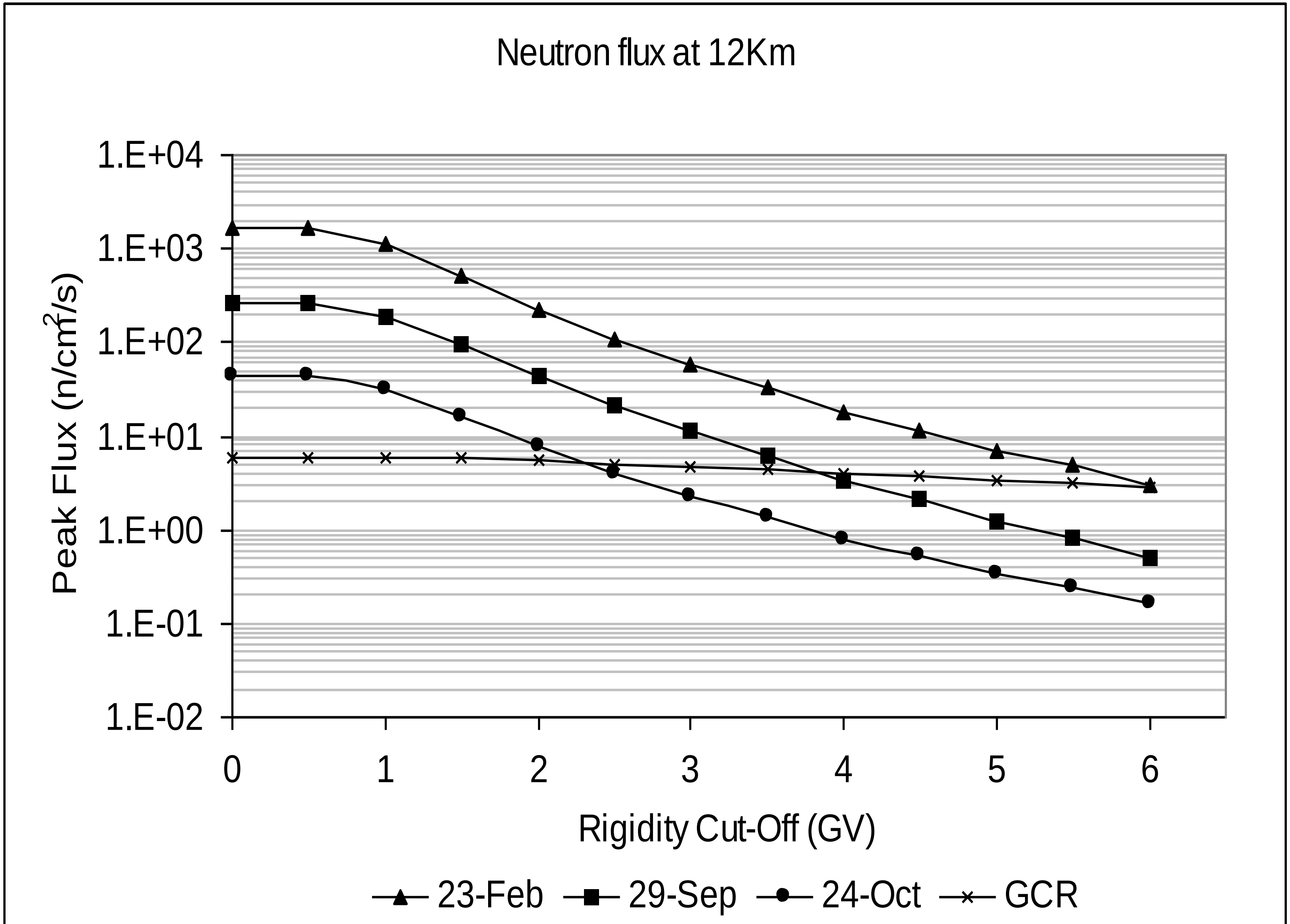

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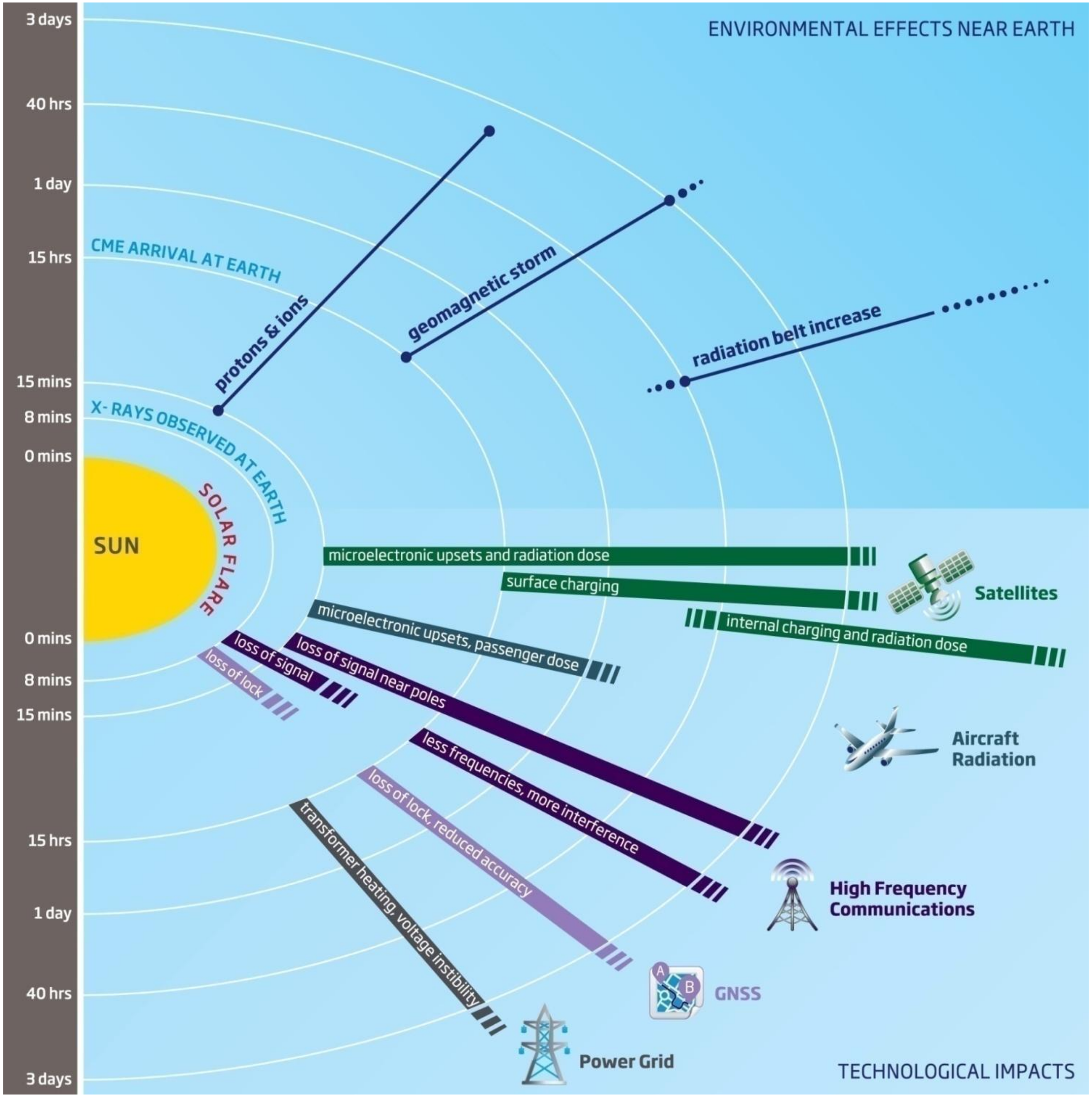
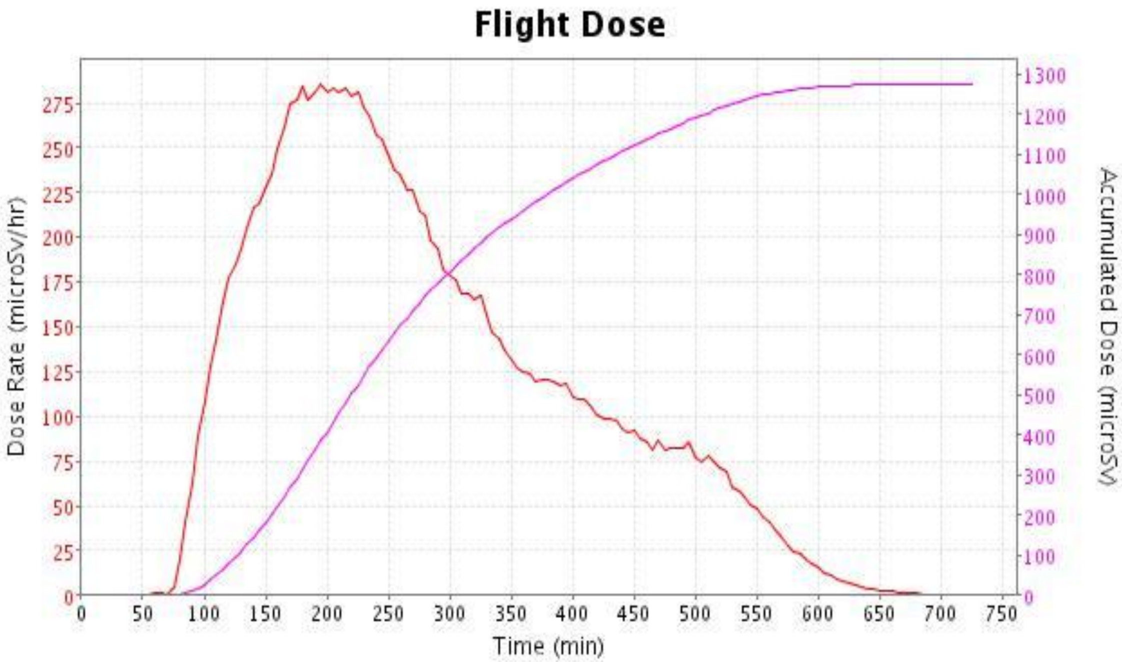
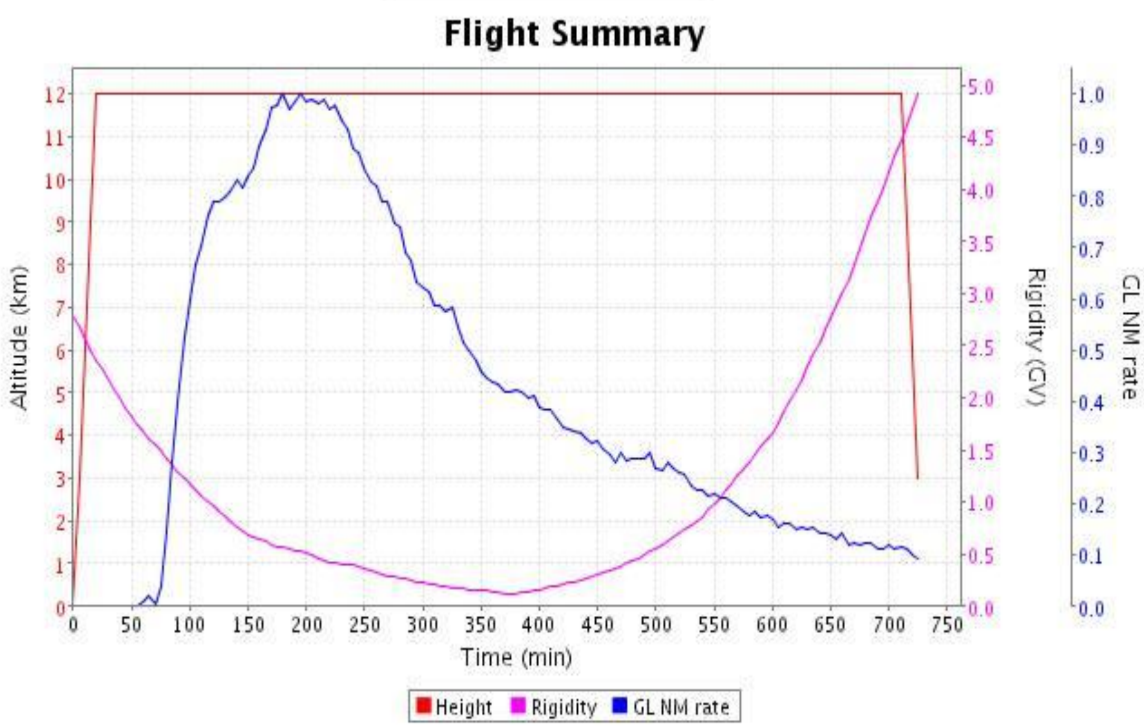


From

RAEng Study





Influence of
Solar Particle Event
of 29 Sept 1989
on LHR-LAX
Flight; Kp=0

Worst case event start
is 1 hour after take-off

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Standards

Several standards exist including JESD89 for soft errors at sea level- no enhancements mentioned.

Probably most useful is:

Avionics Technical Standard IEC 62396 – Part 1

Convened by Bob Edwards, Goodrich with contributions from QinetiQ, Boeing, Airbus, Honeywell, GE, BAE Systems. First published in 2006. Recently updated.

- Atmospheric Radiation Environment- GLEs are mentioned
- Effects of Atmospheric Radiation on Avionics
- System Guidance
- Determination of Avionics SEE Rates
- Considerations for SEE Compliance

Parts 2 to 5 - Guidelines.

- SEE Testing of Avionics Systems (recently updated)
- Optimize Avionics System Design to reduce SEE Rates (recently updated)
- Designing with High Voltage Electronics and potential SEE
- Assessing thermal neutron fluxes and Effects in Avionics Systems
- Part 6 Extreme Space Weather to be added but needs support.

Spallation Neutron Sources are the favoured test method.

Must allow for possible thermal neutron sensitivity.

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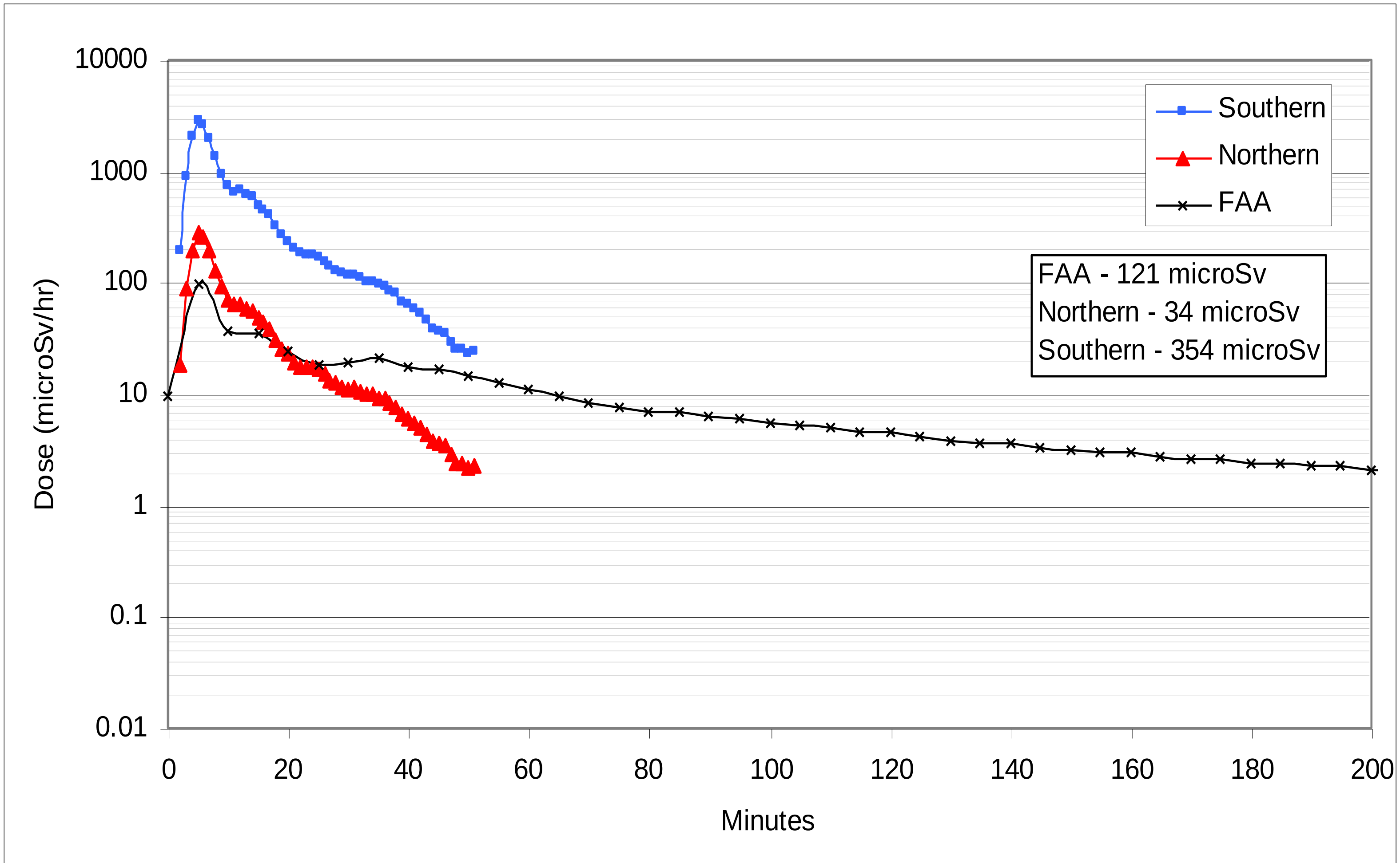
Calculated dose rates for SPE of 20 Jan 2005 for high latitude routes at 39000 ft



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Solar Particle Event Doses for LHR-LAX at 12 km Estimated Using QARM

Event	23 Feb 1956	29 Sept 1989	19 Oct 1989	22 Oct 1989	24 Oct 1989	14 July 2000	15 April 2001
W/C Event Start (hrs)	3	1	0	1	1	2	2
Peak Dose Rate (mSv/hr)	1.82	0.29	0.022	0.039	0.049	0.013	0.041
Route Dose (mSv)	2.27	1.28	0.12	0.15	0.25	0.031	0.078

Note: Additional to GCR Route Dose of 0.05-0.06 mSv
Geomagnetic Conditions Quiet.
W/C increase for Sept 89 gives 1.33 mSv for Kp=6
Event start measured wrt take-off.

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SEE History- From Space to Sea Level

- Problem first predicted in 1962 as a limit to scaling.
- Observed in space with increasing frequency since 1975.
- Major problem realised in 1984 when TDRS-1 attitude control memory showed several upsets per day (several hundred during major solar particle event of Oct 89) requiring expensive ground control.
- Latchup failure of ERS-1 PRARE instrument after 5 days of operation in July 1991 (in heart of South Atlantic Anomaly).
- PCs on Shuttle and MIR required frequent reboot, typically every nine hours.
- Remains a major source of anomalies in space systems, eg NASA Microwave Anisotropy Probe on 5 Nov 2001. (UK data resolved the cause as ions in SPE)

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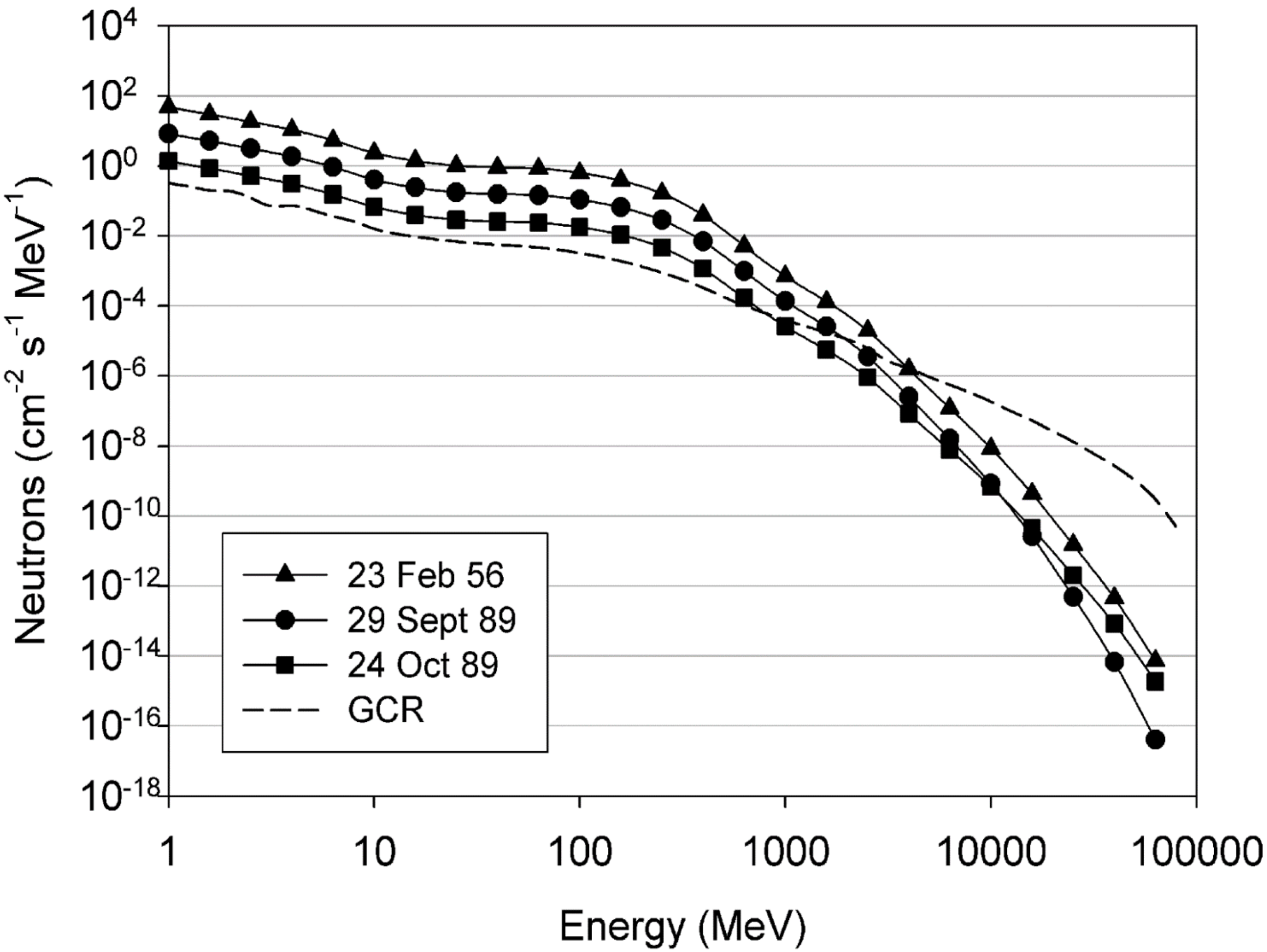
Estimate of worst case sea level radiation environment

- Based on NPL statistical study plus modelling of recent events such as 23 Feb 1956 using Atmospheric Radiation Model.
- Effective time of event reduced to 74 mins but note there might be an initial spike lasting few mins
- Some evidence for 100 and 1000 yr.

Worst case fluxes	& fluences for	Neutrons >10 MeV
Return frequency	**Peak fluence rate**	**Total fluence**
Normal background from galactic comic rays	20 cm^{-2} hr^{-1}	N/A
100y	7,540 cm^{-2} hr^{-1}	9,300 cm^{-2}
1000y	105,405 cm^{-2} hr^{-1}	130,000 cm^{-2}
10,000y	810,811 cm^{-2} hr^{-1}	1,000,000 cm^{-2}

Return frequency	Total fluence protons cm^{-2}	Total fluence pions cm^{-2}	Total fluence muons cm^{-2}	Total fluence electrons cm^{-2}	Total fluence gammas cm^{-2}
100y	167	0.3	61	202	9,720
1000y	2,344	4.3	857	2,822	136,080
10000y	17,912	33	6,548	21,571	1,040,040

Secondary neutron spectra at 10 km altitude from major GLEs cf from Galactic Cosmic Rays



EASA Proposed CM - AS – 004 Issue: 01 Single Event Effects (SEE) Caused by Atmospheric Radiation

Extreme space weather includes the effects of solar flares which can result in large bursts of solar particles arriving in the atmosphere creating an increase in atmospheric radiation of short duration (order of hours). During solar flare activity, the atmospheric radiation may rise to significantly higher levels than that normally expected and could increase by a factor of 300 or more (see document IEC62396-1, Section 5.6). This Certification Memorandum considers the **normal** atmospheric radiation levels, which could be experienced during a typical flight, and not those which could be experienced during a solar flare. It is expected that some prior notification of high solar activity, and thus possible solar flares, will be available to the operator of an aircraft via solar weather information websites. This should result in operational limitations relating to the routing of the flight (i.e. avoiding high latitudes). Further information regarding extreme space weather can be found in the following report: *Extreme Space Weather – Impacts on Engineered Systems and Infrastructure. Royal Academy of Engineering – February 2013 and EASA Safety Information Bulletin SIB No. 2012-09 Effects of Space Weather on Aviation.*

Static Random Access Memories - SRAMs

Multi-transistor cell – loses data when power lost

Widely used and studied for SEE

Earlier generations of SRAMs at the 0.15 to 0.5 micron scale – SEU

SEU saturated cross-sections (>10MeV) from 1 x 10^{-14} cm^2 /bit to 5 x 10^{-13} cm^2 /bit

For worst case cross-section would give (for 1 in 100yr, 1000yr, 10,000y scenarios) 37, 520, 4000 upsets in 1 Gbyte

HV devices (contd)

At ground level the neutron flux is ~ 20 n cm^{-2} hr^{-1} during quiet times

- time to failure in quiet conditions (without any ground level events) is 5 x 10^4 hours or ~6 years (no de-rating)

For extreme solar particle event (10,000 year case) the energetic neutron fluence is estimated at 1 x 10^6 cm^{-2} and thus a MOSFET with the above typical cross-section would be expected to fail (probability of 1) i.e. all such MOSFETs would be expected to fail.

Even in the 1 in 1000 year case, one in ten power MOSFETSs would be expected to fail

In practice these estimates are likely to be pessimistic since many MOSFETs will not be operated at high bias levels or only for a small fraction of the time

Below a certain threshold (often 50% of the rated maximum voltage) the risk is virtually eliminated - this is known as de-rating.

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