The New Jersey Chapter
of the Health Physics Society Presents:


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Shonka Research Associates, Inc.


**Topic:** Radiation in Flight

**Radiation dose to crews and passengers is increasing. Today's presentation discusses the sources and impact on future aviation.**

Thursday, April 14, 2016

# What I hope to Cover

- Why is this an important issue
- What are the significant sources of radiation
- What can/should you do?

# 22,000 Aircraft: 24 hours in 60 seconds

# Something to think about

- There are 22,000 passenger aircraft in use world wide
- They are airborne from 12 to 17 hours per day
- About 5,000 of those are wide body aircraft primarily used on long distance flights
- 4,500,000 people fly each day
- The equivalent of 700,000 people are living full time at 35,000 feet (about the population of Detroit, only 17 US Cities are larger).
- GCR Radiation levels are 5 uSv/hr (0.5 mrem/hr) or 100X levels at sea level, but acute doses from other sources > 100 mSv (10 rem) in a flight are possible

# Collective Dose GCR (alone) to Flying Public

- (US Hours / Departures) X US Passengers X FAA est. Sv/hr X (World/US)
- = (1.69E7 / 9.08E6) X 8.02E8 X 5E-6 X 5
- = 37,000 Person-Sv
  - Compared to Reactor Accidents:
  - TMI = 20 PSv (18,500 X smaller)
  - Fukushima = 36,000 PSv ~ 10 years (10X smaller)
  - Chernobyl = 42,500 PSv ~ (about 14 months of aviation today) (excludes liquidators)
- Aviation is doubling every 11 -12 years (~6% per year, 97% fit to exponential growth) since 1960 and exceeds Chernobyl in 2018.
- WHO estimates 4,000 deaths from Chernobyl, about 10X aviation accidents
- This estimate is based on Galactic Cosmic Radiation (GCR) alone
- US Population Dose from Nuclear Power 323E6 X 0.2E-6 Sv = 65 PSv

# US Aircrew, Highest Exposed Workers

- Since 1970s, emphasis on ALARA has made remarkable strides in reducing worker exposures in most industries
- Aircrew notable exception
- In 1992, the average dose received by US nuclear power workers was 3 mSv (300 mrem), continuing decline seen since the 1950's
- 2013 FAA estimate 6 mSv (600 mrem) from galactic cosmic rays alone (numbers vary)

# AIRCREW MEMBERS ARE THE HIGHEST EXPOSED GROUP OF RADIATION WORKERS

| UNSCEAR | Data Period | NFC* | Person-Sv | ACM** | Person-Sv | ACM/NFC |
|---|---|---|---|---|---|---|
| 2000 | 1992 | 800,000 | 1,400 | 250,000 | 800 | 57% |
| 2008 | 2001 | 660,000 | 660 | 300,000 | 900 | 136% |

*NFC = all radiation workers in the nuclear fuel cycle

** ACM = all aircrew members

average annual dose: NFC = 1 mSv; ACM = 3 mSv

# Dose to Aircrew (from last slide)

- The UNSCEAR compilation is for GCR and does not consider all sources
- All other workers derived from actual dosimetry and not estimates
- The average dose (partial, GCR only) estimated for aircrew is ~2X to 10X other industries
- Aircrew are > 6% of the total workforce but > 24% of the total Person-Sv
- Unlike all other industries, 80% of aircrew dose is due to neutrons
- Unlike all other industries, aircrew have not benefitted over the decades from a consistent ALARA effort
- Unlike all other industries, US aircrew are not provided with Dosimetry

# The FAA has no regulations for Airlines!
# Basis of FAA Approach: justification and limitation with no consideration of optimization

- Dose Limit 100 mSv averaged over 5 years
- GCR dose predictable; SPE dose avoidable
- Only few exposed to  > 5 mSv/year
- NRC monitoring level not met
- Safety assurable without regulation
- Crewmembers can choose low-dose flights
- FAA to provide
    - Advisory information
    - Dose estimates for representative flights

# FAA Advisory Circulars

- FAA does not have regulations for airlines dealing with aircrew dose
- Aircrew are provided Rad Worker training in the form of advisory circulars
- The FAA asserts that they follow ACGIH guidelines
- ACGIH recommends 2 rem per year averaged over 5 years
- ACGIH also recommends ALARA (optimization) in addition to the limit
- FAA does not implement ALARA, but treats the ACGIH guidelines as absolute limits in a similar fashion to structural limits on airframes

# In 2014, FAA Published revised guidance in AC-120-61B, offered aircrew guidance on ALARA

**b. How to Reduce Exposure.** Exposure management should be based on the ALARA principle. The amount of galactic cosmic radiation exposure received while flying depends on the amount of time in the air, altitude, latitude, and solar activity. Lowest dose rates at a given altitude are found near the equator and increase as one approaches the poles. For any location at commercial flight altitudes, a higher altitude will incur a higher dose rate. Responding to a solar radiation alert by flying at a lower altitude can significantly reduce radiation exposure in high-latitude areas of concern, particularly if the response is rapid.

- Flight attendants are min 21 with min High School, but AC-120-61B is written at college level with readability index of only 20% (per WORD).

# Even the best trained pilot have problems calculating their dose using CARI

**FEDERAL AVIATION ADMINISTRATION**
**OFFICE OF AEROSPACE MEDICINE**
**CIVIL AEROSPACE MEDICAL INSTITUTE**

These forms require a javascript enabled browser.

Left Click on HELP
For Instructions
HELP

## Galactic Radiation Received In Flight

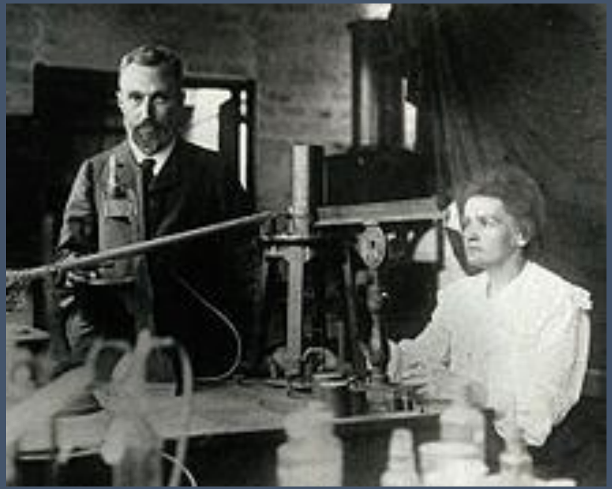
| Enter Flight Data | | |
|---|---|---|
| **Date of Flight** | 05/2015 | 01/1995 = January 1995<br>00/1995 = Average for 1995 |
| **Origin Code** | Klax | - Enter ICAO Code or<br>Look Up Origin Code |
| **Destination Code** | EGLL | - Enter ICAO Code or<br>Look Up Destination Code |
| **Number of en route altitudes** | 3 | |
| **Minutes to 1st en route altitude** | 35 | |
| | Continue | On the next screen you will be asked for en route altitudes, flight times and time spent in final descent.. |

## Galactic Radiation Received In Flight

| **Flight Summary** | | |
|---|---|---|
| Date of Flight | **05/2015** | |
| Origin Code | **KLAX** | LOS ANGELES, CA |
| Destination Code | EGLL | LONDON, UNITED KINGDOM |
| Number of en route altitudes | 3 | |
| Minutes to 1st en route altitude | 35 | |
| **En route altitude(s) and time(s)** | Altitude (in feet)<br>**310**<br>**330**<br>**350** | Minutes at altitude<br>**124**<br>**209**<br>**189** |
| Minutes descending to touchdown | 28 | |
| **Effective Dose** | **0.41 microsieverts (0.00041 millisieverts)** | |

# Galactic Cosmic Radiation

Curies discovery radium 1903

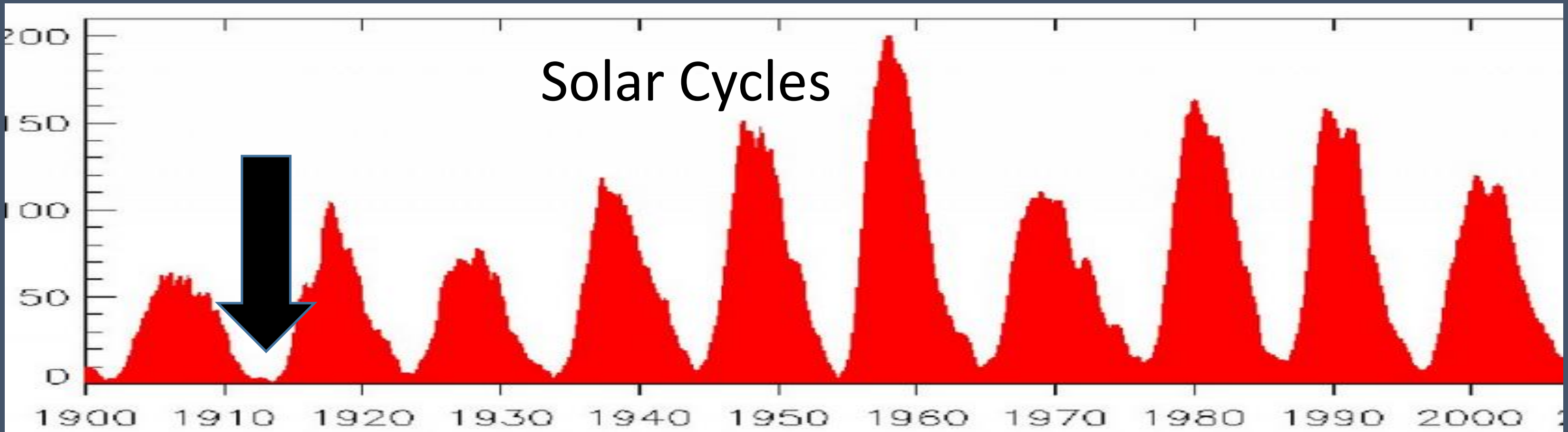


Fr. Wolf Eiffel Tower 1910, 900’

Hess 8/7/1912 Discovery of Cosmic Rays

1935 **Hideki Yukawa Meson Theory 1949**

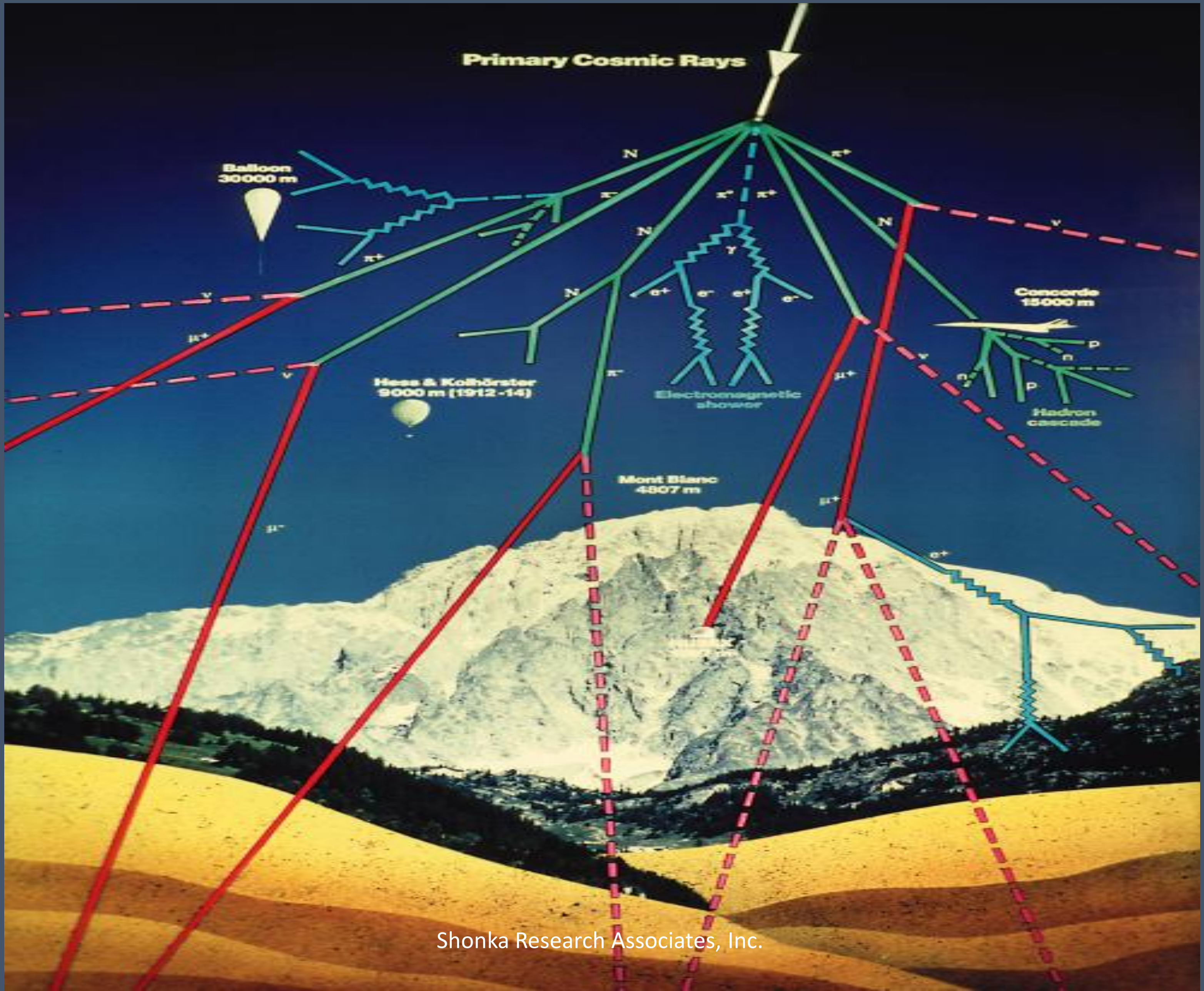
# Lucky Hess


Solar Cycles
200
150
100
50
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000


2,300 km Eclipse
Bay of Biscay
France
Prague
Czech Re
Bern
Vienna
Austria
Buda
Hun
Ljubljana
Slovenia
Croatia
11.3W
Portugal
Spain
Madrid
Lisbon
Italy
Sarajev
Balearic Sea
Rome

# Hess Flight Plan, 7 August 1912

# GCR Produces a Cascade of Particles

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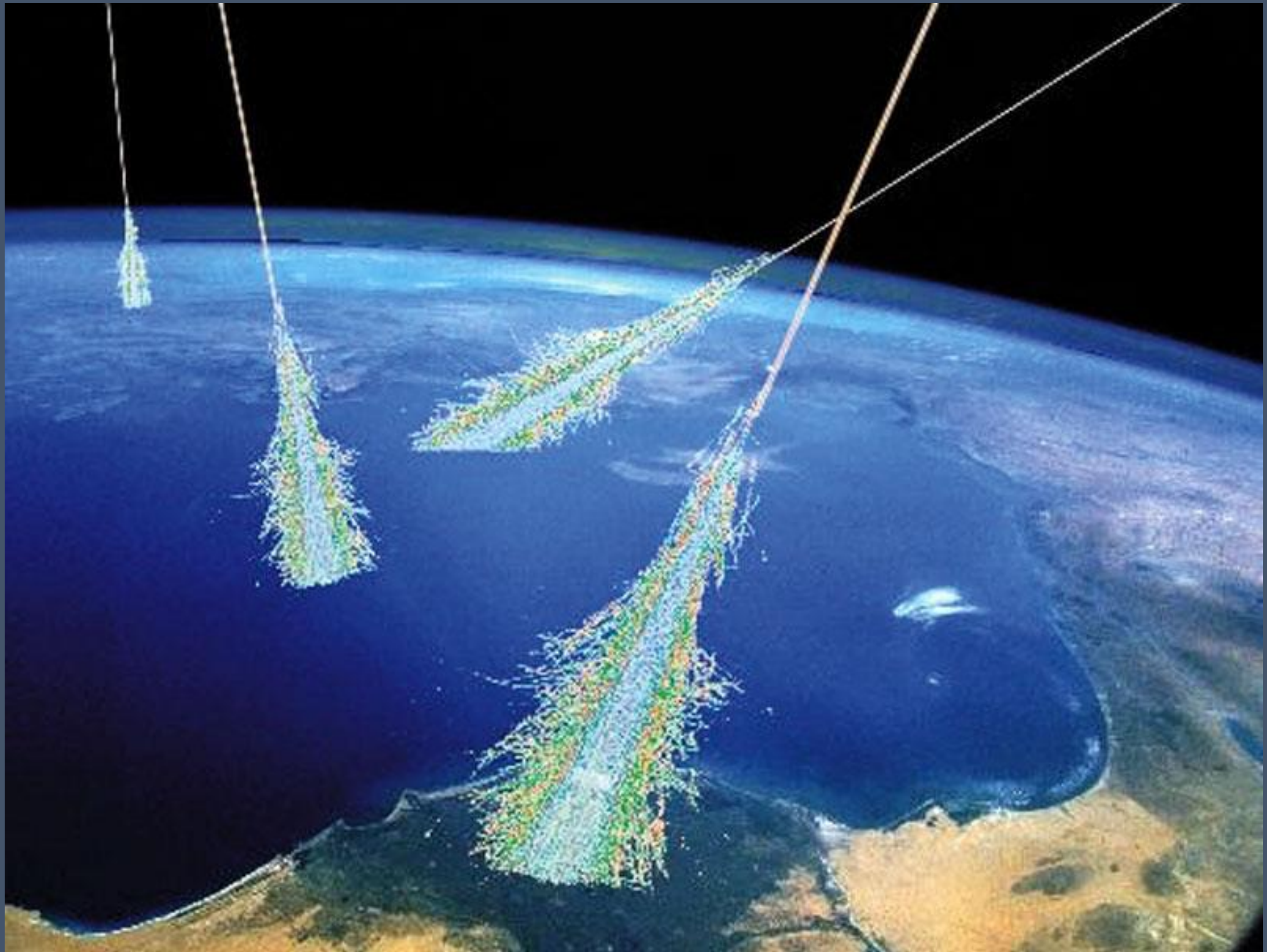
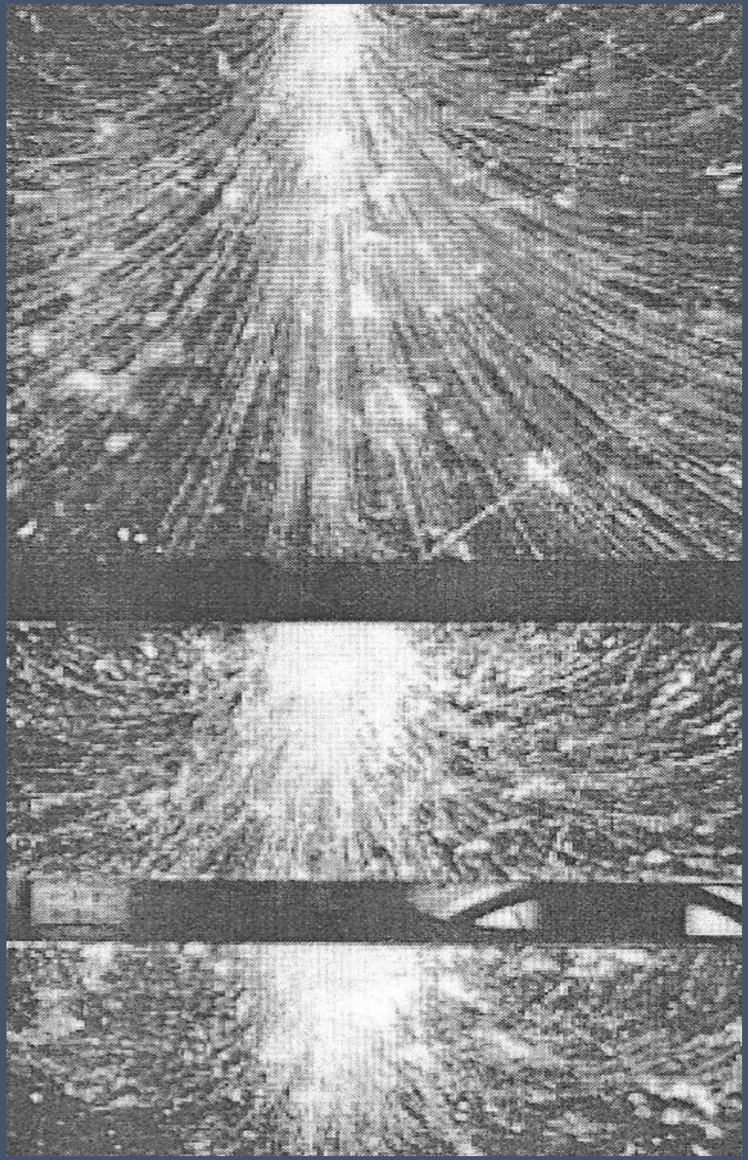
# Artist Conception of Nuclear Cascade



# 1950's Bubble Chamber Image of Electromagnetic Cascade

A single 50 MeV Electron Entered from above and initiated the electromagnetic cascade. Mag field bends positrons and electrons in opposite directions. The sweeps them out, limiting the cascade.  Blank regions are 1.27 cm lead which restarts the cascade.

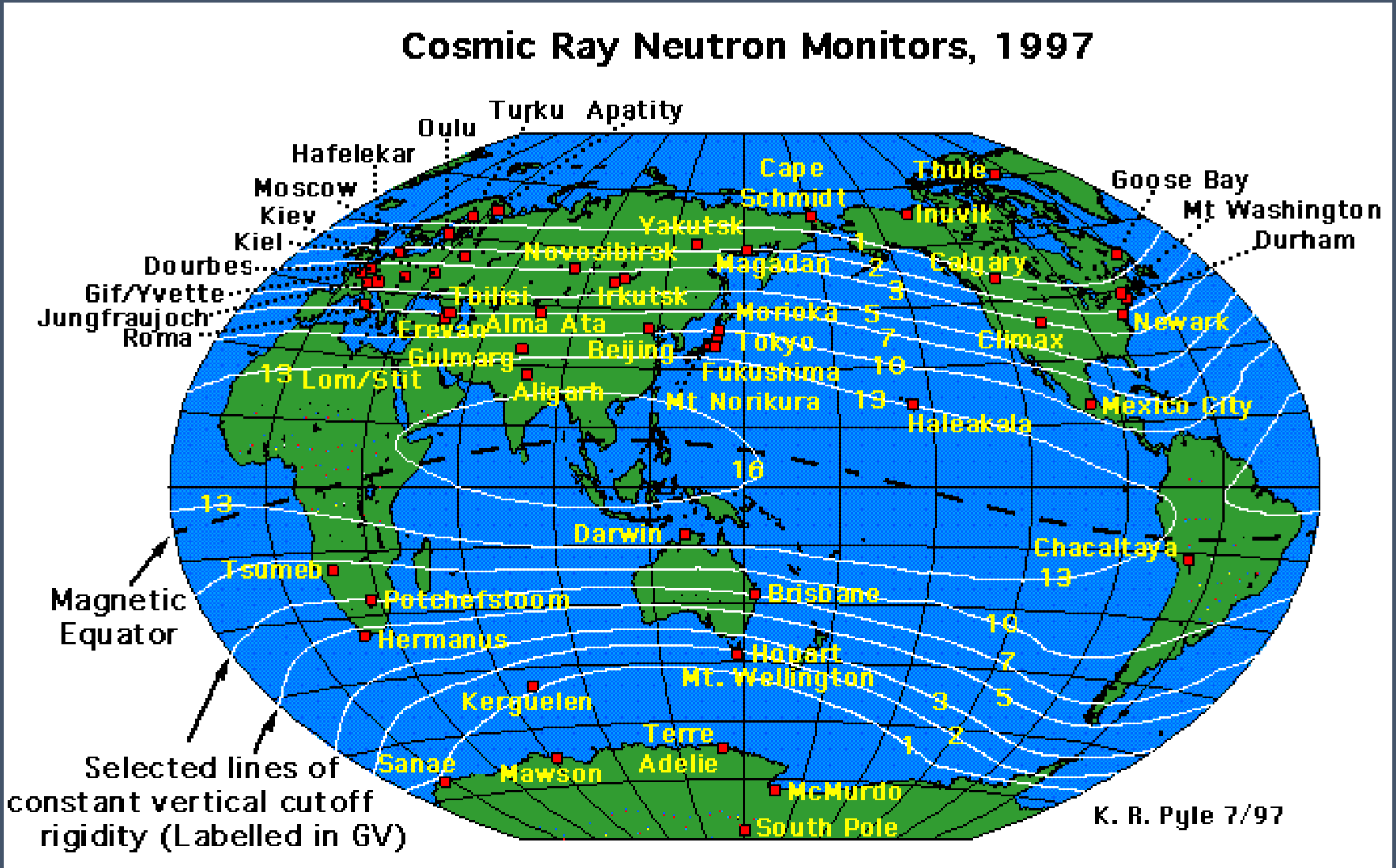


# GCR Penetration Through Air

**0.2** kg/cm²
**32%**

**0.32** kg/cm²
**16%**

**1.03** kg/cm²
**0.3%**

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# WHAT IS A NEUTRON MONITOR ?

Neutron Monitor in Nain, Labrador
Construction completed November 2000

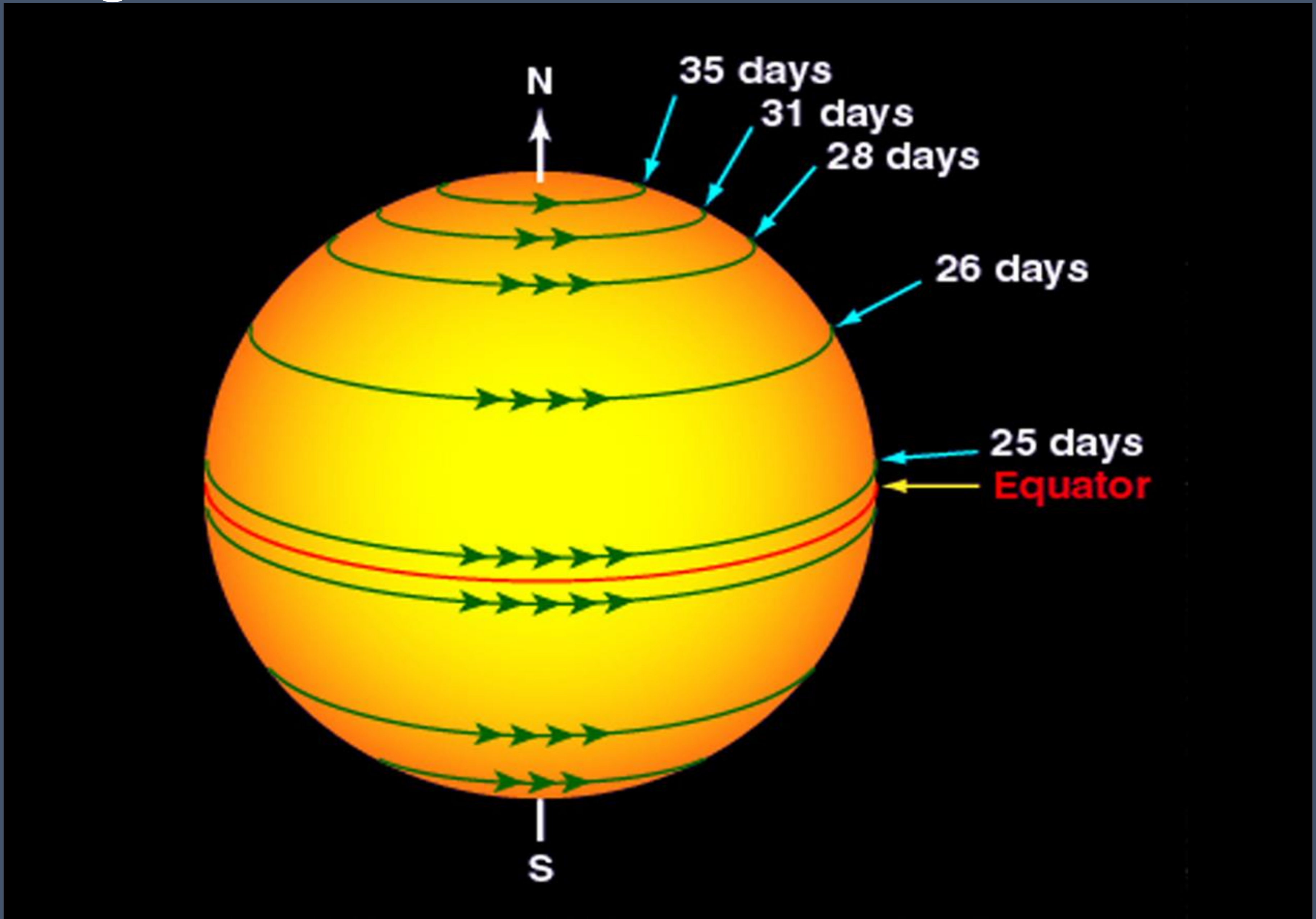
- A large instrument, weighing ~32 tons (standard 18-tube NM64)
- Detects secondary neutrons generated by collision of primary cosmic rays with air molecules
- Detection Method:
  - Older type – proportional counter filled with $BF_3$:
    $n + {}^{10}B \rightarrow \alpha + {}^{7}Li$
  - Modern type – counter filled with ${}^{3}He$:
    $n + {}^{3}He \rightarrow p + {}^{3}H$

# Sources for Aircrew other than GCR
(arrow bullets = not well known)

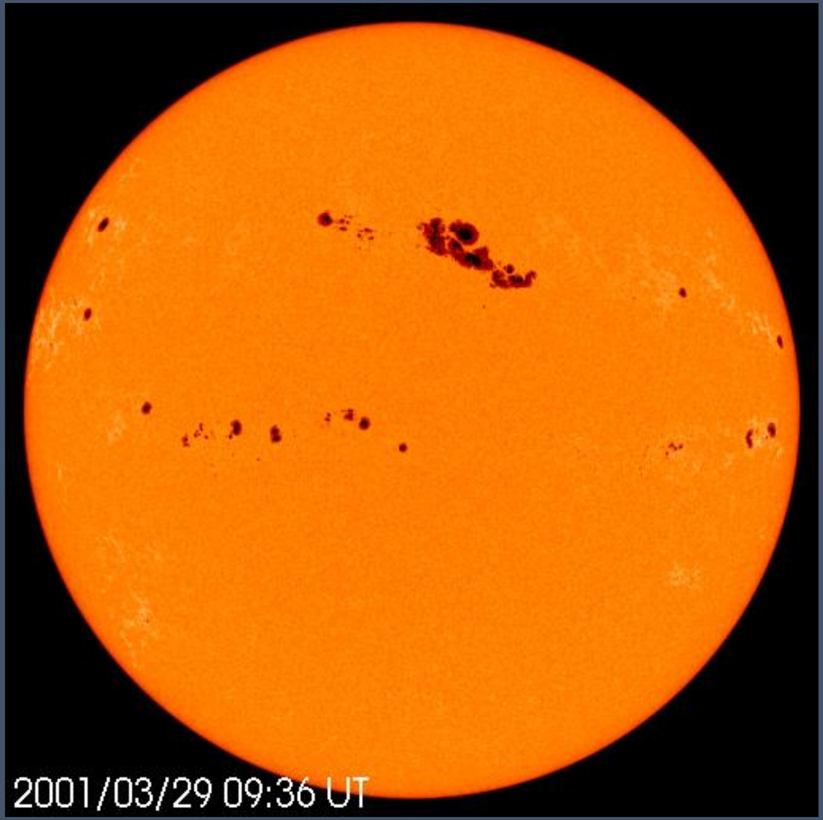
- ❖Solar Proton Events (SPE)
- ➢Solar Neutron Events (SNE)
- ➢Solar Gamma-Ray Events (SGE)
- ➢Terrestrial Gamma-Ray Flashes (TGF)
- ➢Terrestrial Neutron Flashes (TNE)
- ➢Thundercloud Gamma Event (TGE, also called “glow”)
- ❖Radioactive Cargo
- ➢Required Medical Exams
- ➢Transpolar Routes (since 2000)

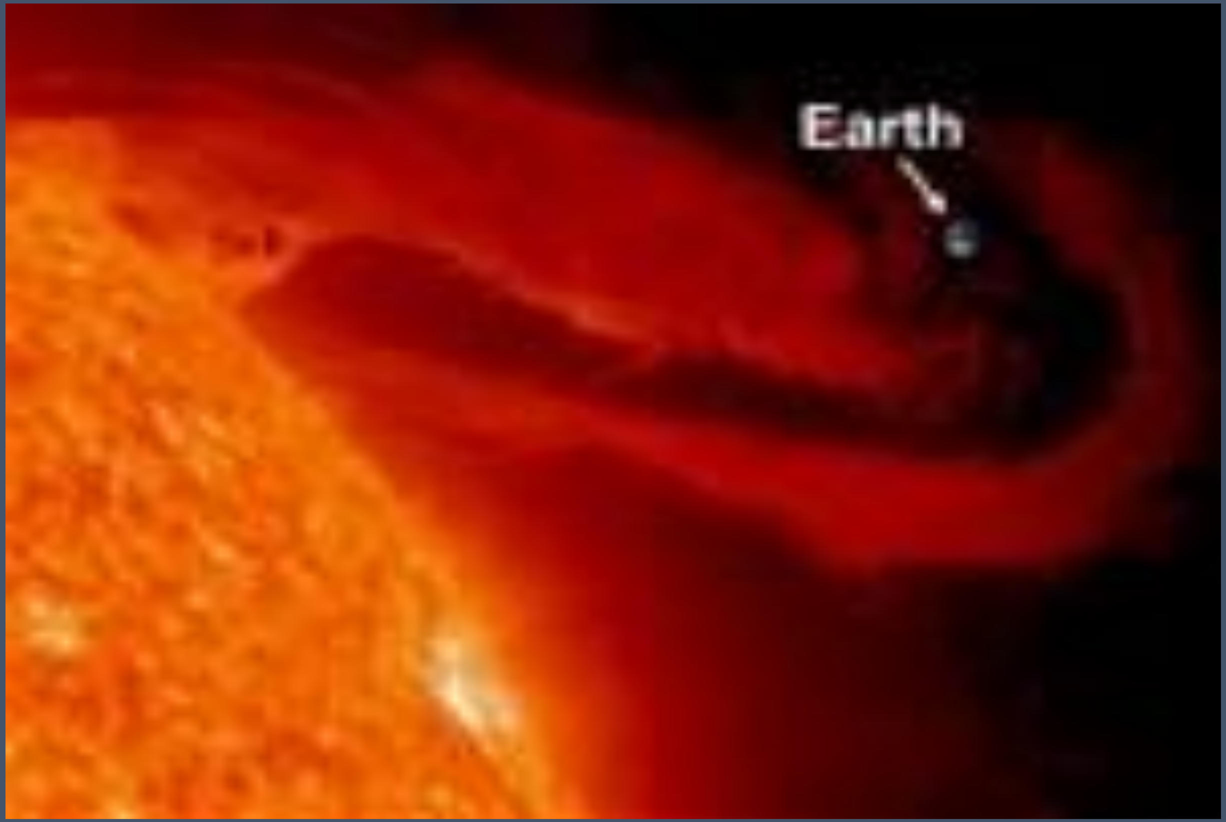
See Bramlitt and Shonka HPJ 108(1) 76-86 (2015)

# Regions of Sun Rotate at Different Rates

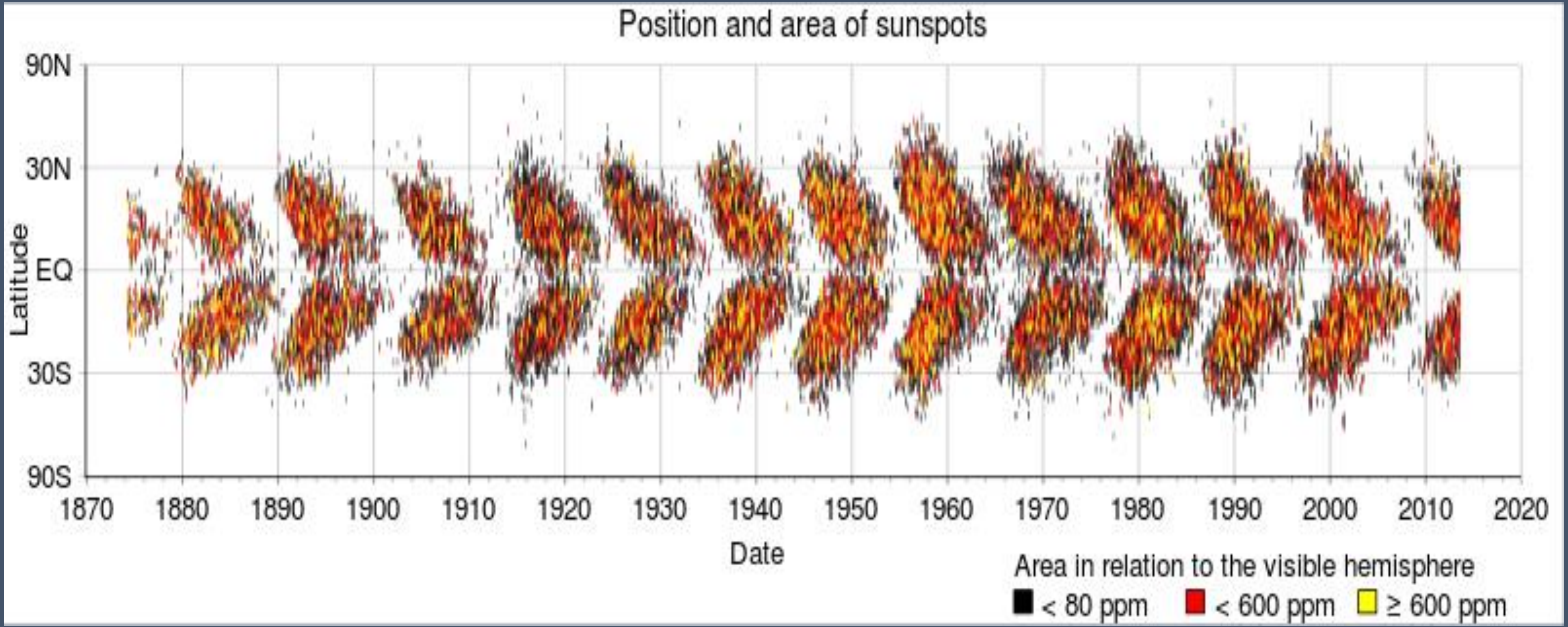


# Sunspots are created, which can flare and eject particles



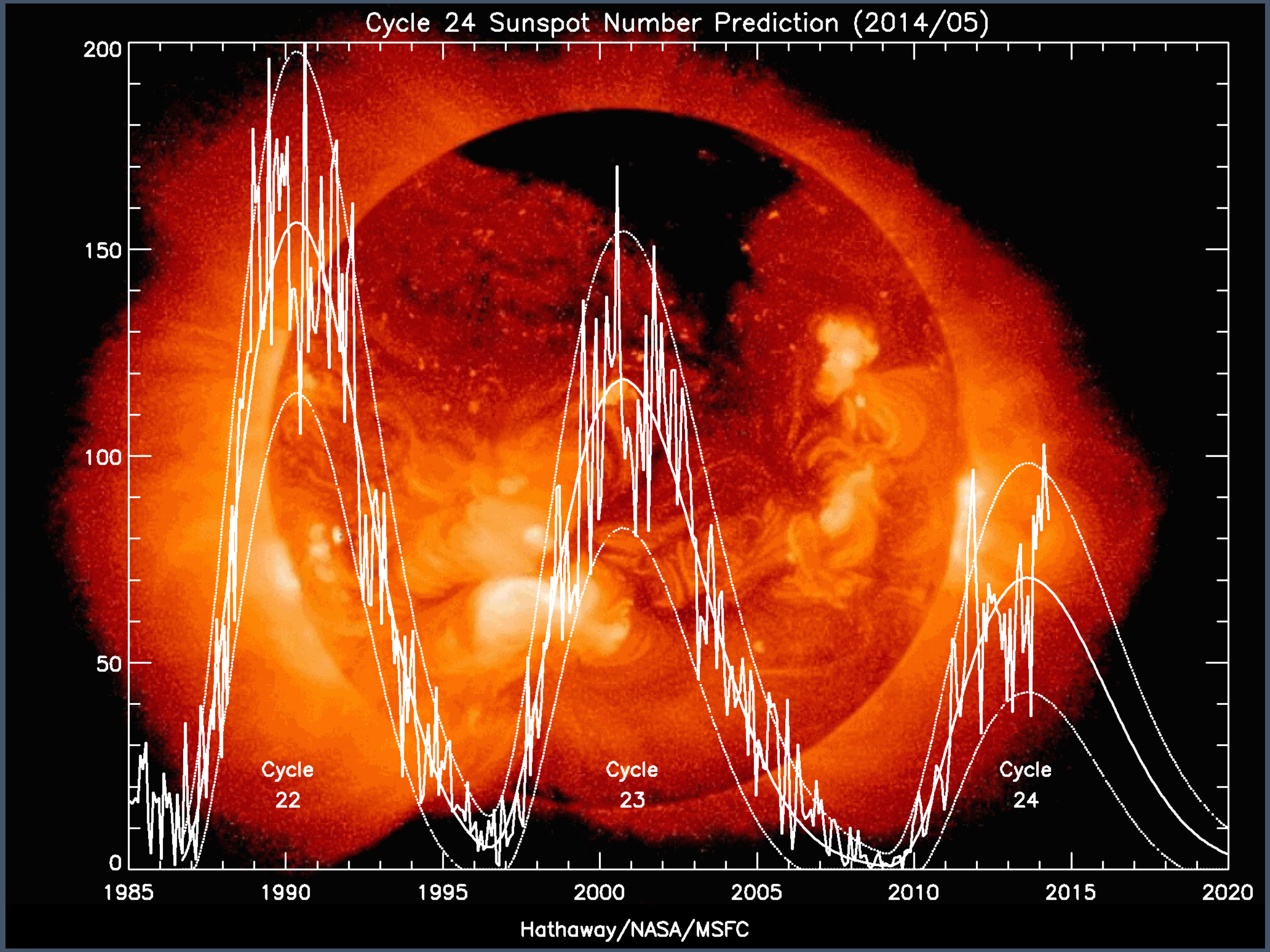



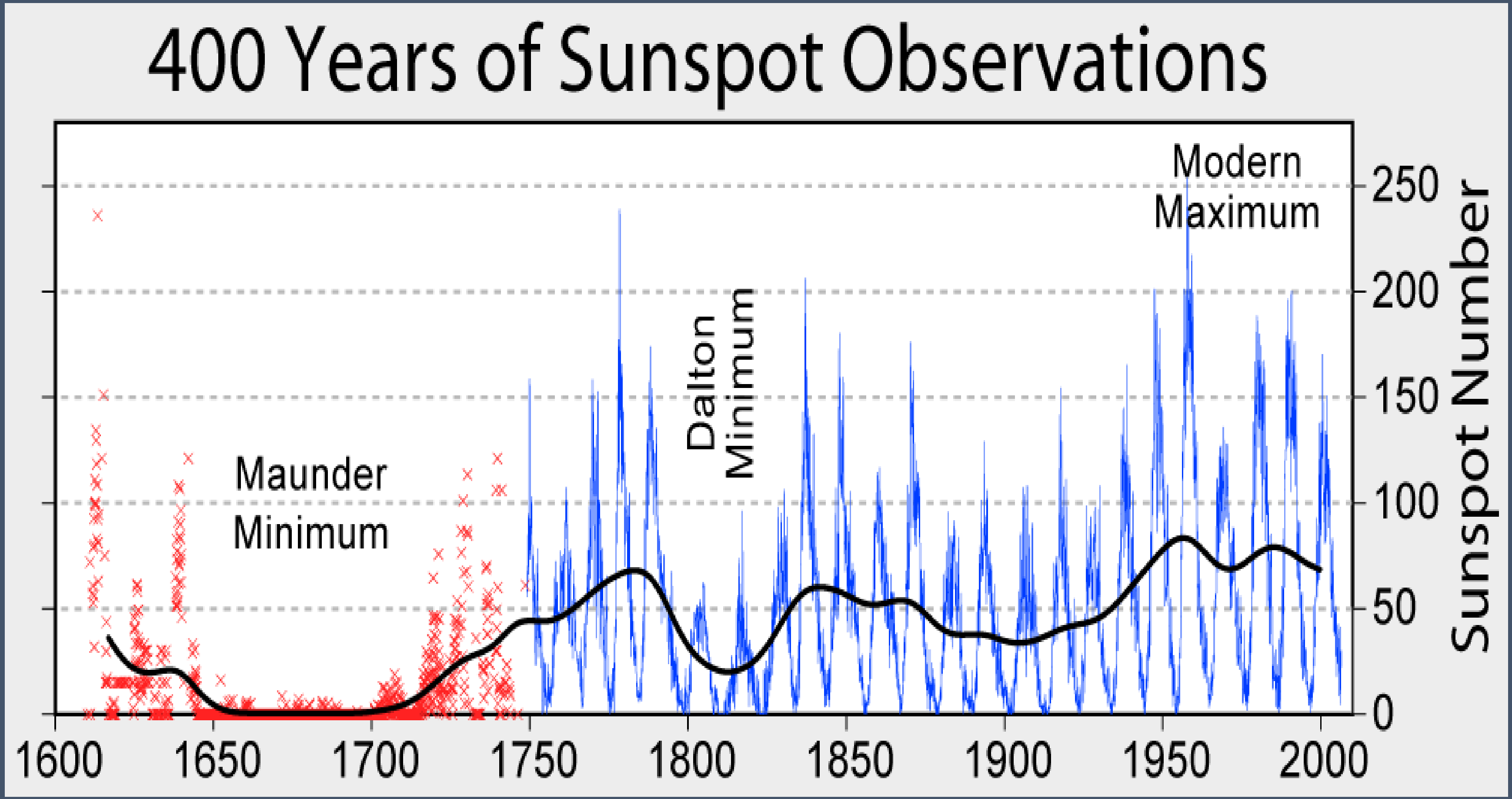
# Butterfly Pattern of Sunspots showing 11 year cycle of pole reversal



# Ionizing Radiation from Sun Flares

Charged particles, Neutrons, Gamma Rays





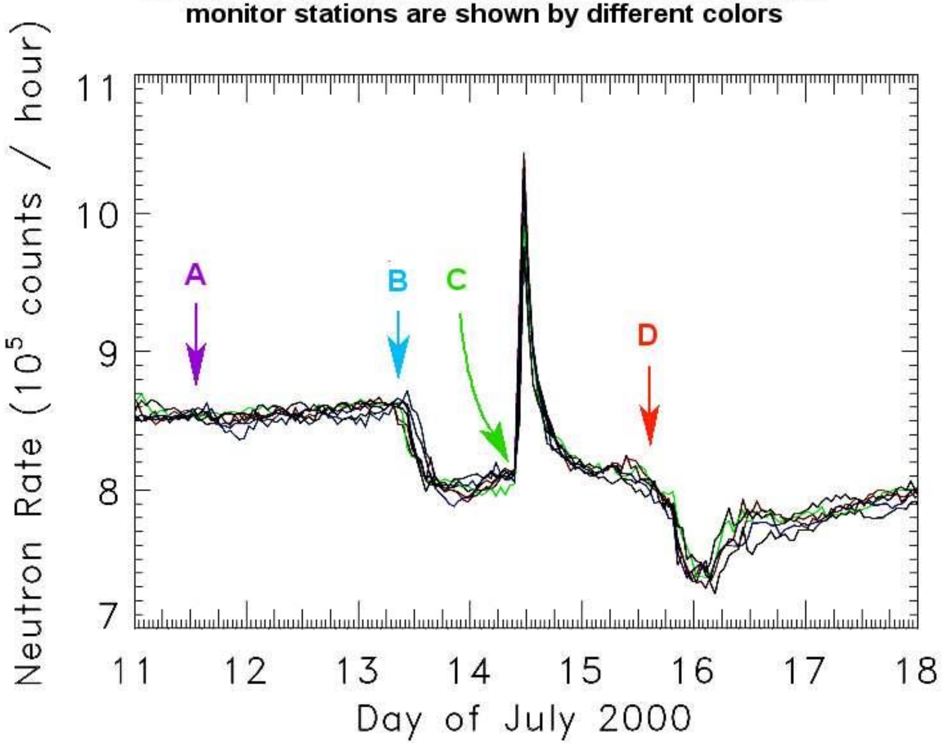
400 Years of Sunspot Observations
Modern
Maximum
Dalton
Minimum
Maunder
Minimum
250
200
150
100
50
0
Sunspot Number
1600
1650
1700
1750
1800
1850
1900
1950
2000

# Major Solar Storms

- Since 1859, more than 300 major solar storms
- 8/28/1859 – Carrington event (largest in 500 years)
- 1862 – Fredericksburg
- 1956 – Acheron Storm
- 2/11/1958 Storm that formed the basis for requiring radiation detectors in the Concorde SST
- 1989 – Quebec Blackout
- 6/4/91 – Muraki Neutron Event Measurement (more on this later)
- October – November, 2003 Series of Storms lead to the creation of SWPC

## Cosmic Rays during High Solar Activity

**Cosmic ray variations recorded at 7 different neutron monitor stations are shown by different colors**




**A: First coronal mass ejection (CME) at Sun.**

**B: First CME arrives at Earth. Cosmic rays decrease suddenly --- a "Forbush decrease."**

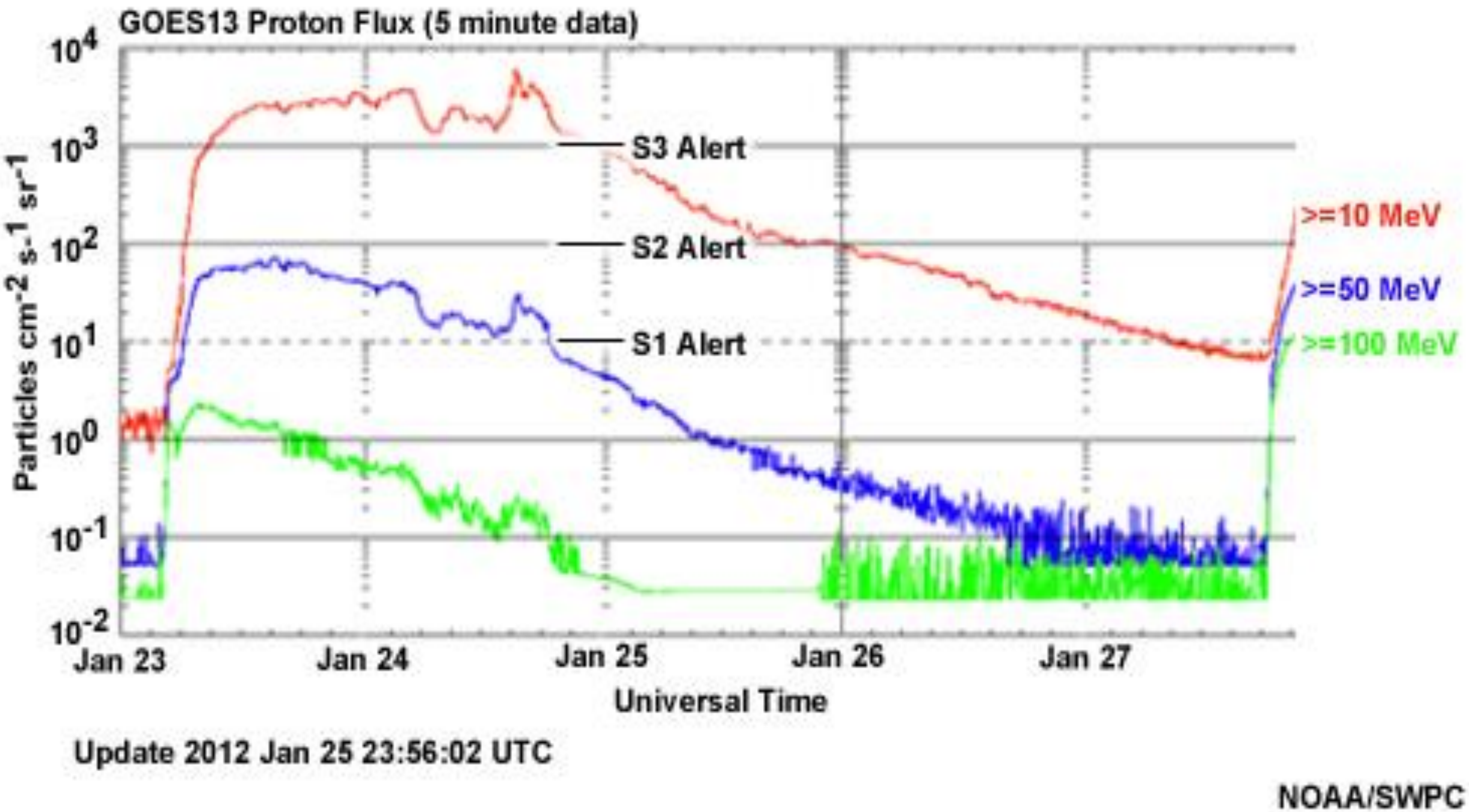
**C: Second CME at Sun. This one accelerates high energy particles that reach Earth minutes later. The sudden increase recorded by the neutron monitor is a "ground level enhancement."**

**D: Second CME arrives at Earth. Cosmic rays decrease again. This CME produces the largest geomagnetic storm in 10 years. Aurora observed as far south as Georgia.**

# Solar Proton Events (SPE)

- Affected by Magnetic Fields
- Dose impacts high latitude and Polar Route flights
- *GOES* (weather) satellite detections
- When ground-based neutron monitor (NM) detect (event is then called GLE)
- SWPC warnings/alerts based on *GOES* counts
- *GOES* reports 250 SPE; NM report 39 GLE

# GOES 13 Proton Flux Data



# Solar Neutron Events (SNE)

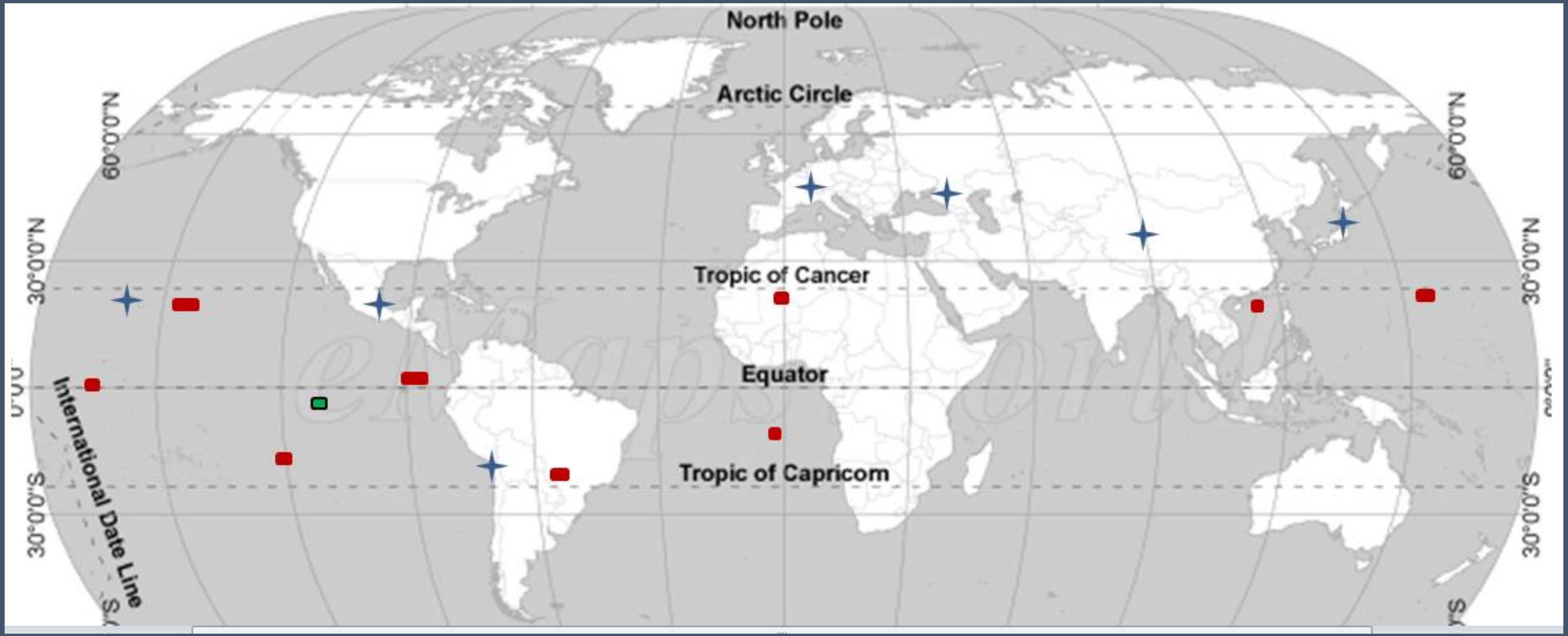
- Unaffected by Magnetic Fields
- Expose entire Daylight side of Earth
- Intensity greatest within Solstice Latitudes
- Solar Neutron Telescopes can detect (only 8 worldwide)
- Details in Note submitted to HPJ by Bramlitt and Shonka
- CO-2 increase in 775 AD may be due to SNE/SGE
- If so, dose to aircraft up to 400 mSv (paper in preparation)

# 1992 Muraki reported SNT Measurement of SNE

- Muraki Y, et al ,Solar neutrons associated with the large flare on 1991 June 4. Astrophys J 400:L75−L78; 1992.
- The SNT located at Mount Norikura at elevation 2,770 m and 36.10 degrees N and 137.55 degrees East.
- Reported 188 counts, 16.5% efficiency, 165 to 196 MeV energy bin only
- Factor of 400 less shielding from SNT (776 g/cm^2) to FL390 (200 g/cm^2)
- 0.5 mSv from that energy bin alone.
- SPEs have E^-2 to E^-5 energy spectra, if SNEs are similar, total dose depends on spectra

# Solar Neutron Events (SNE)

SNT Locations as Blue Stars

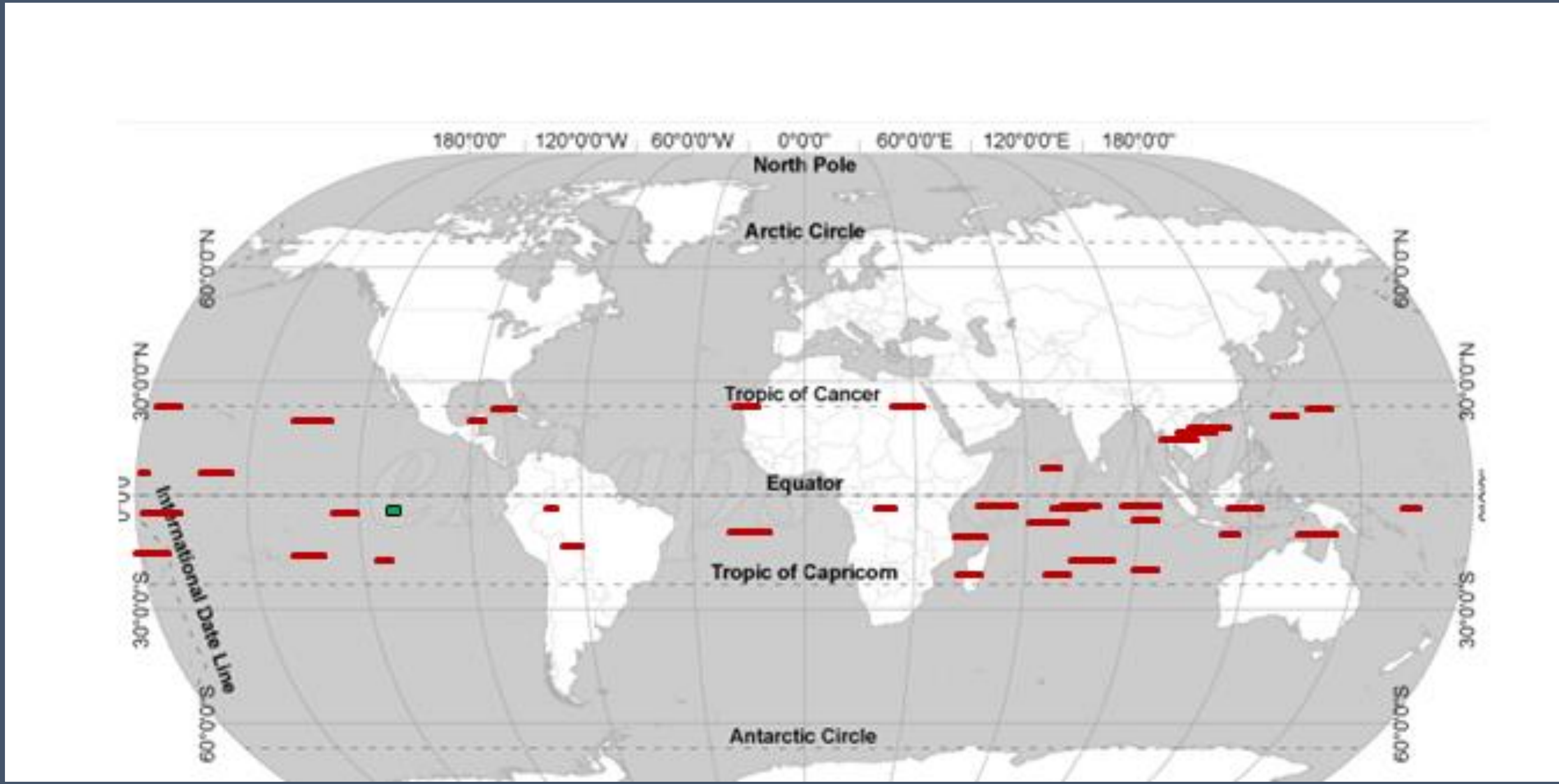


# Solar Gamma-Ray Events (SGE)

- Unaffected by magnetic fields
- Expose entire daylight side of Earth
- No detection system for radiation safety
- Largest measured SGE detected by Fermi Satellite (launched 2008)

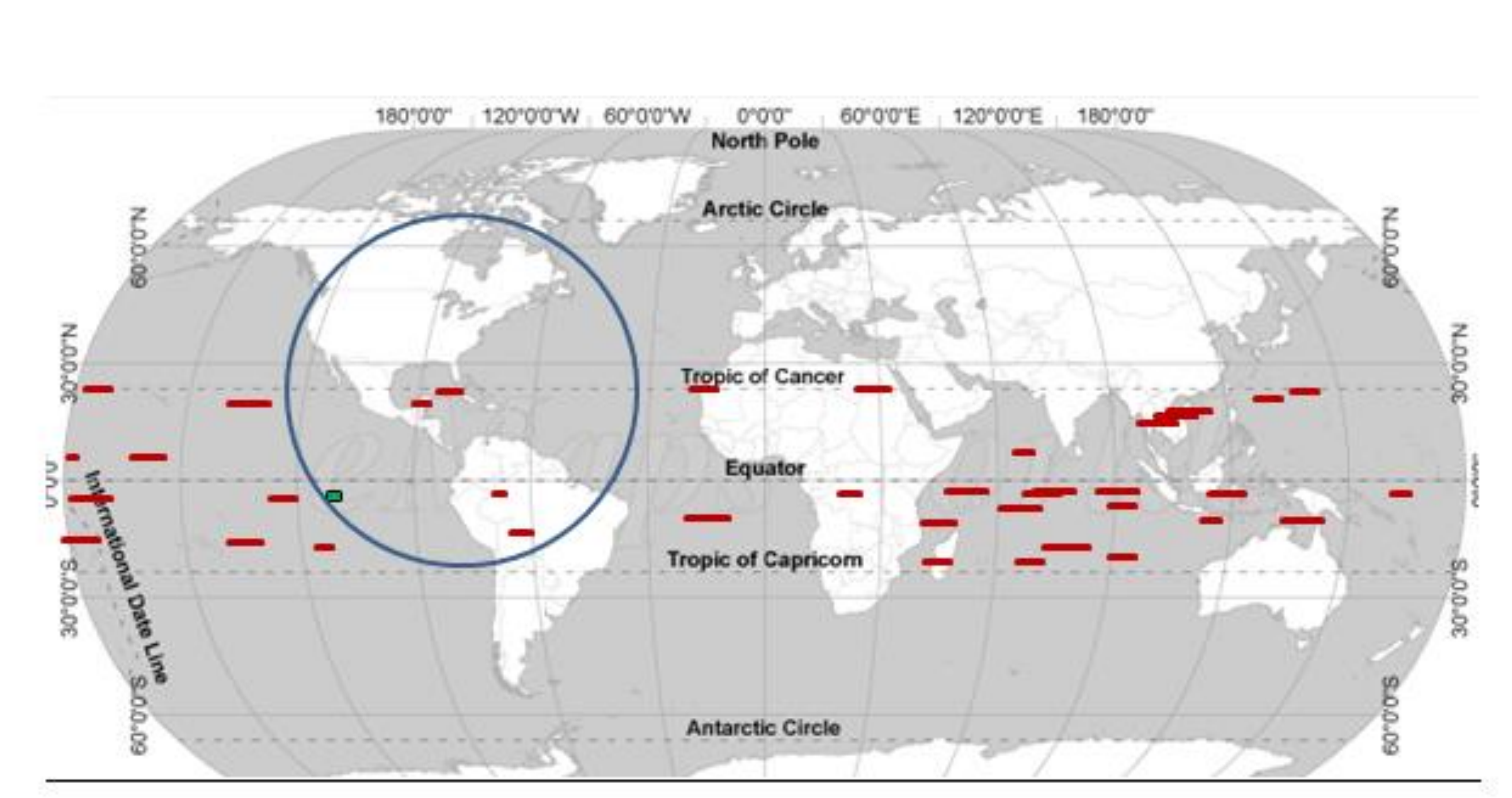
# Solar Gamma Ray Events (SGE)

## Detections Near and On Earth



# Airplane Shielding from SGE/SNE

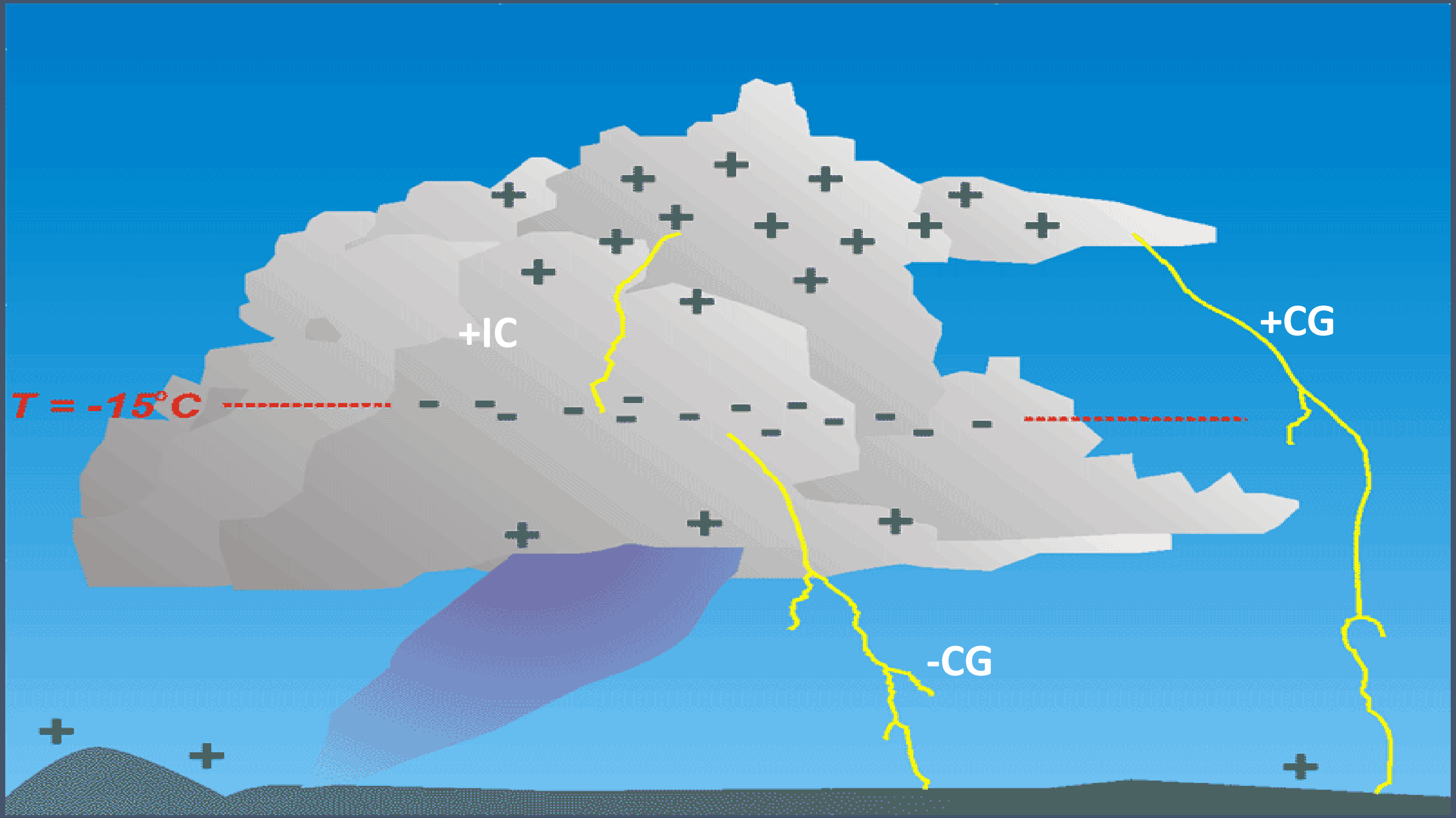
Sub-solar Points at 0.2 kg/cm²; Circle at 0.3 kg/cm² which is factor of 2 lower than sub-solar



# Terrestrial Gamma-Ray Flashes (TGF)

- **Associated with lightning**
- **Discovered in 1990 (CGRO)**
- **Pulsed gamma rays to 100 MeV, (detected by Fermi)**
- **2005 estimate at flight level: 30 to 100 mSv to all on board**
- **After briefing by NASA, FAA acknowledged in 2013**
- **FAA issued warning to pilots to avoid flying through or over thunderstorms stating that dose could be 30 mSv**

Types of lightning strokes:



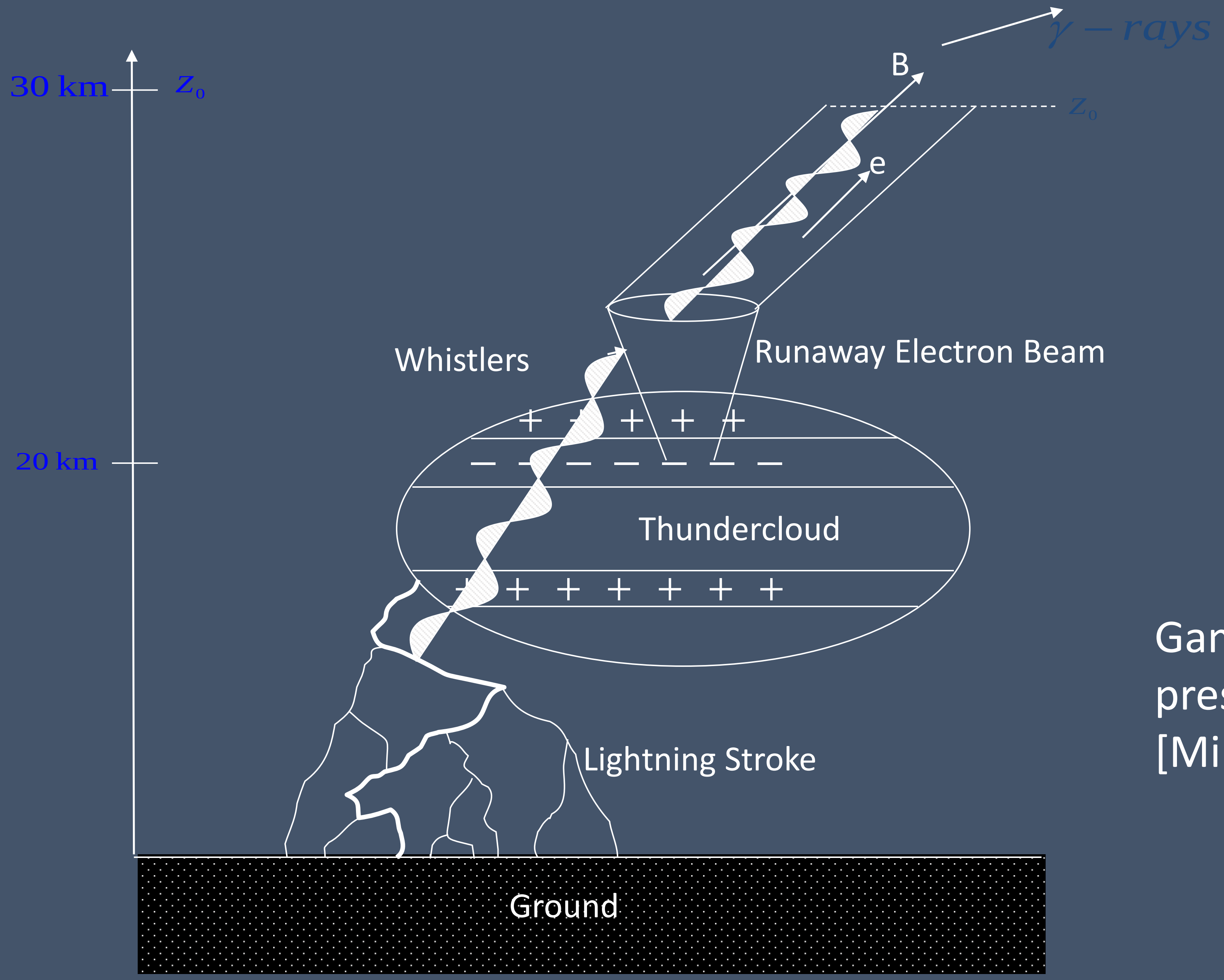
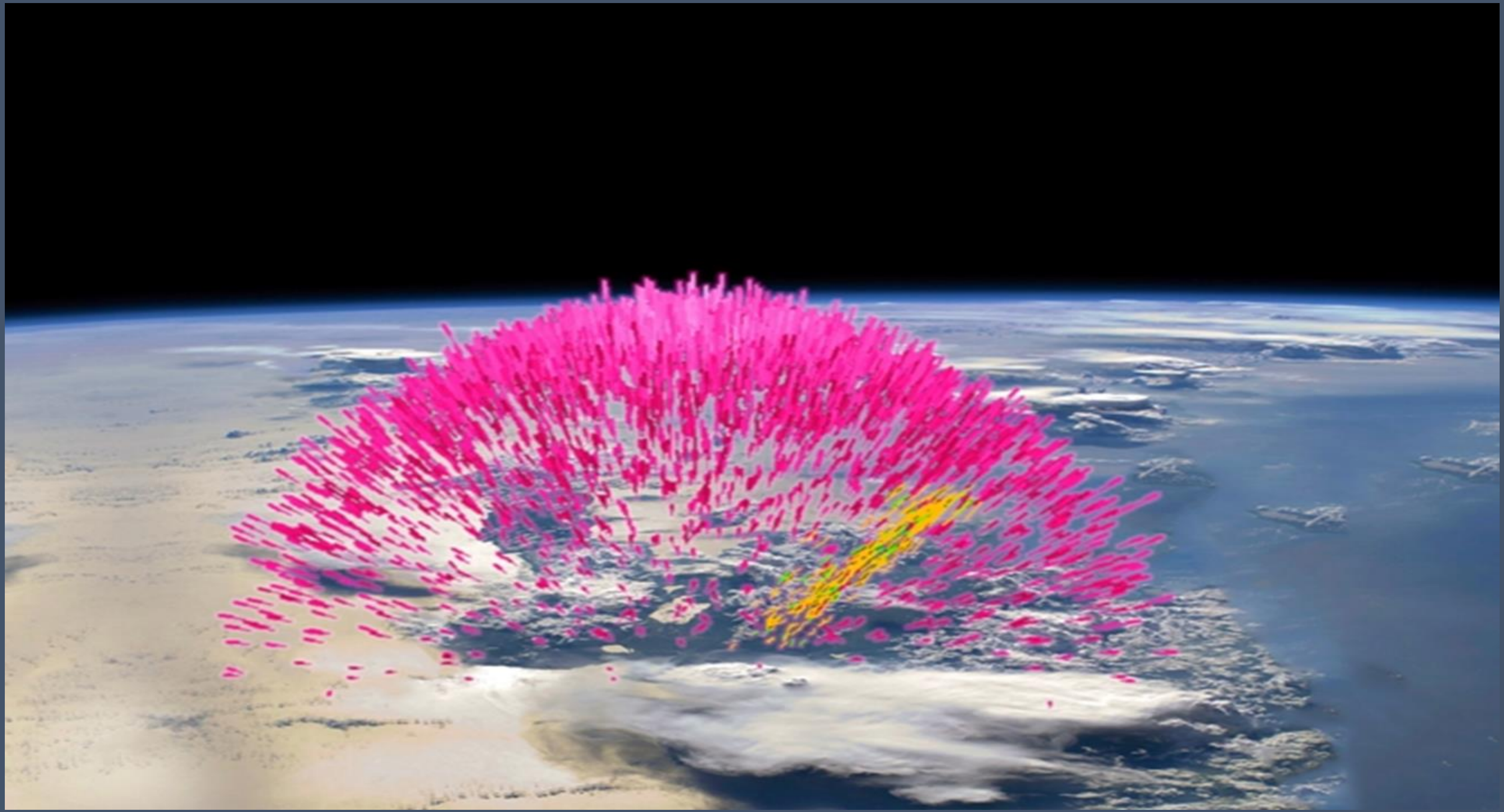


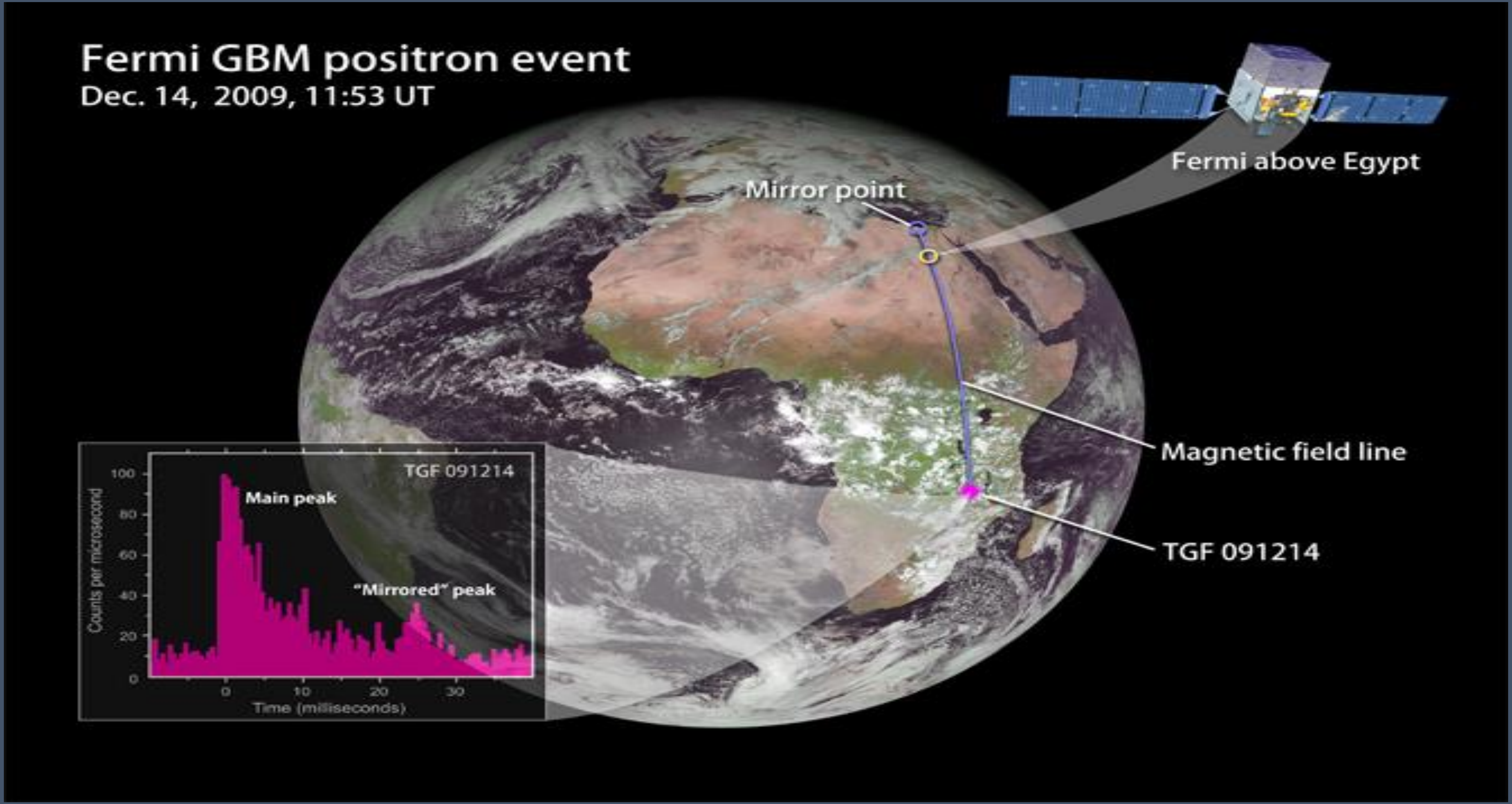

Fig. 1
Gamma-ray bursts in the presence of thunderclouds [Milikh et al., 2005]
(Univ. Md.)

Red – Gamma rays (isotropic in upward hemisphere)

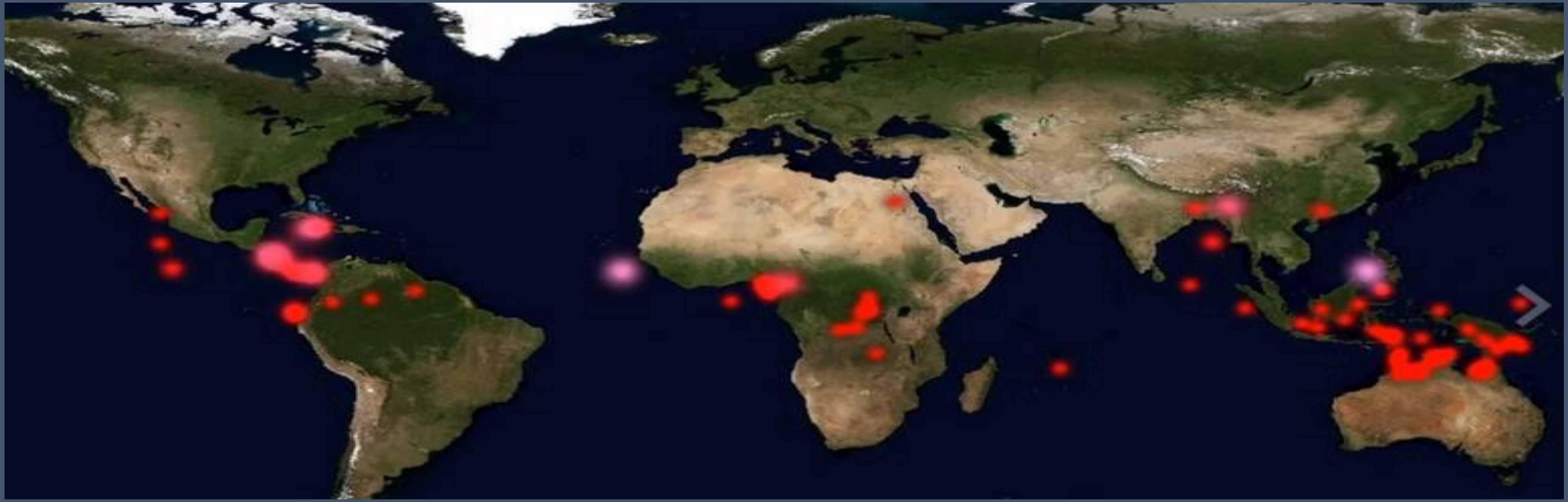
Altitude origin yet unknown, but within thunderstorm region (troposphere)

Yellow – Electrons and positrons trapped on Mag. Field lines




Fermi GBM positron event
Dec. 14, 2009, 11:53 UT
Fermi above Egypt
Mirror point
Magnetic field line
TGF 091214
TGF 091214
Main peak
"Mirrored" peak
Counts per microsecond
Time (milliseconds)

# Terrestrial Gamma Ray Flashes



1,200 ± 100 per Day

# TGFs

<u>Radiation Concerns for Air Passengers and Crew:</u>

I. Are the TGFs that are observed by spacecraft at 550 kilometers in space (more than a million reduction from inverse square law and and additional 1,000 reduction from the 200 g/cm^2 air shielding) produced at aircraft altitudes?

II. Is there a class of “mini-TGFs” that are much more numerous and produced at aircraft altitudes (that we cannot measure in space at 550 km)? Are they lower energy than the 100 MeV events observed in space?

III. If they are produced above aircraft altitudes, is significant radiation scattered downward?

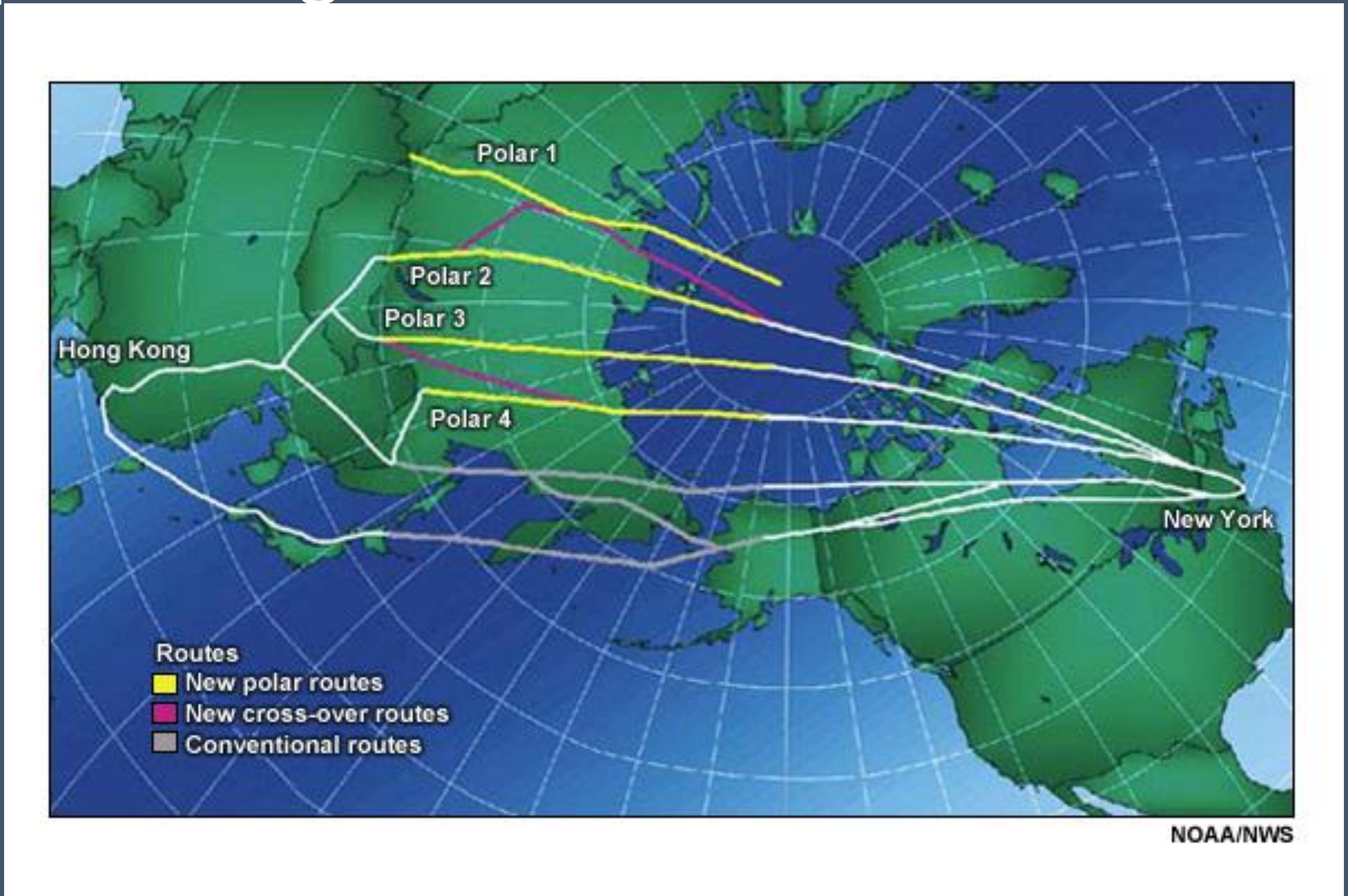
IV. Dwyer has published estimates that a single TGF can produce as much as 100 mSv to all occupants of a commercial airliner (and the FAA, based on that estimate has revised their advisory circular warning aircrew about TGFs). Dwyer, et al. *<u>JGR</u>*, Dec. 2009

V. Are there any precedents that Radiation Safety professionals are aware of that would shape actions that should be taken?

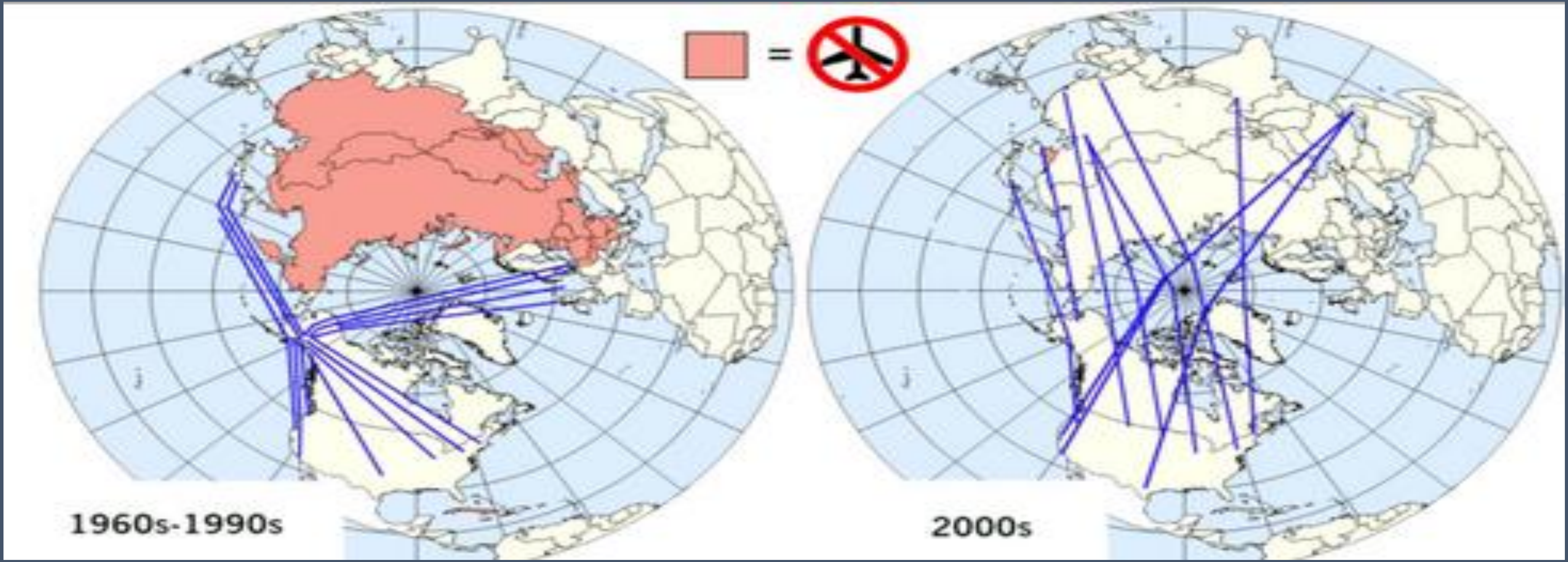
# TGF and flying while Pregnant

- *HPS – FAQ: Can I continue flying (domestic as well as international flights) while I am pregnant?*
- **When a pregnant passenger is flying on a commercial airline, she should not be concerned about the effect of flying on the developing fetus.**
- There are estimates for Terrestrial Gamma Flashes (TGF) of 100 mSv, and NASA est. 1100/day, 1% of which reach 100 mSv
- NCRP has 0.5 mSv per month once a pregnancy is known

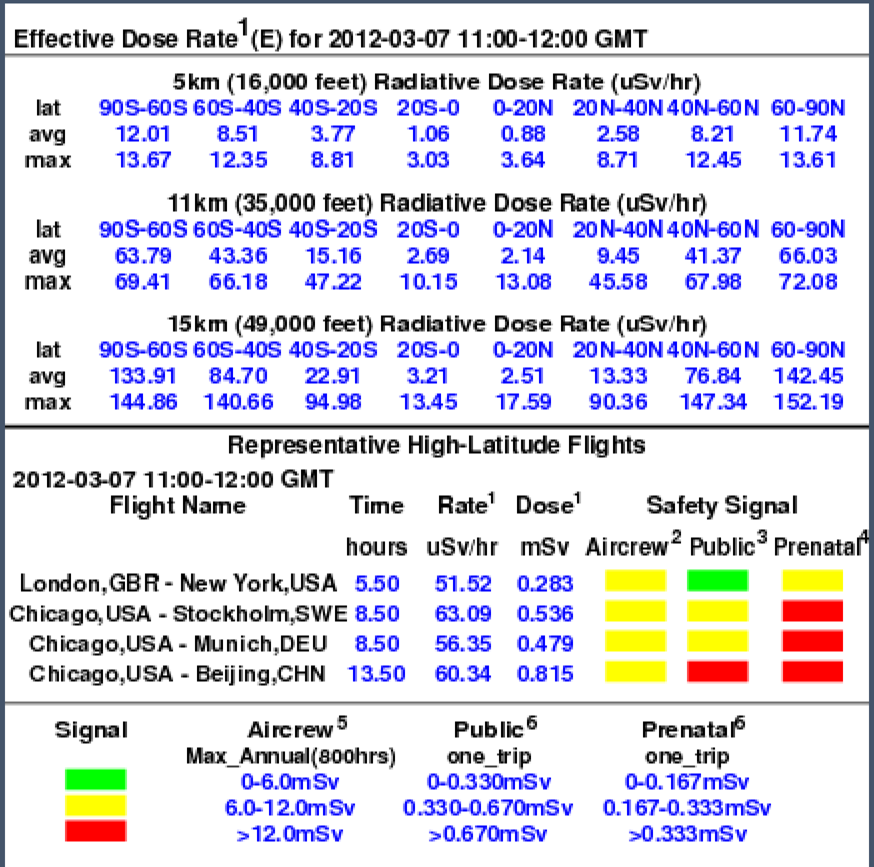
# Transpolar Flights



# Polar Flights



# NAIRAS Model Predictions During March 2012 Solar Storm Events



Effective Dose Rate[1](E) for 2012-03-07 11:00-12:00 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 | 12.01 | 8.51 | 3.77 | 1.06 | 0.88 | 2.58 | 8.21 | 11.74 |
| max | 13.67 | 12.35 | 8.81 | 3.03 | 3.64 | 8.71 | 12.45 | 13.61 |

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 | 63.79 | 43.36 | 15.16 | 2.69 | 2.14 | 9.45 | 41.37 | 66.03 |
| max | 69.41 | 66.18 | 47.22 | 10.15 | 13.08 | 45.58 | 67.98 | 72.08 |

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

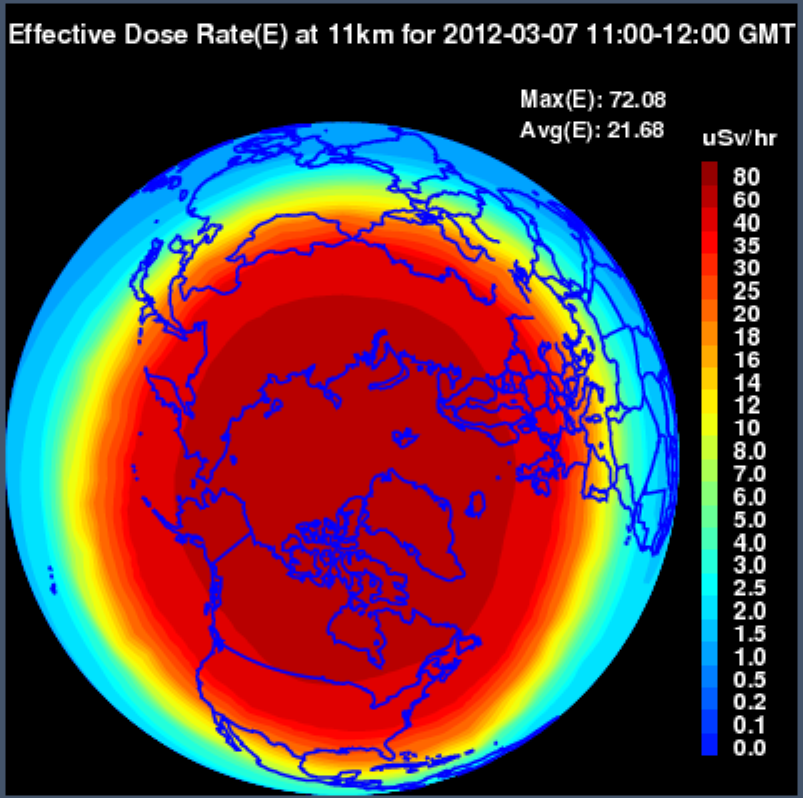
| lat | 90S-60S | 60S-40S | 40S-20S | 20S-0 | 0-20N | 20N-40N | 40N-60N | 60-90N |
|---|---|---|---|---|---|---|---|---|
| avg | 133.91 | 84.70 | 22.91 | 3.21 | 2.51 | 13.33 | 76.84 | 142.45 |
| max | 144.86 | 140.66 | 94.98 | 13.45 | 17.59 | 90.36 | 147.34 | 152.19 |

Representative High-Latitude Flights

2012-03-07 11:00-12:00 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 | 51.52 | 0.283 | | | |
| Chicago,USA - Stockholm,SWE | 8.50 | 63.09 | 0.536 | | | |
| Chicago,USA - Munich,DEU | 8.50 | 56.35 | 0.479 | | | |
| Chicago,USA - Beijing,CHN | 13.50 | 60.34 | 0.815 | | | |

| Signal | Aircrew[5] Max_Annual(800hrs) | Public[6] one_trip | Prenatal[6] 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 |




**Public Web site: http://sol.spacenvironment.net/~nairas/ (or google NAIRAS)**

Credit: Dr. Mertens NASA, NOAA SWW 2013

# PCAST and CST Collaboration

- The US President's Council on Science and Technology (PCAST) and the UK Prime Minister's Council on Science and Technology (CST) recently looked for ways to collaborate on issues of mutual interest
- What was the first item they considered?
  - Climate Change?
  - Terrorism?
  - Internet Issues?
  - Biomedical Concerns?
  - Other?
- They Chose: The Impact of Space Weather on Aviation

# Atmospheric Radiation Environments and Effects

22nd -23rd March 2015

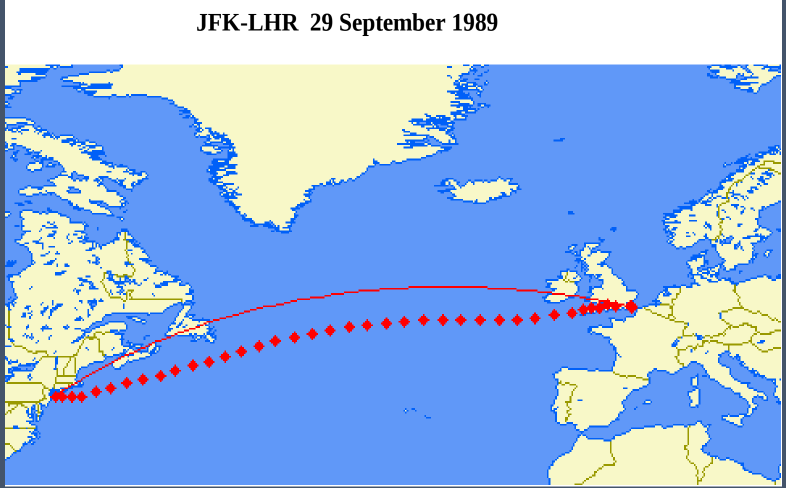
UK-US Workshop on Space Weather and Aviation

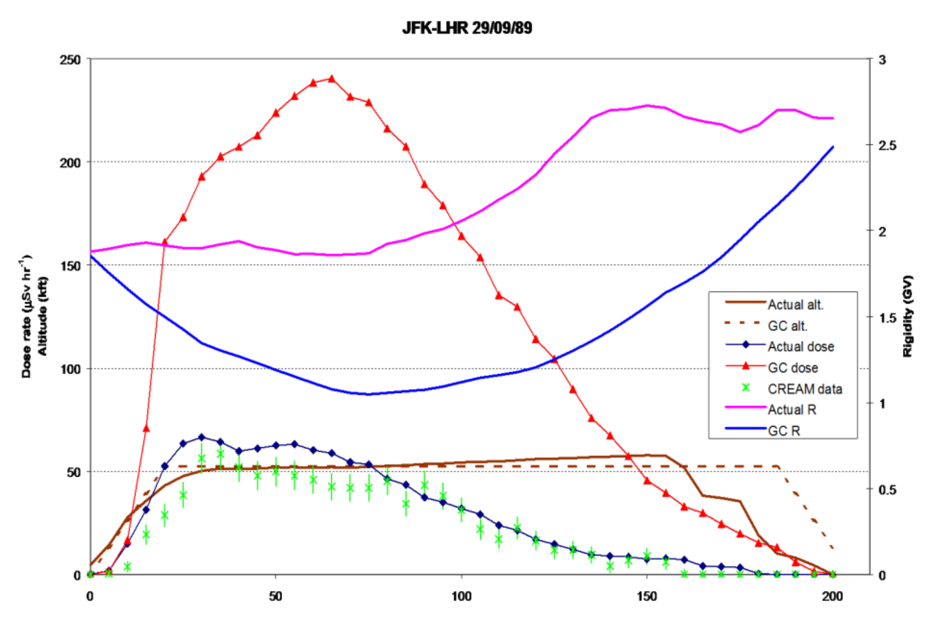
NIA, Virginia

[redacted]

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

## Great Circle vs. Actual Flight Path




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).

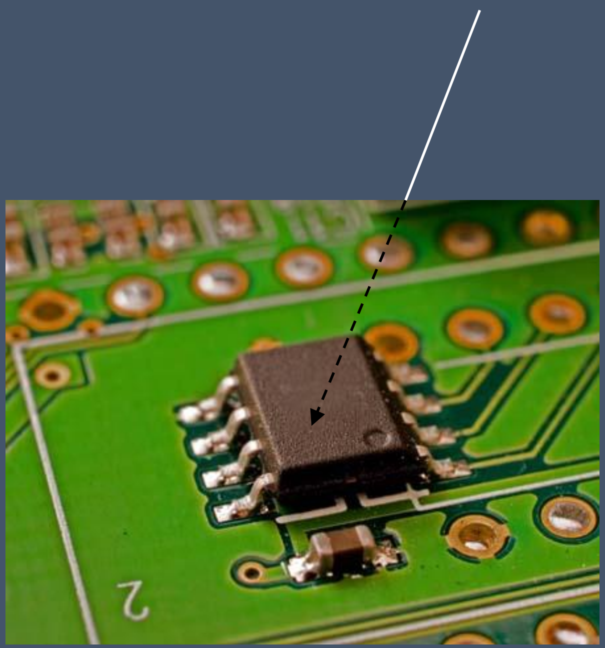
# Dose Estimates for Widebody Aircraft from past Solar Particle Events for LHR-LAX at 12 km

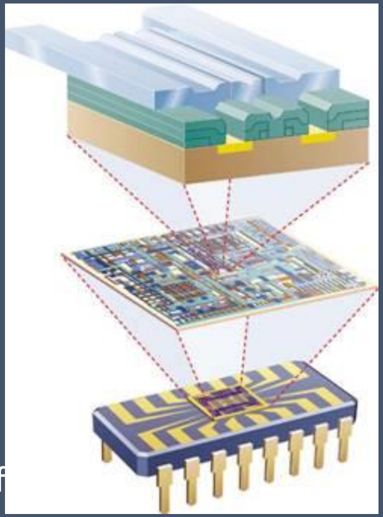
| Event | 23 Feb 1956 | 29 Sept 1989 | 19 Oct 1989 | 22 Oct 1989 | 24 Oct 1989 | 14 July 2000 | 15 April 2001 |
|---|---|---|---|---|---|---|---|
| W/C Event Start (hrs) | 3 | 1 | 0 | 1 | 1 | 2 | 2 |
| Peak Dose Rate (mSv/hr) | 1.82 | 0.29 | 0.022 | 0.039 | 0.049 | 0.013 | 0.041 |
| Route Dose (mSv) | 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.
Event start measured wrt take-off.

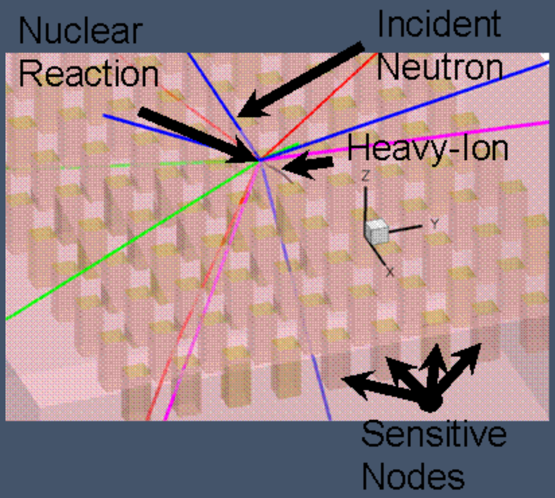
# Single event effects

- Single event effects (SEE) result from interactions of single particles and include:
  - Upsets (bit-flips)
  - **Multiple cell upsets**
  - Transients
  - **Functional Interrupts**
  - Latch-up
  - **Burn-out**
  - Gate rupture,
  - Dielectric failure





NB: Single events can cause multiple ef



# Quantas Flight QF72, 10/7/2008

- Emergency landing due to two uncommanded pitch down maneuvers
- 1 crew member, 11 passengers serious injuries
- 8 crew members, 95 passengers minor injuries
- Attributed to SEE fault in one (of three) inertial reference units along with A330’s fly by wire flight control computer

# 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
  - ✓ In general ~0.1% addition cancer risk – not large.
  - ✓ But special considerations for pregnant travellers and crew members .
  - ✓ Need post-event dosimetry based on measurement and modelling
  - ✓ Future crew rostering will need to take account of dose received (20mSv absolute limit but practical limit is usually 6mSv)
  - ✓ Could be very difficult to manage without accurate measurements

# 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

# Workshop Conclusions

1. Single most important activity….routinely fly radiation monitors on commercial aircraft…to characterize the radiation environment.
2. Ensure agencies accept responsibilities for funding
3. Develop test facilities for avionics
4. Conduct R&D to improve space weather forecasting
5. Define extremes of space weather

# What Should HPs and the HPS do about Radiation in Flight????

- Suggest that the FAA’s lack of regulation has not worked and should be changed?
- Revise FAQs on flight, especially for pregnant crewmembers as well as the flying public who are pregnant?
- Suggest US funding to determine frequency versus severity for the “known – unknowns” of radiation in flight?
- Facilitate a center of excellence in this area at a university to train the HPs needed for aviation?
- What else?