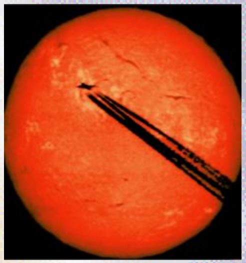

Space Weather Affecting Airlines During Solar Minimum

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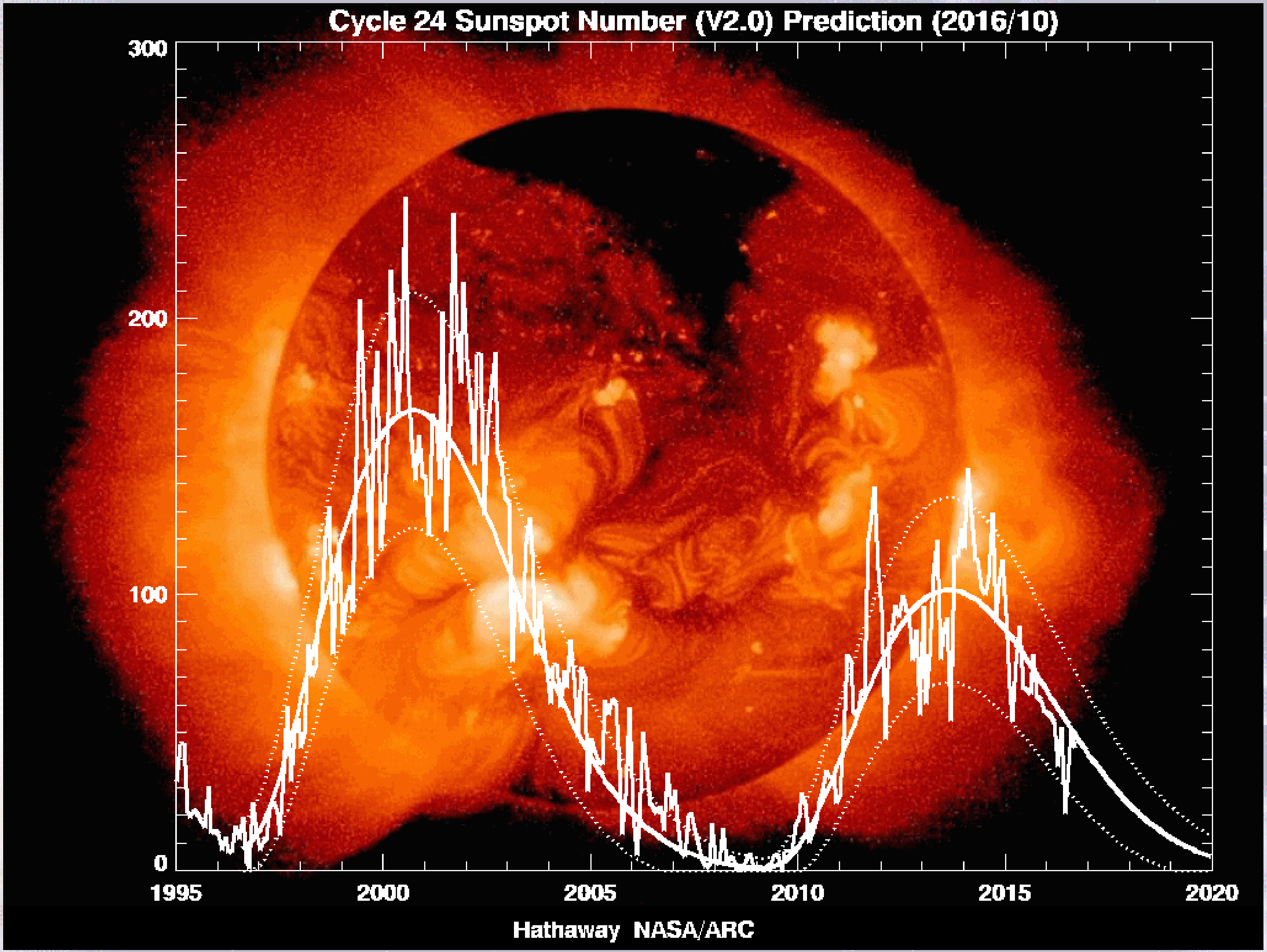
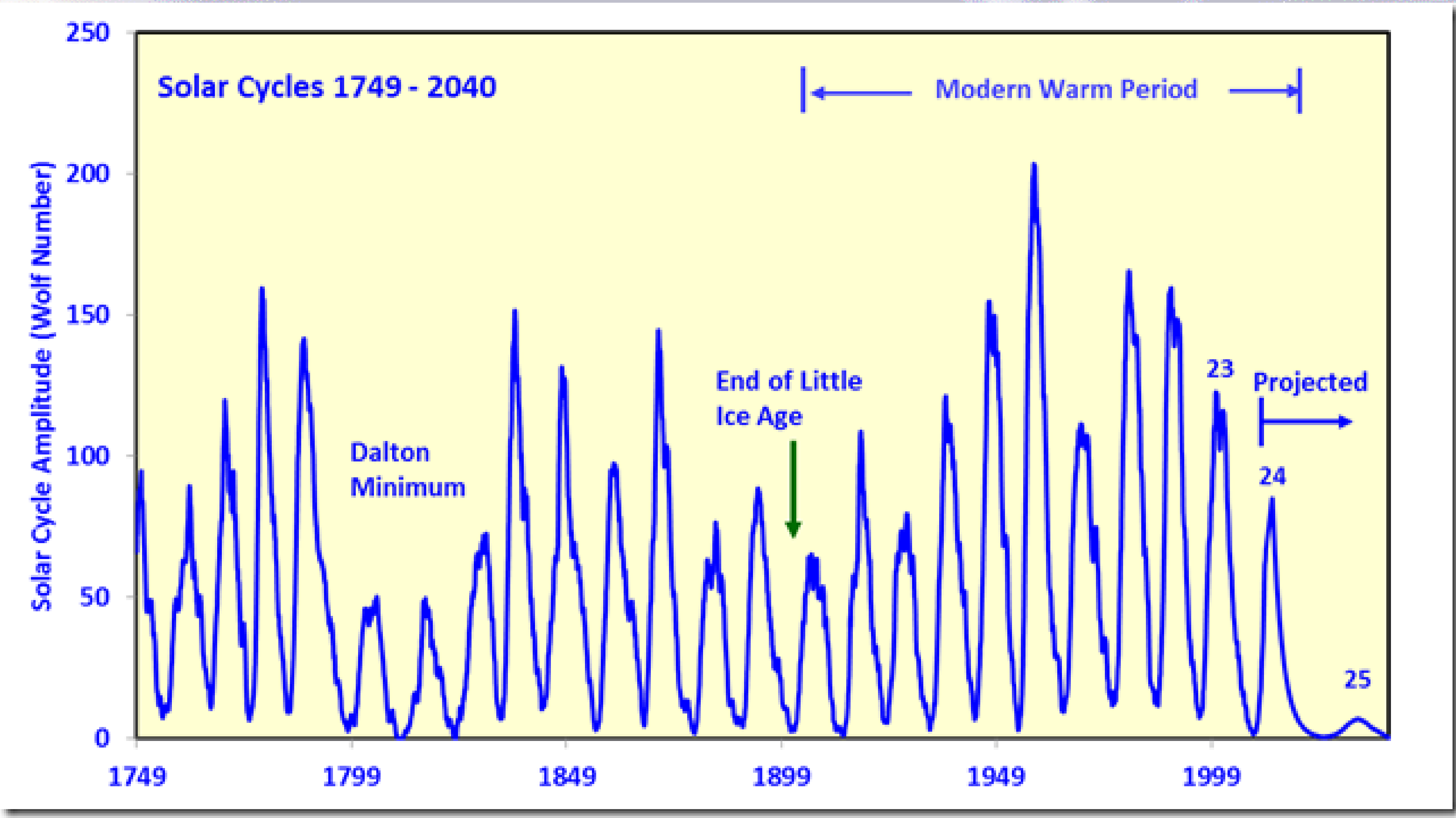
Space Weather Writer, The Washington Post

Overview

- The Sun is quieting, space weather now changing
- Solar minimum means few – very few – Australia, U.S. Japan, China, Korea, ... Alerts, Warnings & Watches
- Many airlines have built ConOps based on the alerts
- Main threat in the next 5 years, is radiation to satellites, aircraft, and crew
- ICAO approved Sp Wx SARPS for amendment 78 of annex 3, planned for 2018


Cycle 24 Sunspot Number (V2.0) Prediction (2016/10)
300
200
100
0
1995
2000
2005
2010
2015
2020
Hathaway NASA/ARC


Solar Cycles 1749 - 2040
Modern Warm Period
Solar Cycle Amplitude (Wolf Number)
250
200
150
100
50
0
Dalton
Minimum
End of Little
Ice Age
23
Projected
24
25
1749
1799
1849
1899
1949
1999

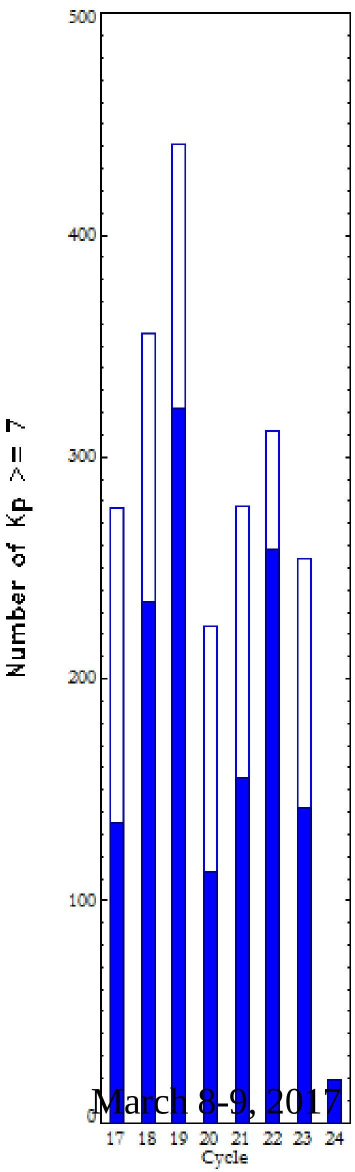
Periods with Kp >= 7

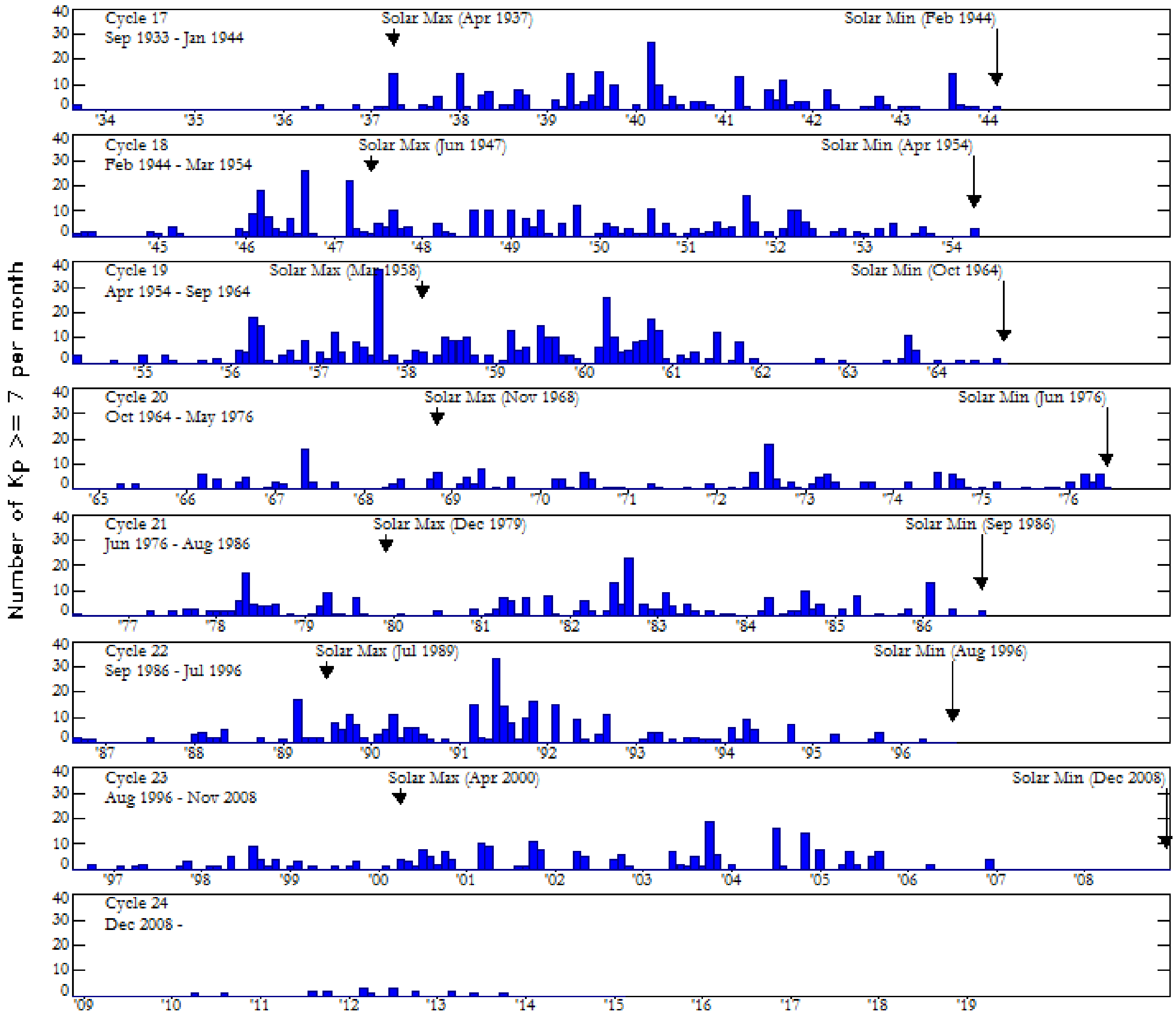
February 2015

(Month 75)

G3 Level

Comparison of Cycles at current month in cycle





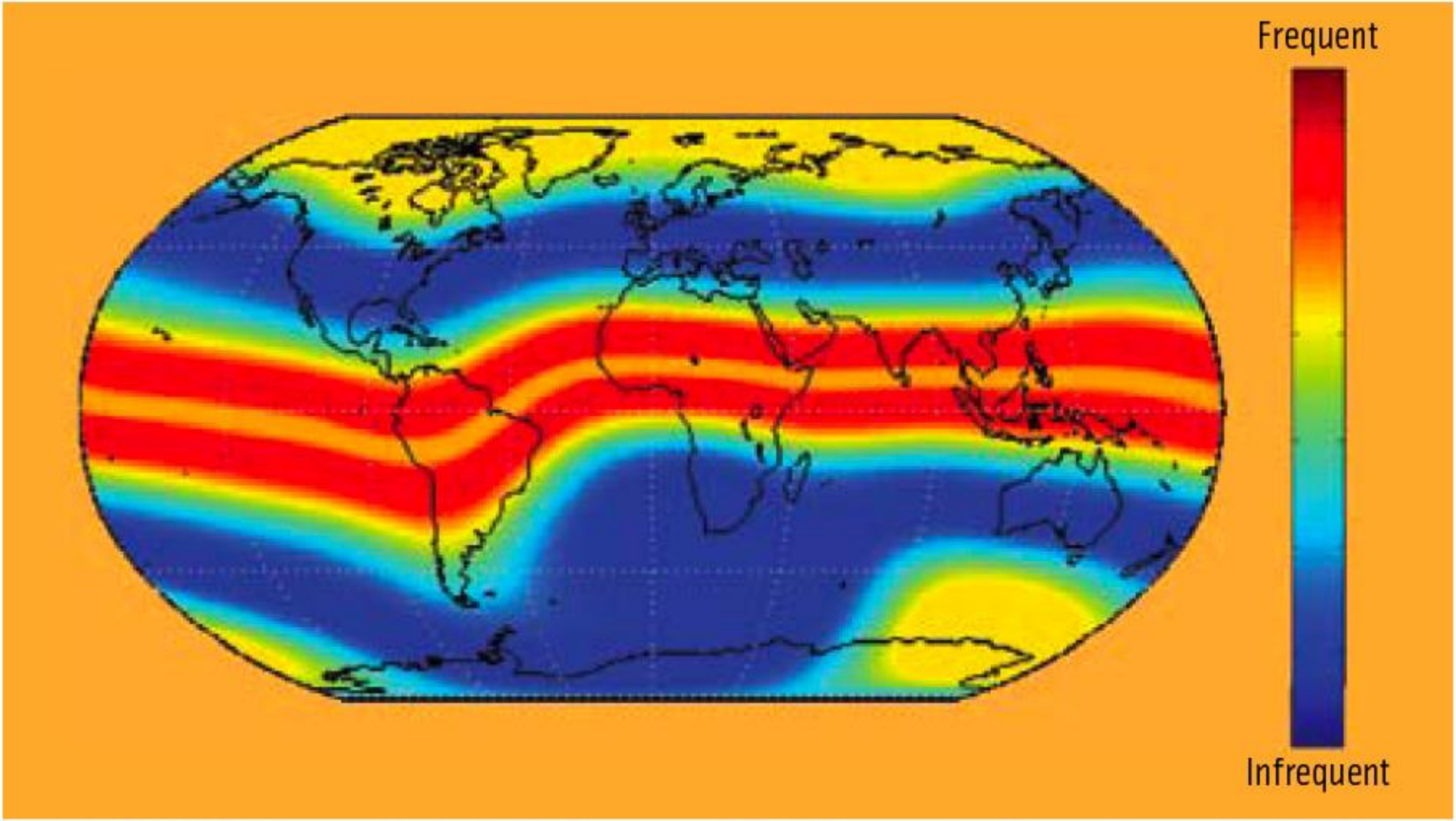
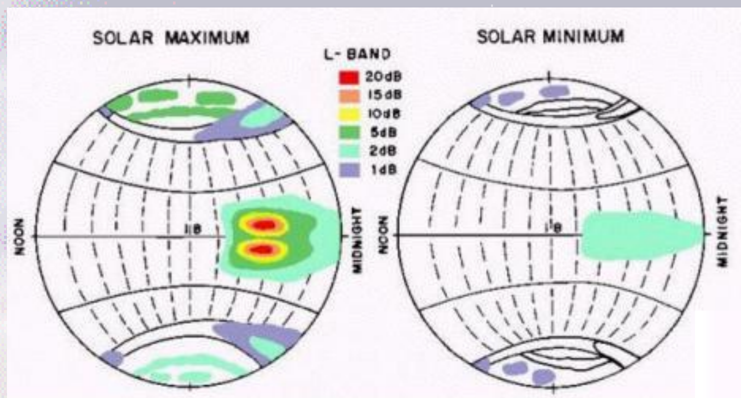
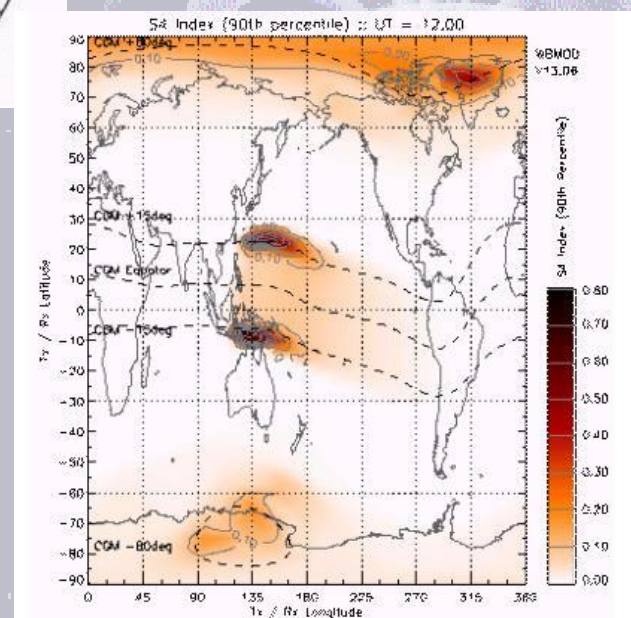


FIGURE 1 Scintillation map showing the frequency of disturbances at solar maximum. Scintillation is most intense and most frequent in two bands surrounding the magnetic equator, up to 100 days per year. At poleward latitudes, it is less frequent and it is least frequent at mid-latitude, a few to ten days per year.

GNSS-Based Services Improving



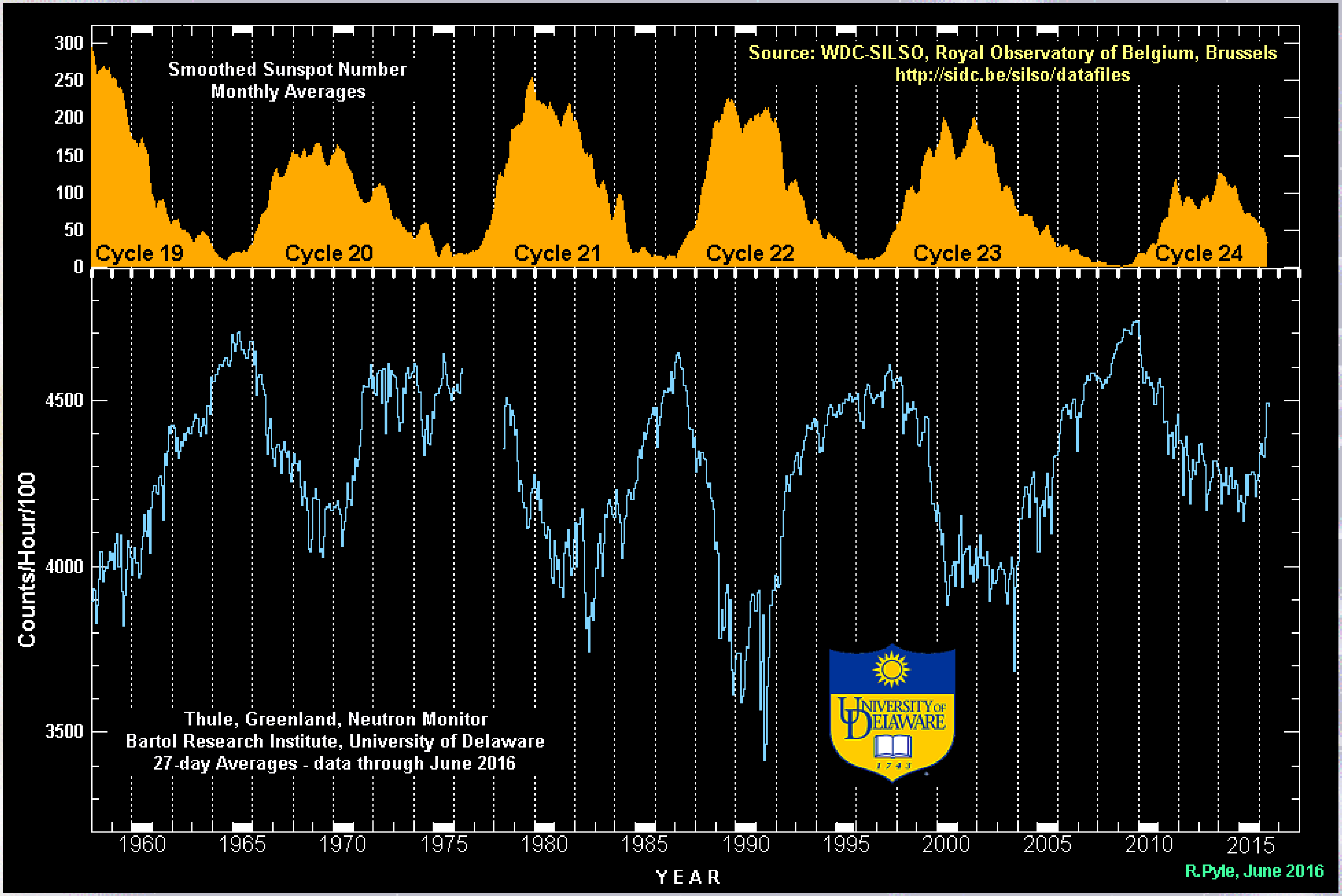


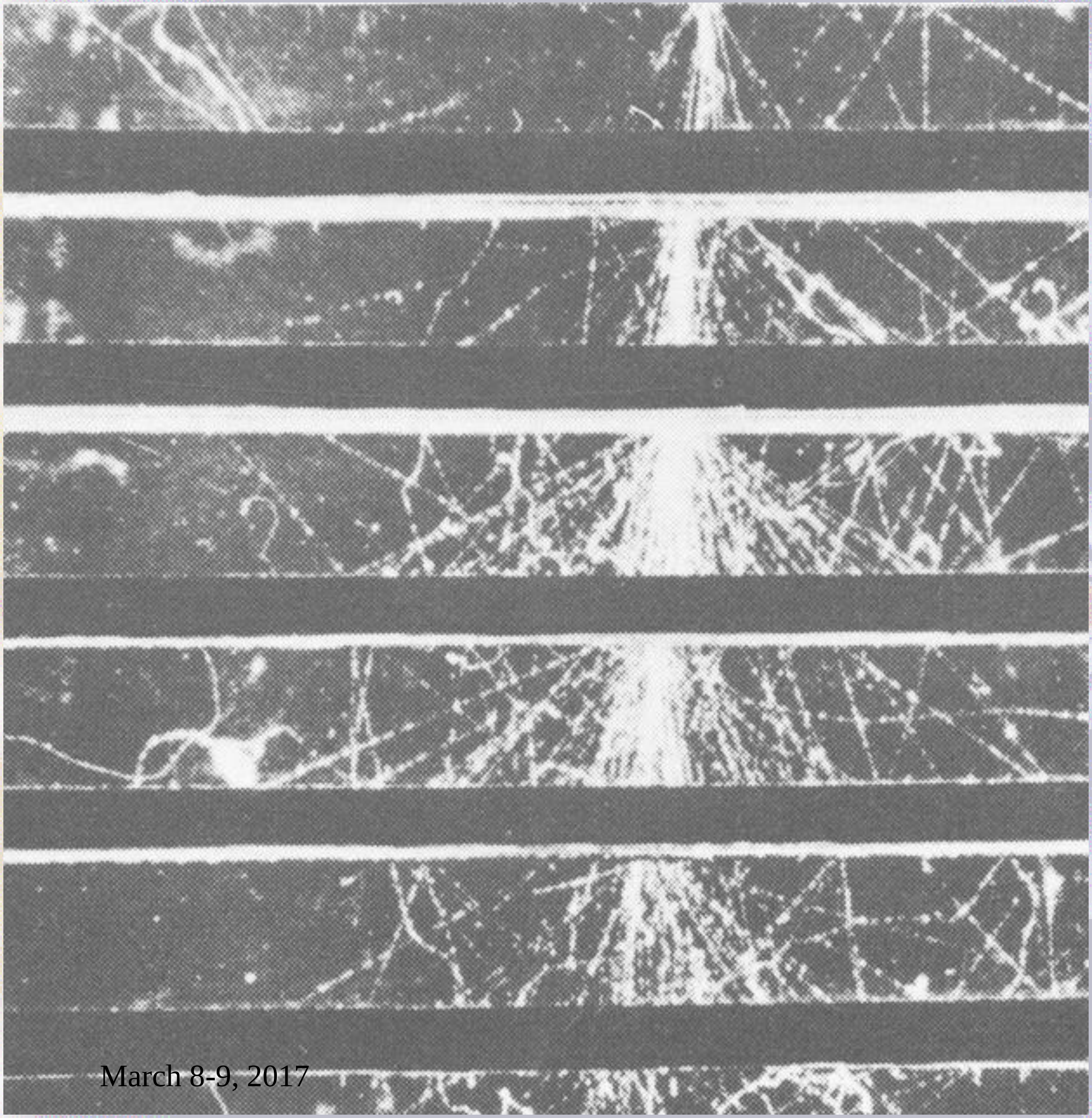
Good/Bad of Solar Minimum

- ***Good***
- Very low flare and CME activity
- Systems – GPS smooth sailing, sat comm too

- ***Bad***
- High Galactic Cosmic Ray (GCR) counts, more radiation
- Systems – HF loses high frequencies; satellite upsets more likely

Solar Cycles vs. Neutrons from Galactic Cosmic Rays





Photon cascade in lead plates in cloud chamber.

Maximum number of particles after passing through 10 cm of lead

Incident photon is several GeV

Neutrons Initiate Approximately 50% of the Dose

Table 5-I. Relative Biological Effectiveness

Radiation	RBE
X-rays	1
Gamma rays	1
Beta particles	1
Alpha particles (into the body)	10 to 20
Neutrons:	
For immediate radiation injury	1
For cataracts, leukemia and genetic changes	4 to 10

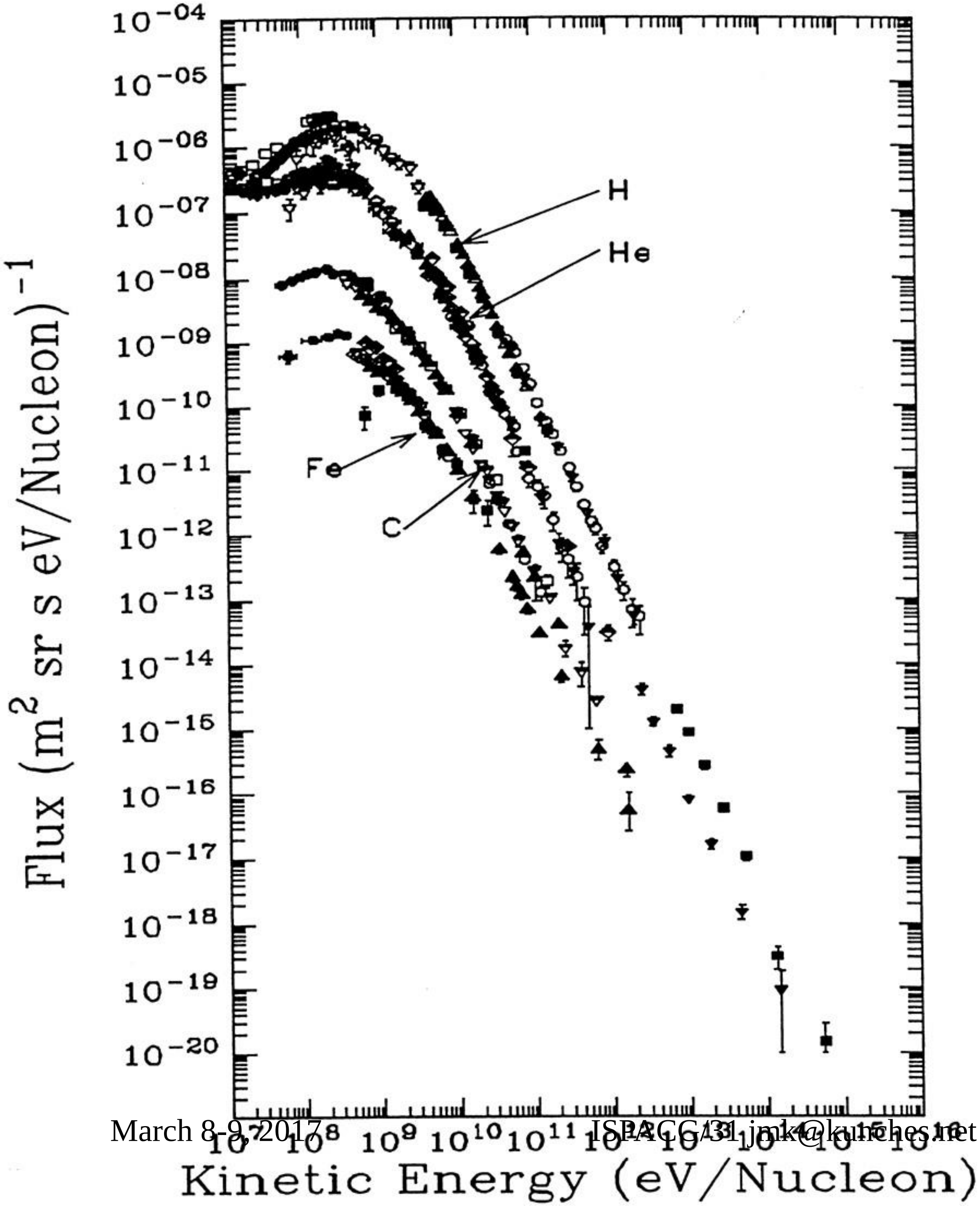
Source: Biophysical and Biological Effects, Ch.5, NATO AMedP-6(B)

Space Weather
Radiation Hazards
Outline

- Simple Tutorial
  - Cosmic Rays
  - Solar Radiation Storms
  - Earth's Influence
    - Magnetospheric Shielding
    - Atmospheric Shielding
- Radiation Impacts on Airline Passengers

Space Radiation

- Composed of two major components
  - **Cosmic Rays**
    - Always present and very energetic
    - Composed of many different elements
    - Intensity varies throughout 11 year Solar Cycle
    - Intensity varies with Solar Activity



Cosmic Rays

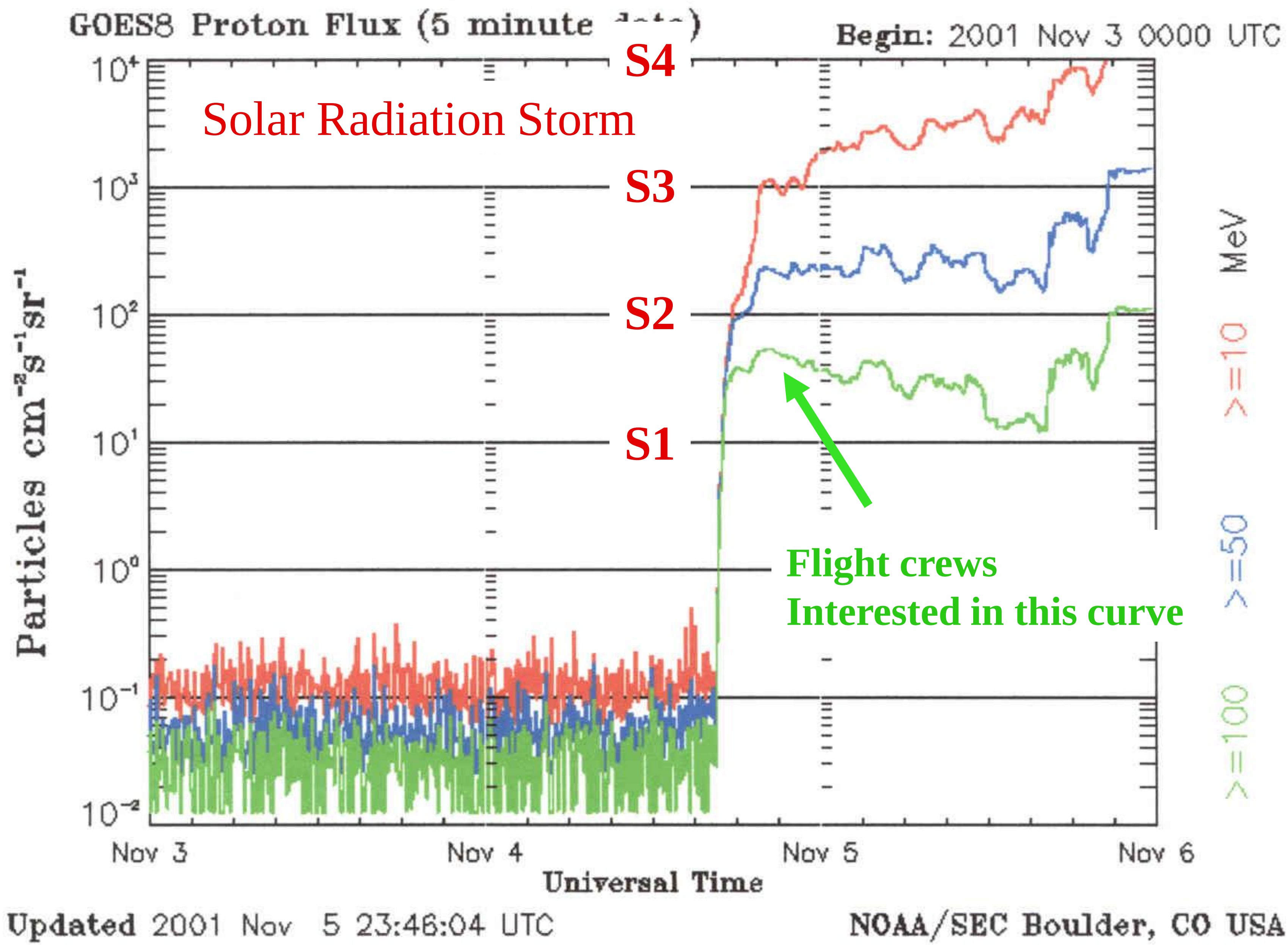
- **Composed of many different Elements, such as Hydrogen Helium, Carbon, and Iron**

- **They cover a very wide range of energies**

- **They are always present**

Space Radiation

- Composed of two major components
  - **Cosmic Rays**
    - Always present and very energetic
    - Composed of many different elements
    - Intensity varies throughout 11 year Solar Cycle
    - Intensity varies with Solar Activity
  - **Solar Radiation Storms**
    - Infrequent, very intense, with rapid onsets
    - Composed of many different elements
    - Origin strongly linked to Solar Activity
    - Variable energy and composition dependence


GOES8 Proton Flux (5 minute data)
Begin: 2001 Nov 3 0000 UTC
S4
Solar Radiation Storm
S3
S2
S1
Flight crews
Interested in this curve
Particles cm^-2 s^-1 sr^-1
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
MeV
>=10
>=50
>=100
Nov 3
Nov 4
Nov 5
Nov 6
Universal Time
Updated 2001 Nov 5 23:46:04 UTC
NOAA/SEC Boulder, CO USA

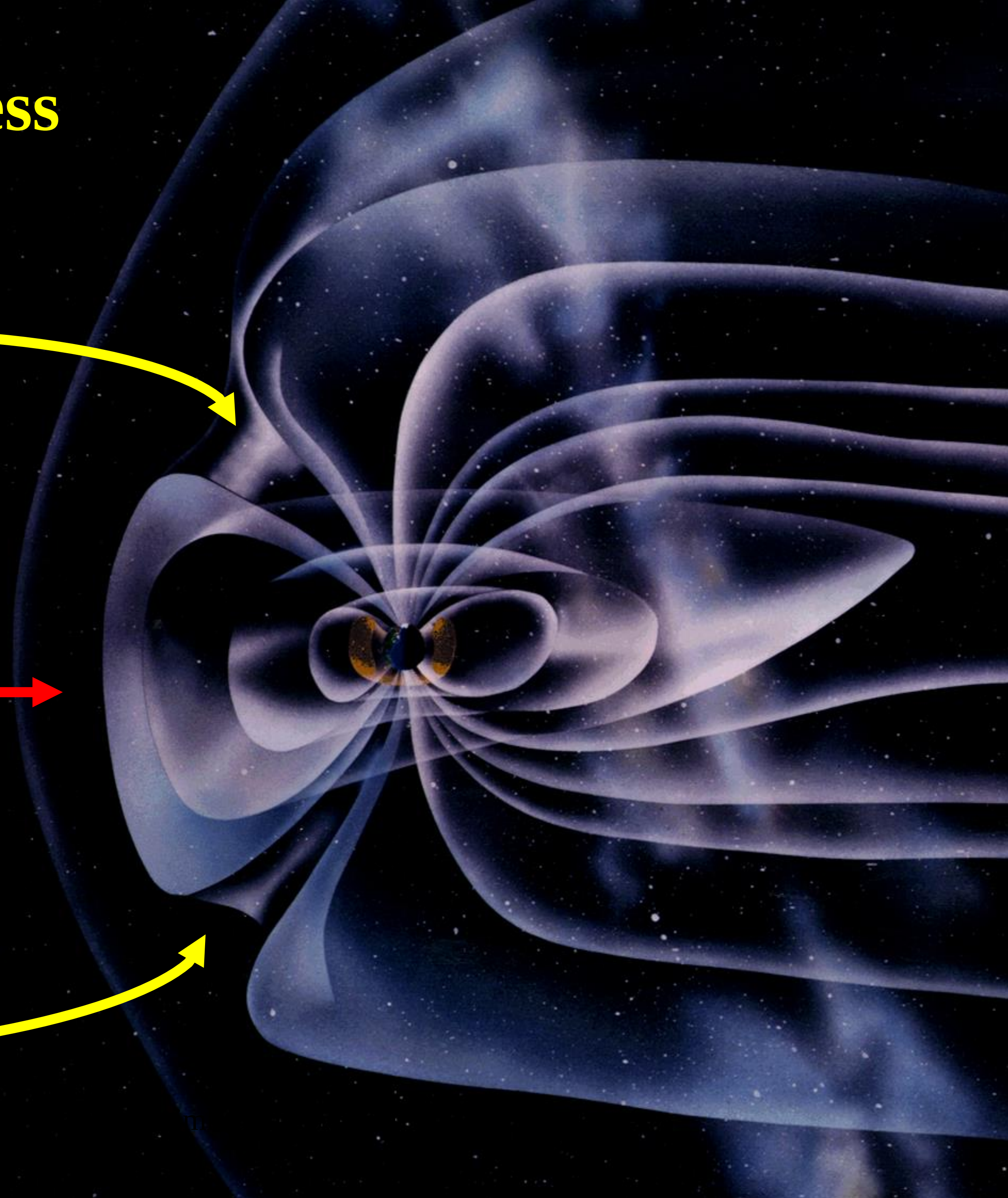
Space Radiation

- **Earth's Influence on the radiation level**
  - **Magnetic Field Shielding**
    - **Always present, but has holes!**

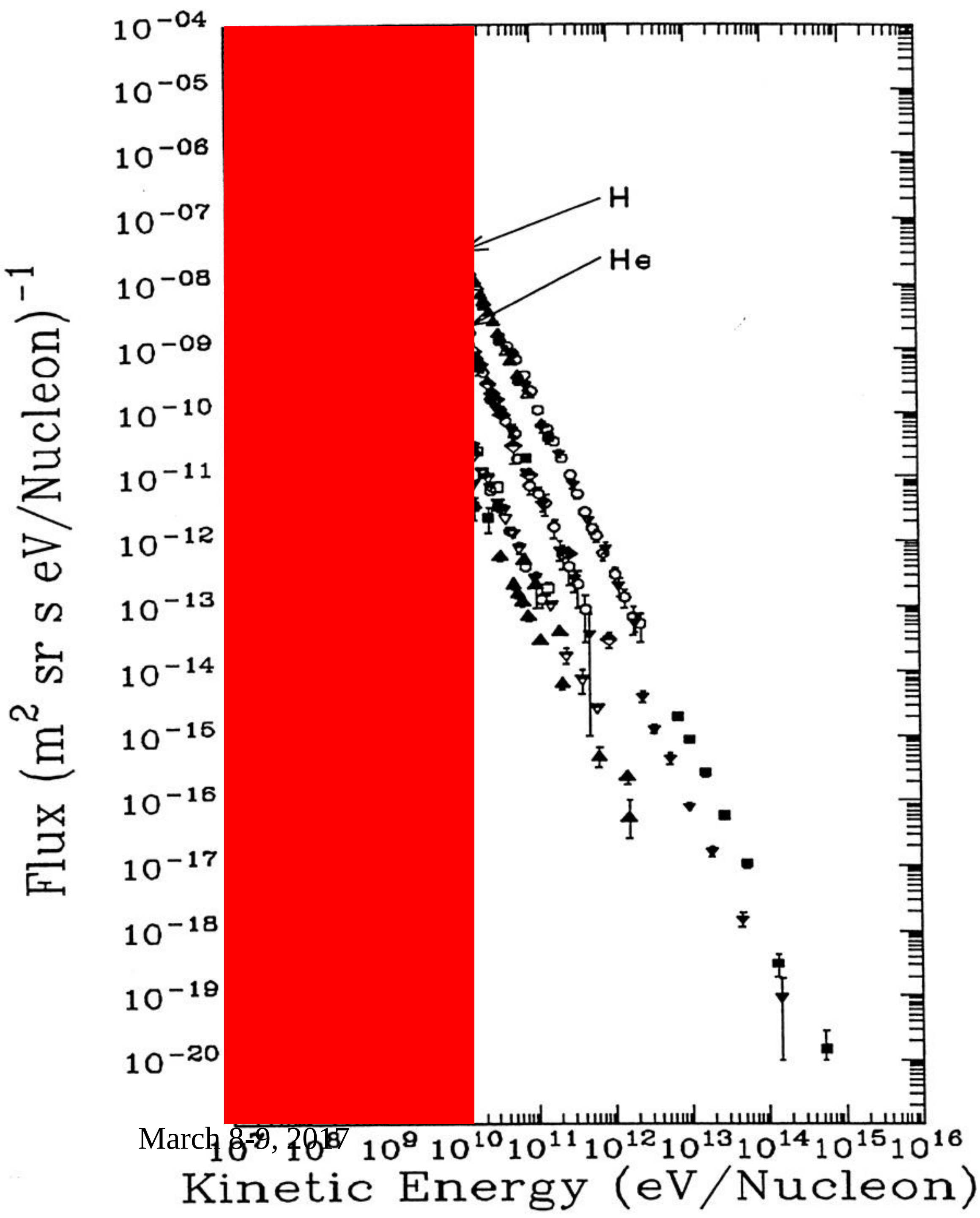
Cosmic Ray Access

Open

Closed



Open



Earth's

Magnetic Shield

to Cosmic Ray Access

Magnetic Poles: **Open**

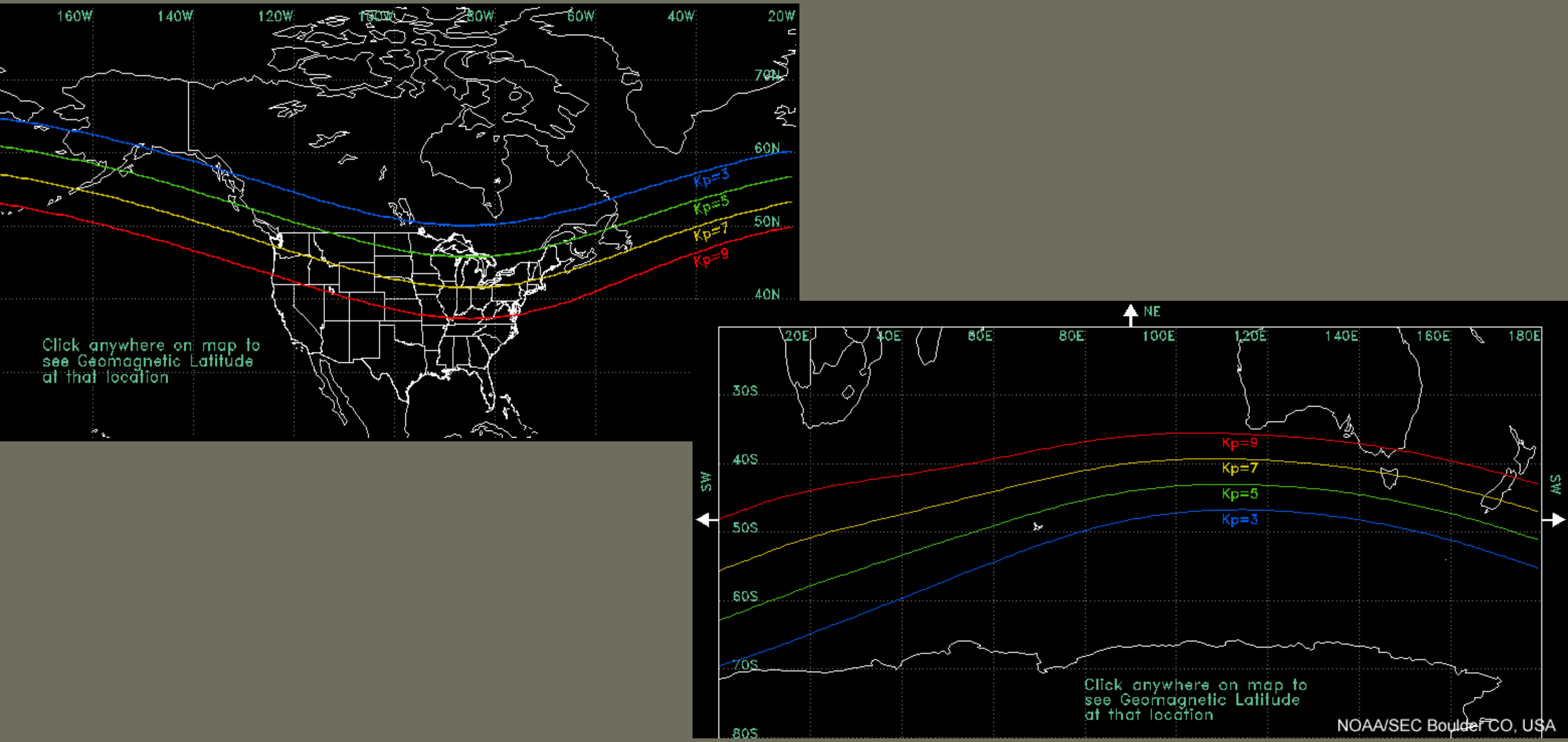
Magnetic Equator: **>15 GeV**

Red bar varies as function of magnetic latitude

Space Radiation

- Earth's Influence on the radiation level
  - Magnetic Field Shielding
    - Always present, but has holes!
  - **Geomagnetic Activity**
    - **Changes magnetic field shield location**

Influence of Geomagnetic Activity on auroral boundary
(geomagnetic poles expand with increased activity)

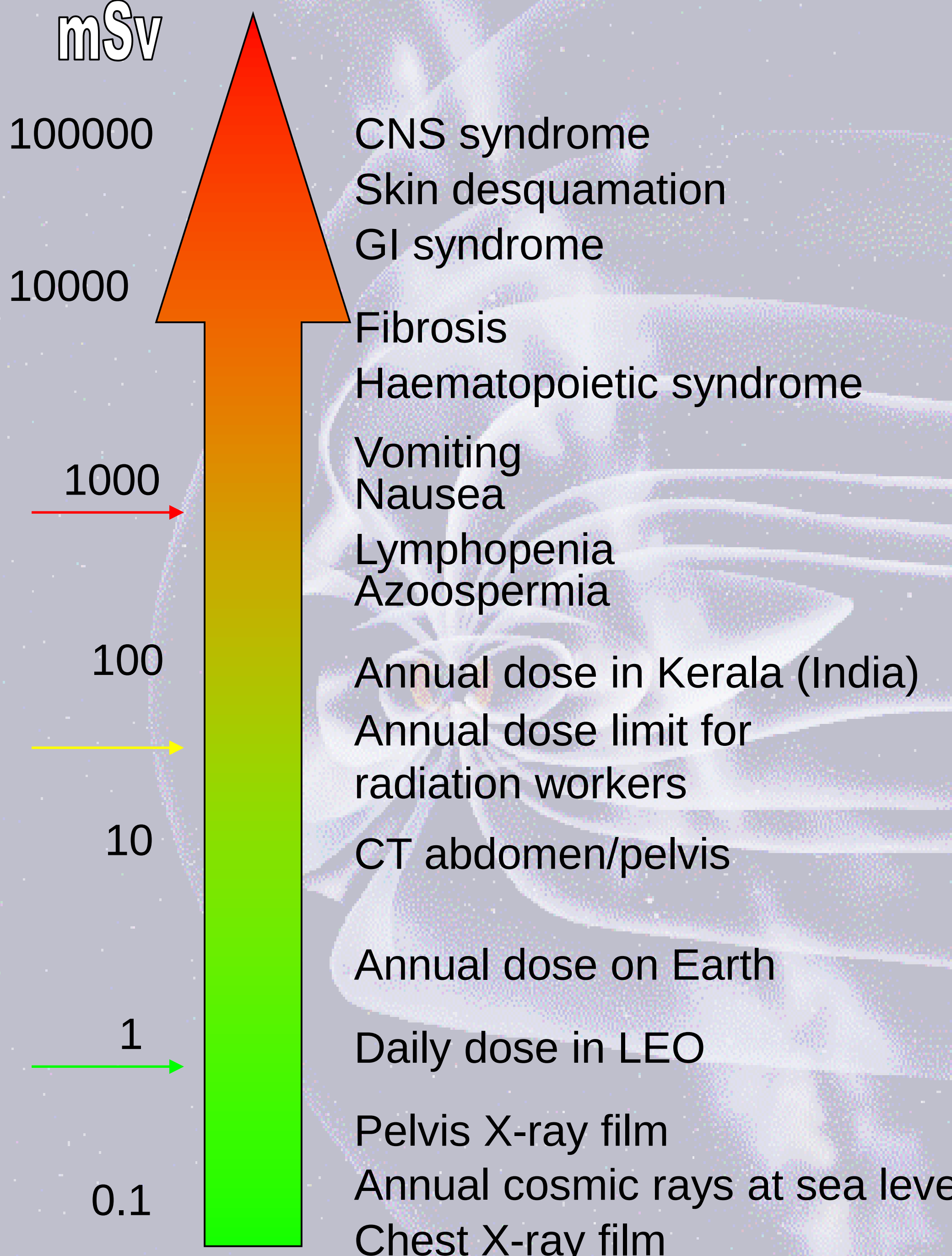


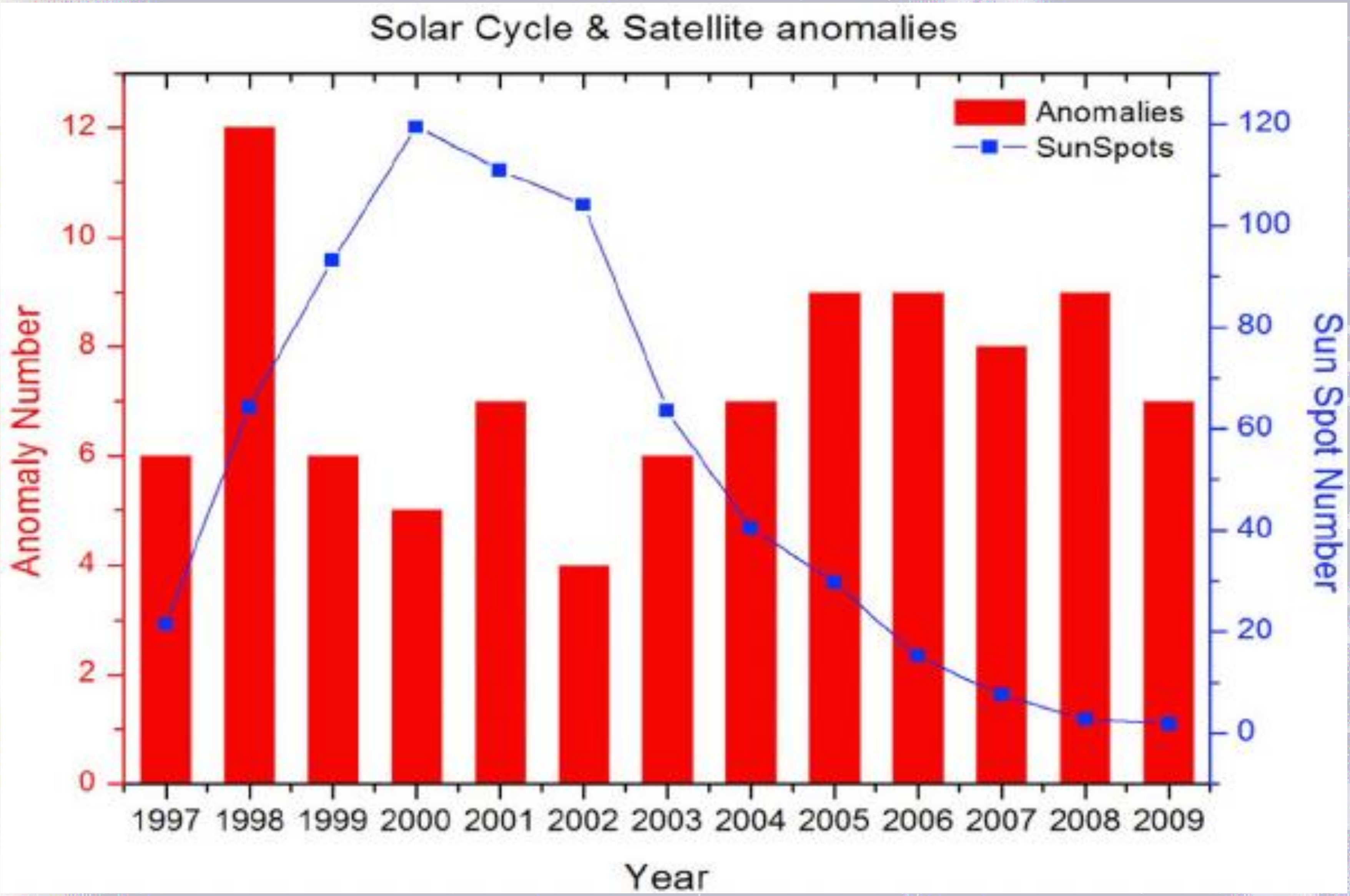
Space Radiation

- **Earth's Influence on the radiation level**
  - **Magnetic Field Shielding**
    - **Always present, but has holes!**
  - **Geomagnetic Activity**
    - **Changes magnetic field shield location**
  - **Atmospheric Shielding**
    - **Upper atmosphere acts as a target**
    - **Lower atmosphere acts as absorbing shield**

Two major radiation risks in exploratory missions

- SPE: sporadic, high dose. Shielding generally effective. Acute (deterministic) effects
- GCR: chronic, low dose. Shielding poorly effective. Late (stochastic) effects





Choi et al, SpWx, 2009

What Can Airlines Do?

- Drop in altitude – dose rate halves every 2 km lower
- Not likely, but if possible, fly at a lower latitude
- Be informed

- Open question – Is there appreciable radiation from composites?

ICAO Sp Wx SARPs

- Ratified March 2, 2017
- For inclusion in amendment 78 to annex 3
- Work in progress to draft supporting documents

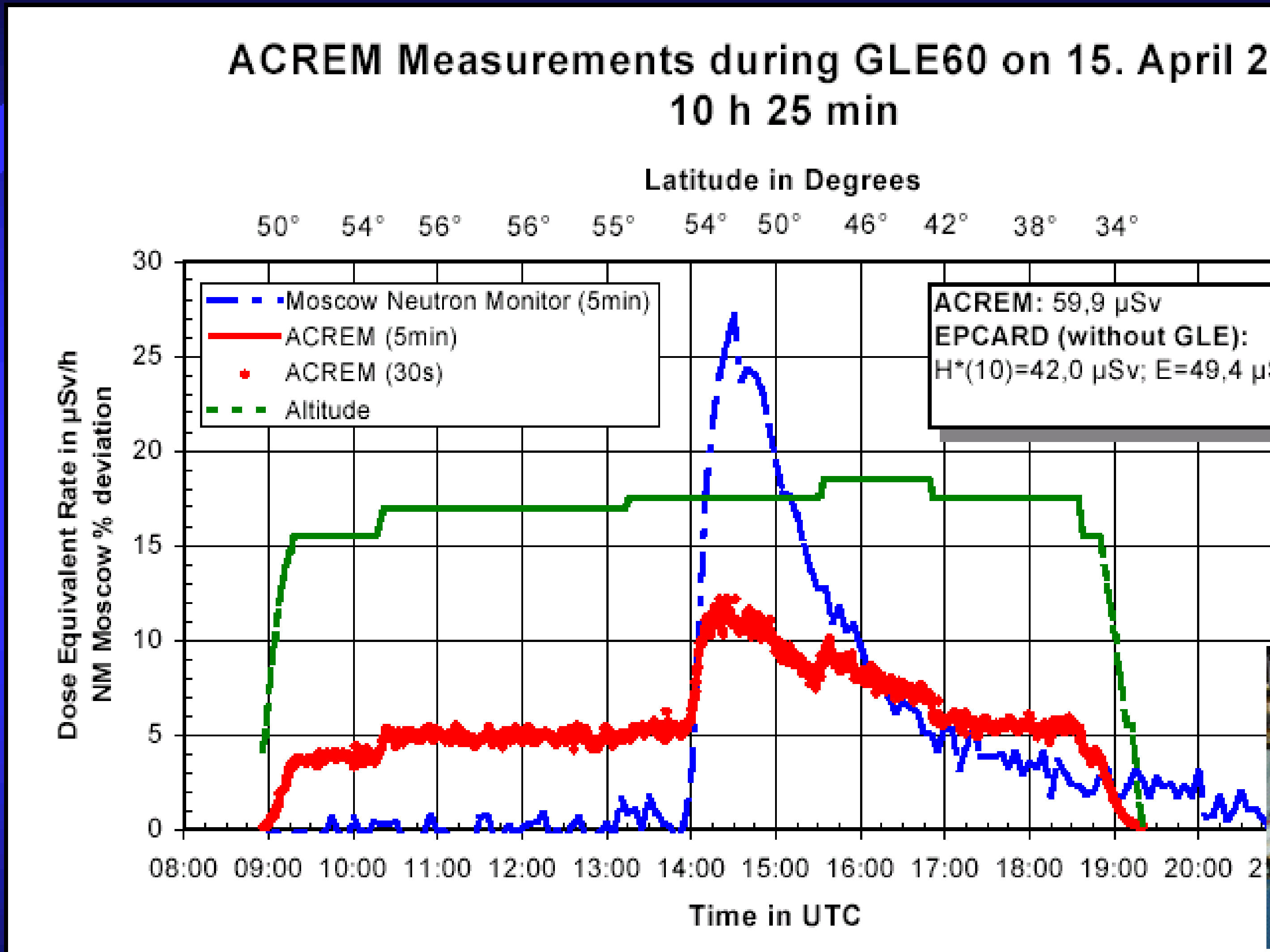
Space Radiation
Summary

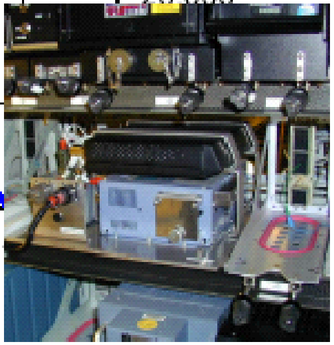
- Two primary components
  - Cosmic Rays
    - Steady but variable w/solar cycle
  - Solar Radiation Storms
    - Rare, highly variable, and can be intense
- Earth's natural defenses
  - Magnetic field shields Earth
    - Makes calculations very complex
    - Geomagnetic Latitude dependent
    - Geomagnetic activity can expand poles
  - Atmosphere acts as target and as shield
    - Radiation strongly dependent upon altitude

Thanks to R. Zwickl for his contributions.

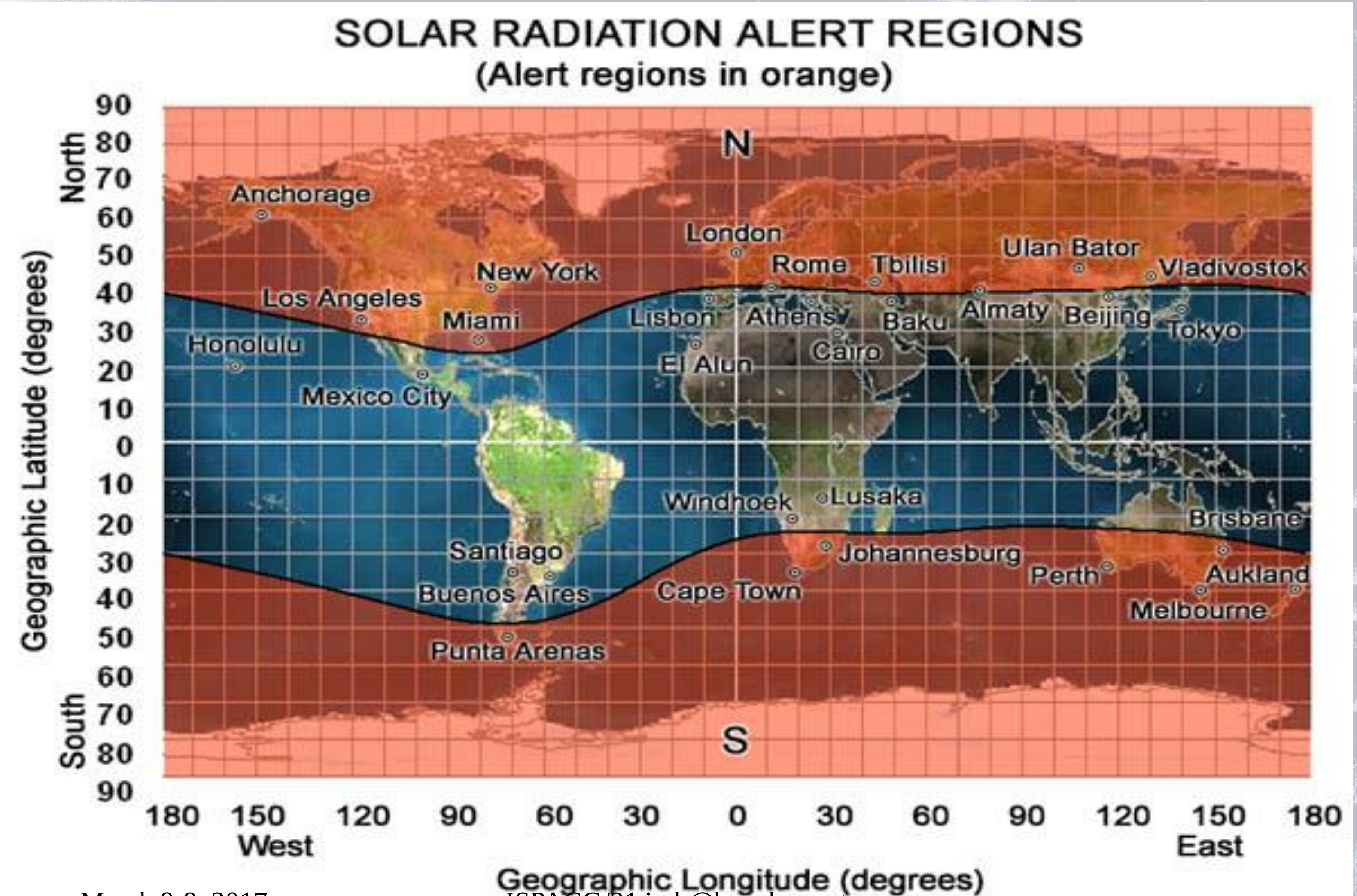
Additional Slides

FRA to DFW flight





Space Weather and Aviation

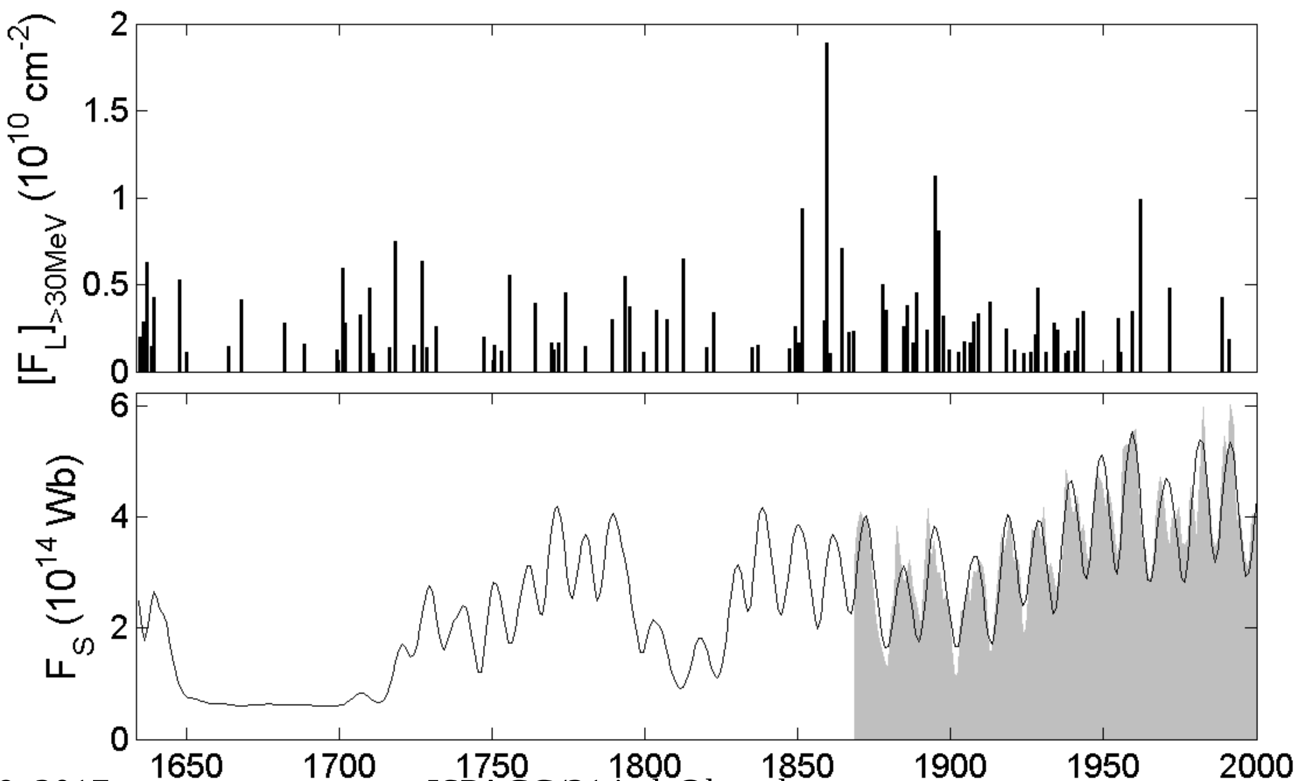


Kyle Copeland & Wallace Friedberg Civil Aerospace Medical Institute, FAA

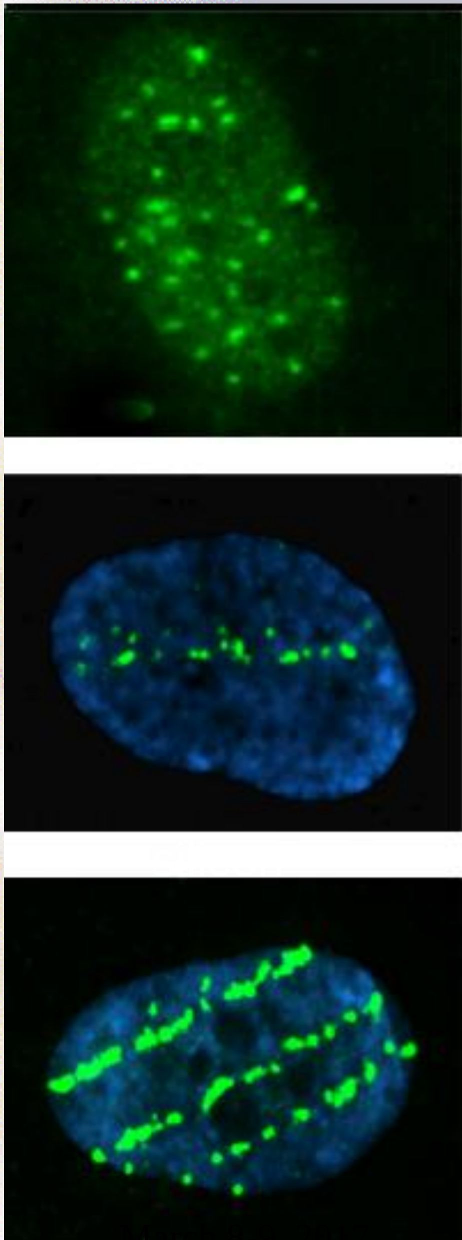
Major SEP Events

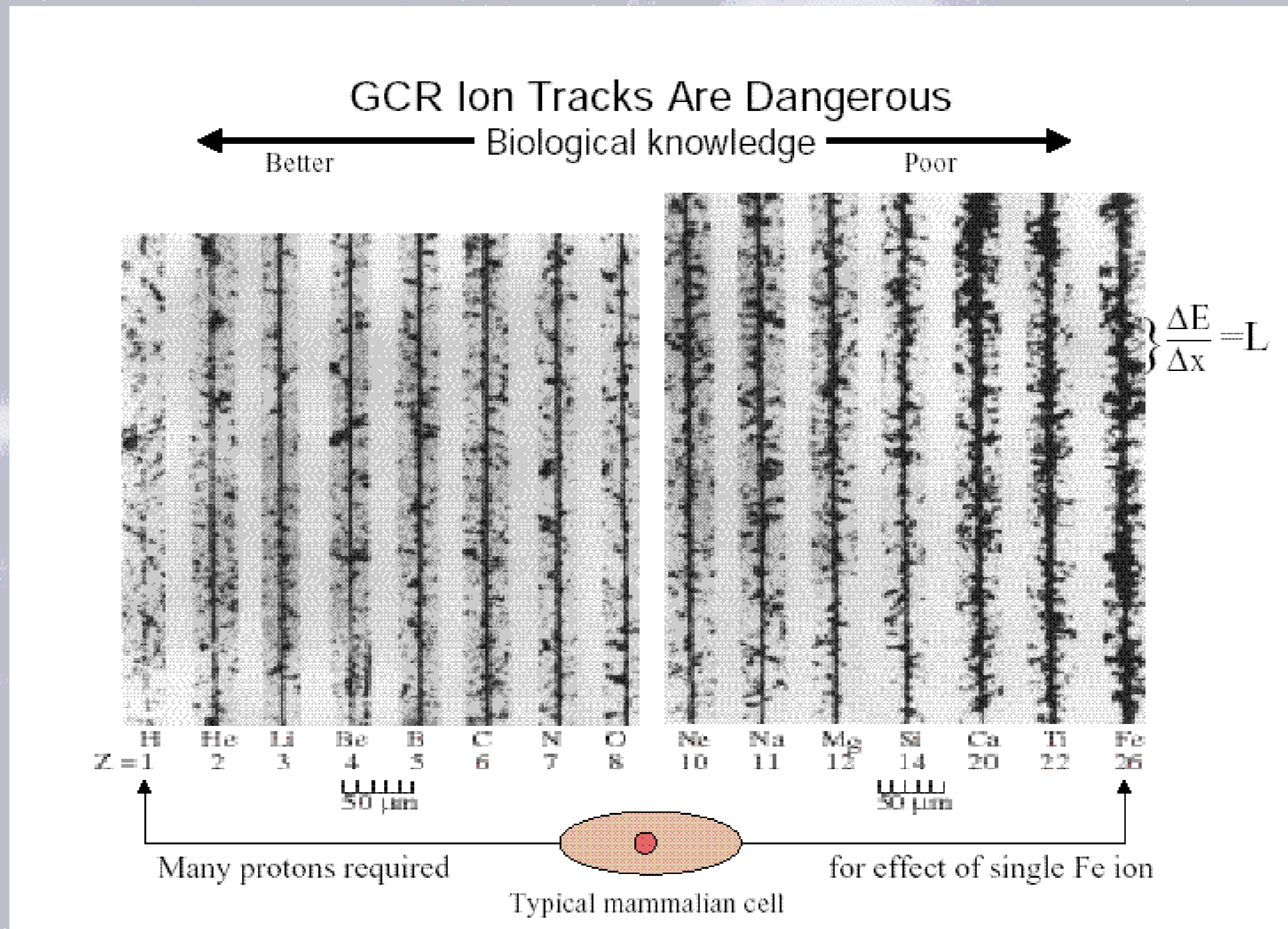
From nitrates in polar ice sheets

- SEP (>30MeV) fluence from ice sheet data *(McCracken, 2001)*
- Open flux model from sunspot number *(Solanki et al., 2000)*
- Open flux derived from aa index *(Lockwood et al., 1999)*



DNA dsb visualized by immunofluorescence of γ-H2AX histone in human skin firbroblasts exposed to 2 Gy of ionizing radiation





iron

Cucinotta and Durante, *Lancet Oncol.* 2006

Issue Time: 2001 Nov 04 2045 UTC
ALERT: Solar Radiation Alert at Aviation Flight Altitudes
Conditions Began: 2001 Nov 04 2035 UTC

Altitude (feet)	Solar proton effective dose rate (millisieverts/hour) *
20 000	<0.0010
30 000	0.0052
40 000	0.019
50 000	0.040
60 000	0.060
70 000	0.074
80 000	0.088

*** Estimates at high latitude locations. Dose rates are based on near real-time GOES satellite readings and are recalculated every 3 minutes.**

Kyle Copeland & Wallace Friedberg Civil Aerospace Medical Institute, AAM-610

Effective Doses From Solar Radiation at 40 000 ft for Selected Solar Proton Events From January 1986 Through December 2001 (16 y)

			Total Effective Dose (mSv)		
Date	Event	Time (hh:mm)*	3 h	5 h	10 h
Aug. 16, 1989	GLE 41	01:10	0.055	0.072	0.087
Sept. 29, 1989**	GLE 42	08:35	0.26	0.42	0.59
Oct. 19, 1989	GLE 43	20:30	0.074	0.17	0.41
Oct. 22, 1989	GLE 44	03:25	0.15	0.19	0.23
Oct. 24, 1989	GLE 45	10:25	0.14	0.37	0.64
May 24, 1990	GLE 48	00:05	0.13	0.019	0.026
Jun. 15, 1991	GLE 52	00:50	0.041	0.048	0.055
Nov. 2, 1992	GLE 54	00:20	0.039	0.054	0.072
Nov. 6, 1997**	GLE 55	08:00	0.15	0.26	0.39
Jul. 14, 2000**	GLE 59	07:05	1.1	1.3	1.51
Apr. 15, 2001**	GLE 60	07:35	0.73	0.97	1.1
Apr. 18, 2001**	GLE 61	01:15	0.049	0.083	0.14
Nov. 4, 2001**	GLE 62	03:20	0.082	0.12	0.17
Dec. 26, 2001	GLE 63	01:35	0.069	0.081	0.090

* Time that recommended maximum flight altitude is below 40 000 ft

** Dose rates are underestimated for more than 0.5 h

Kyle Copeland & Wallace Friedberg Civil Aerospace Medical Institute, AAM-610