Assessment of terrestrial effects during strong and extreme SEPs using neutron monitor records

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Outline

1. **Introduction**
2. **Model for analysis of strong GLEs using NM data**
3. **Examples of derived spectra and PAD**
4. **Terrestrial effects (exposure to radiation and ionization)**
5. **Conclusion**

Introduction

GLEs, what, when and where

An important topic of solar physics, space weather, atmospheric physics is

Assessment

Primary SEP parameters:

energy spectrum

anisotropy

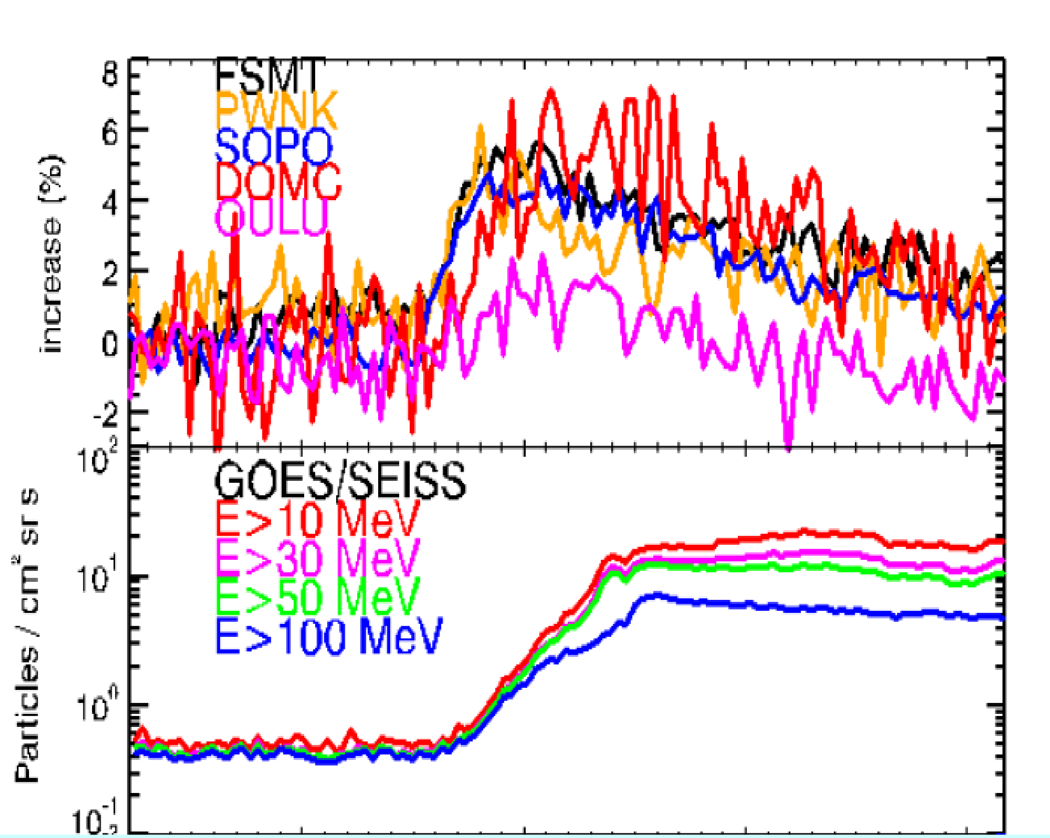
using the information from NMs

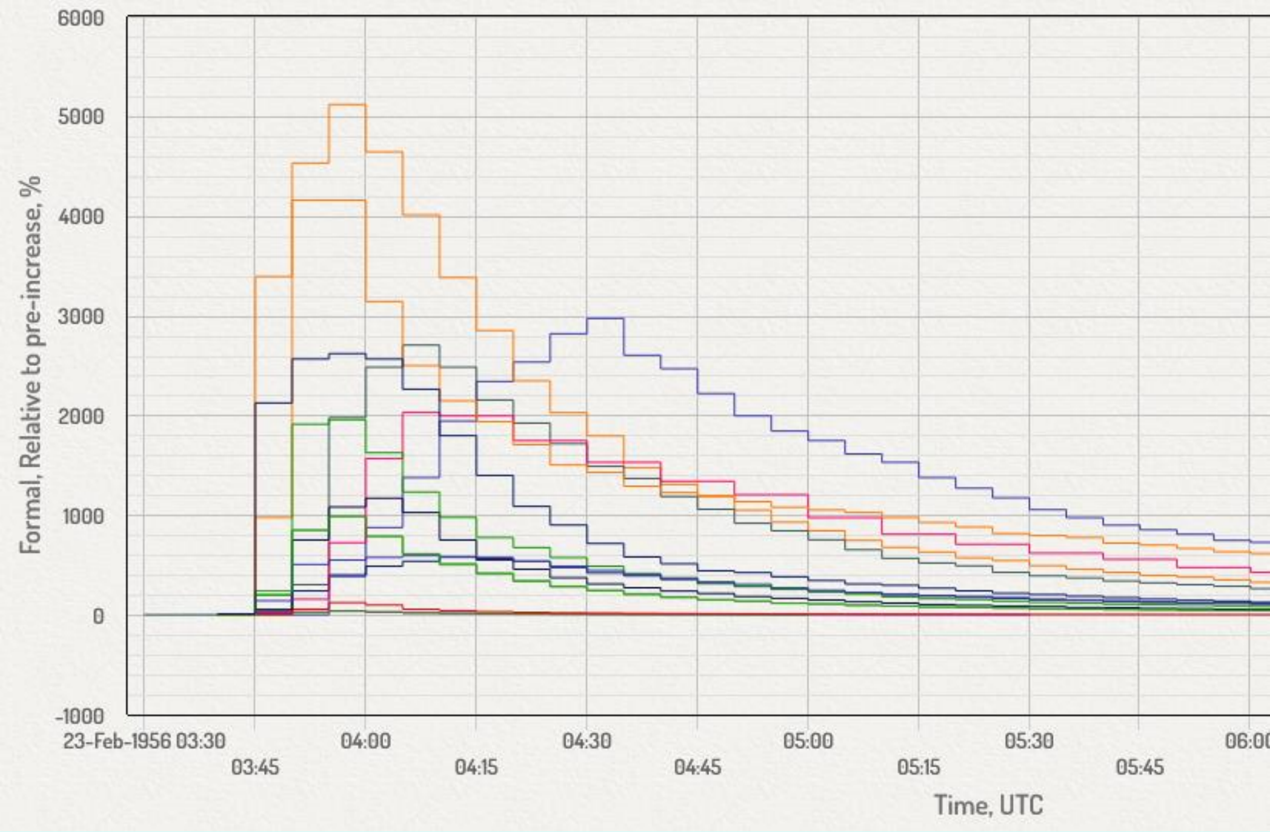
GLE # 73 on 28 October 2021

GLE # 5 on 23 February 1956

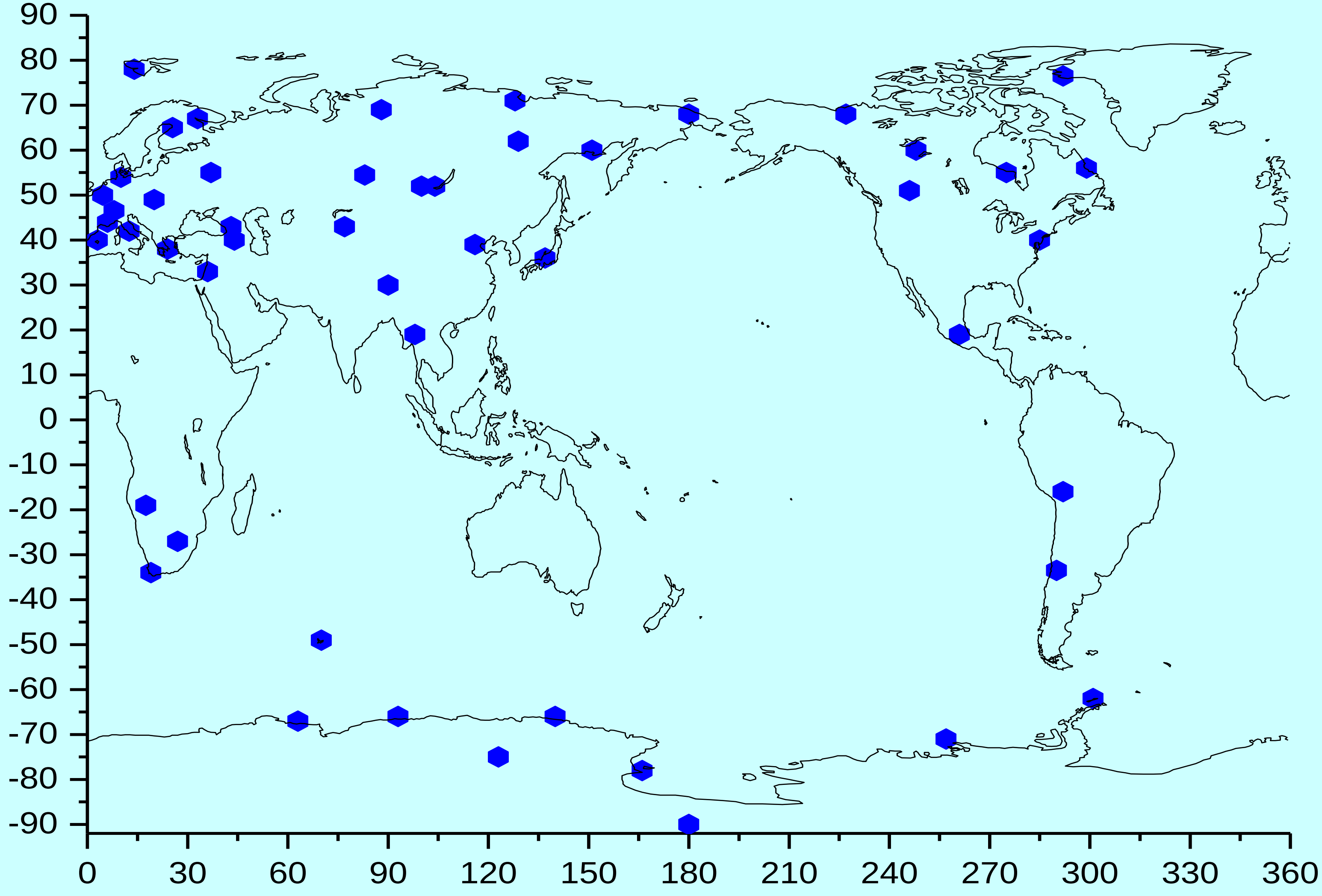
GLE73 revealed a typical gradual increase, and slight anisotropy during the onset

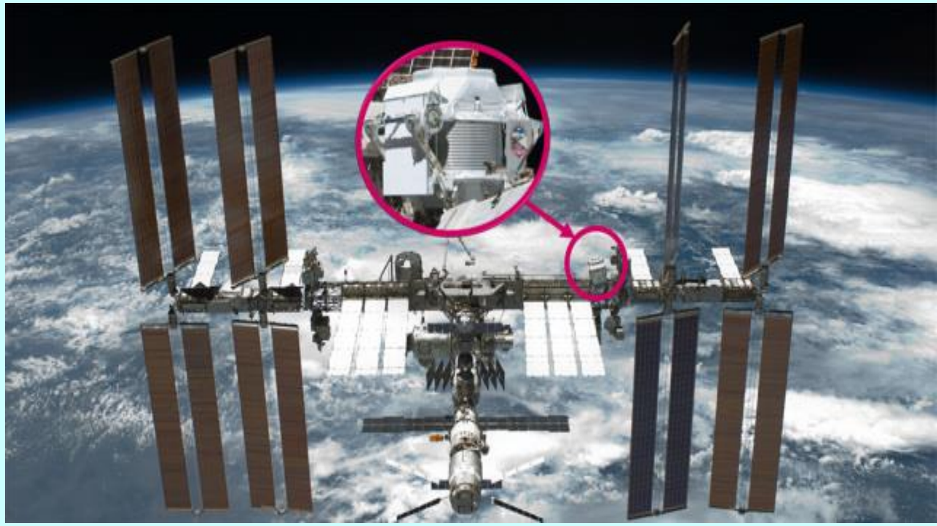
The flux remained above the background level for **~ 4.5 hours**



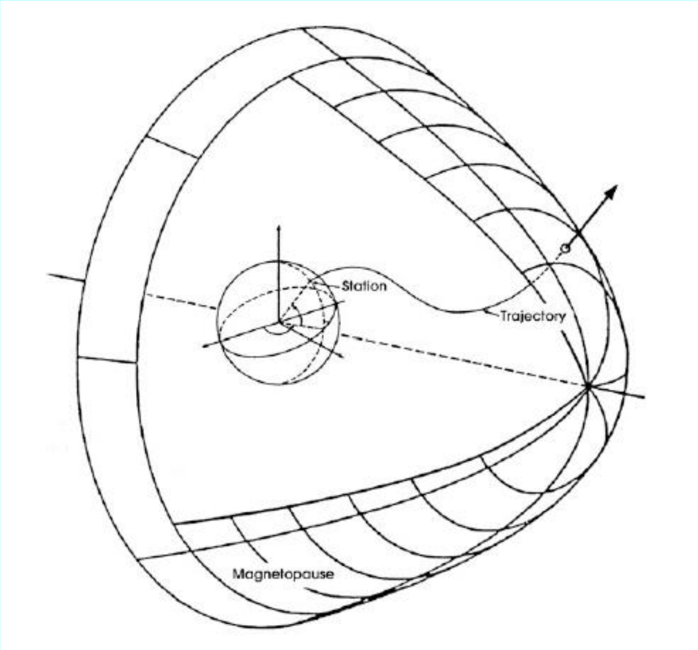


Global neutron monitor network, AMS 02





Method for GLE analysis

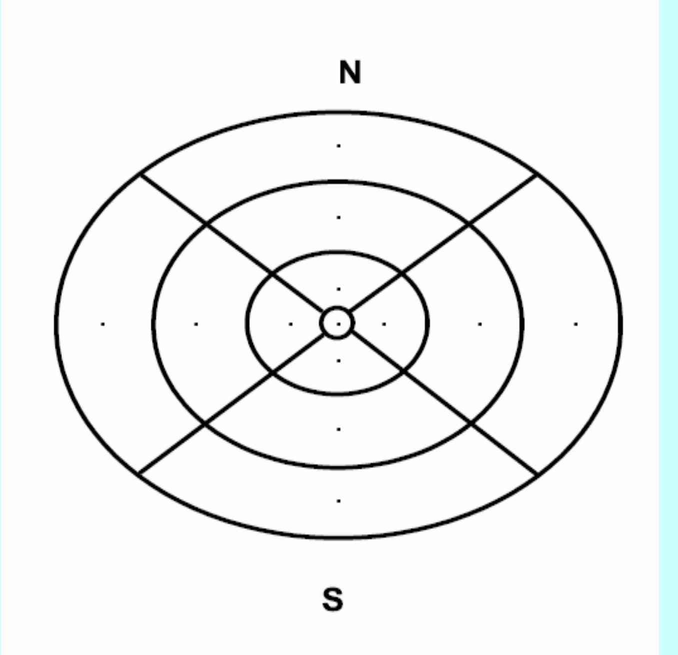


Modelling the global NM network response

$$N(P_c, h, t) = \sum_i \int_{P_c}^{\infty} S_i(P, h)\, J_i(P, t)\, dP$$

$$S_i(P, h) = G(P) \sum_j \int \int A_i(E, \theta) \cdot F_{i,j}(P, h, E, \theta)\, dE\, d\Omega$$

$$\frac{\Delta N(P_{cut})}{N} = \frac{\frac{1}{13} \sum_k \int_{P_{cut}}^{P_{max}} J_{sep}(P, t) S_k(P) G(\alpha(P, t)) A(P) dP}{\int_{P_{cut}}^{\infty} J_{GCR}(P, t) Y(P) dP}$$



Computation of asymptotic viewing cones and Pc of the NM stations:
Computation of particle trajectory in a model magnetosphere.
Application of a optimization procedure (inverse method)
primary solar proton parameters:
(energy spectrum, anisotropy axis direction, pitch-angle distribution)

Modeling of spectra and PAD of SEPs

Modified power law, exponent or Ellison-Ramaty

$$J_{||}(P) = J_0 P^{-(\gamma+\delta\gamma(P-1))}$$

At $P \le 1$ GV

$$J_{||}(P) = J_0 P^{-(\gamma+\delta\gamma\cdot P)}$$

$$J_{||}(P) = J_0 \exp(-P/P_0)$$

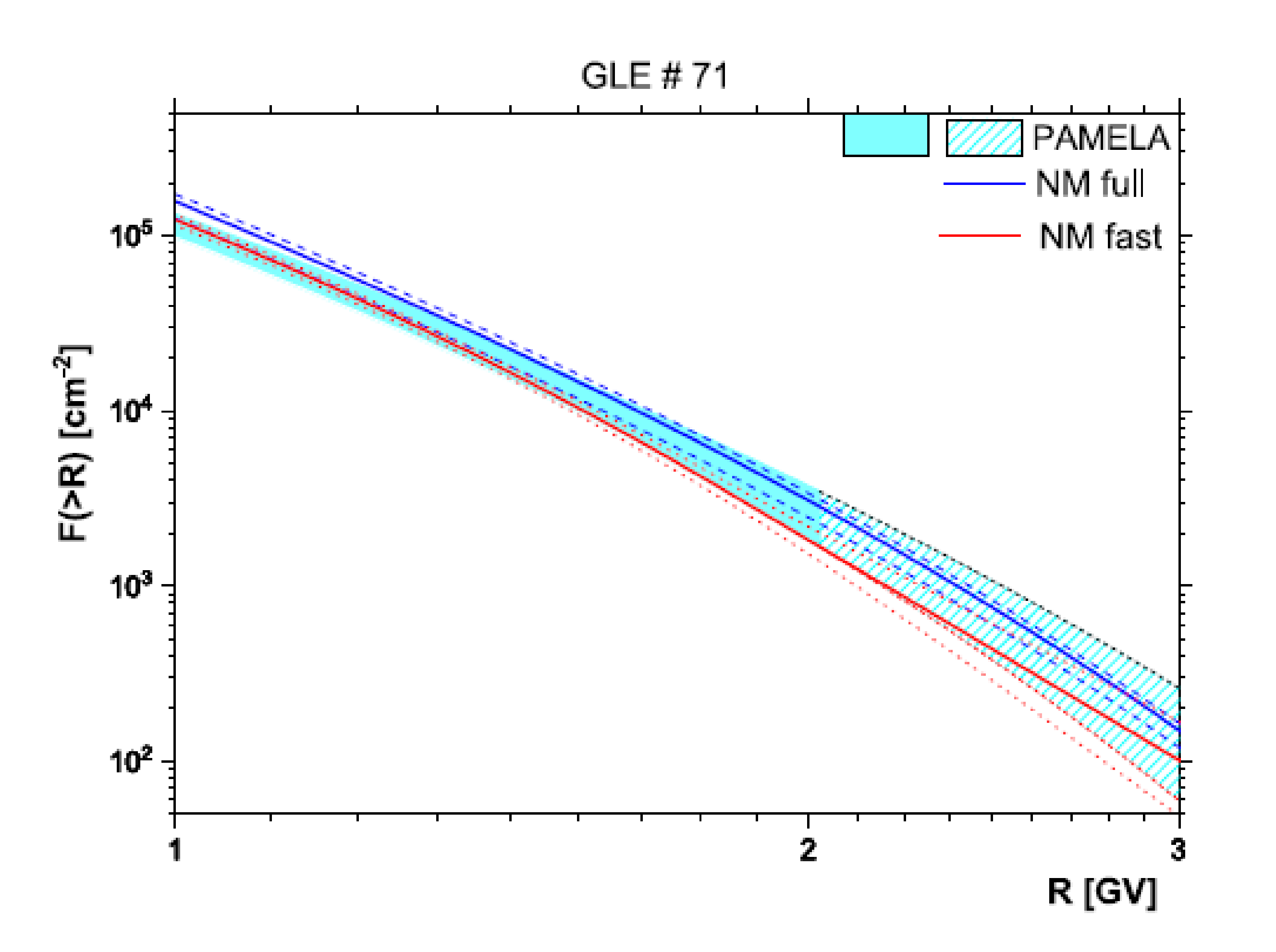
$$F(R) = J_1 \left(\frac{R}{1\,\mathrm{GV}}\right)^{-\gamma_1} \exp\left(-\frac{R}{R_1}\right) \quad \text{if } R < R_\mathrm{b},$$

$$F(R) = J_2 \left(\frac{R}{1\,\mathrm{GV}}\right)^{-\gamma_2} \exp\left(-\frac{R}{R_2}\right) \quad \text{if } R \ge R_\mathrm{b},$$

PAD – Gaussian

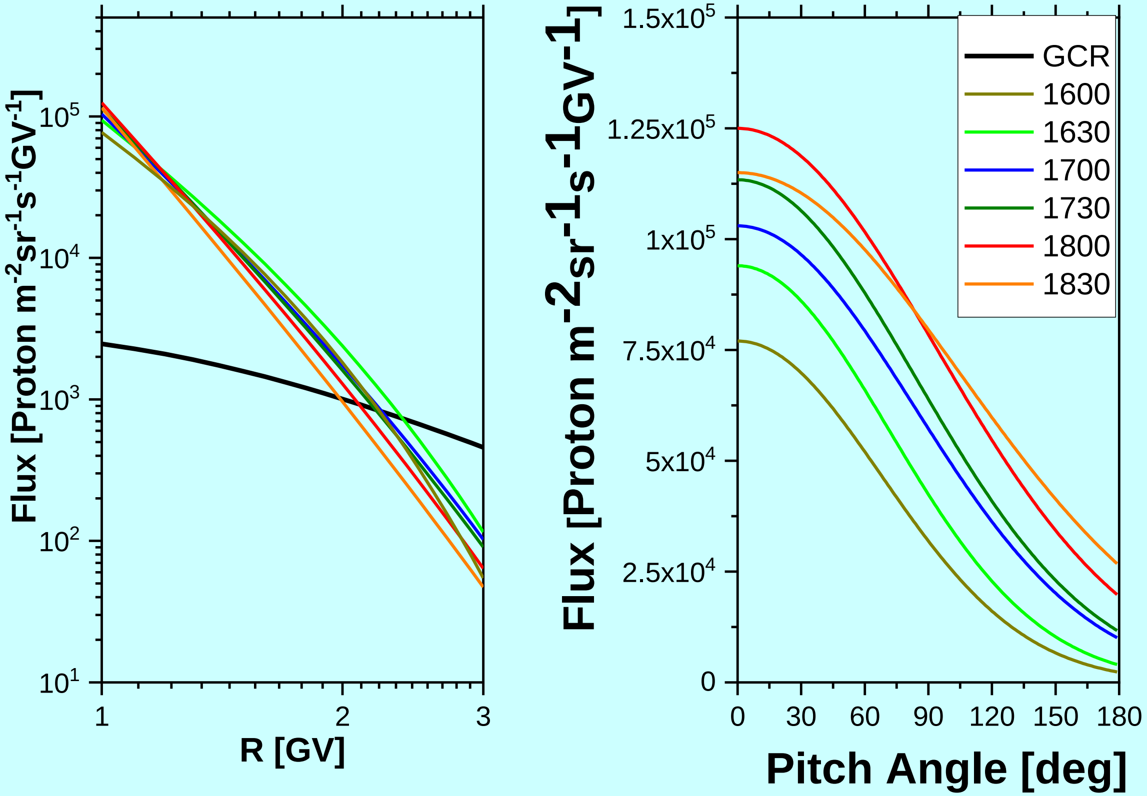
$$G(\alpha) = \propto \sum_i \exp - (\alpha_i - \alpha_i^{'})^2 / \sigma_i^2$$

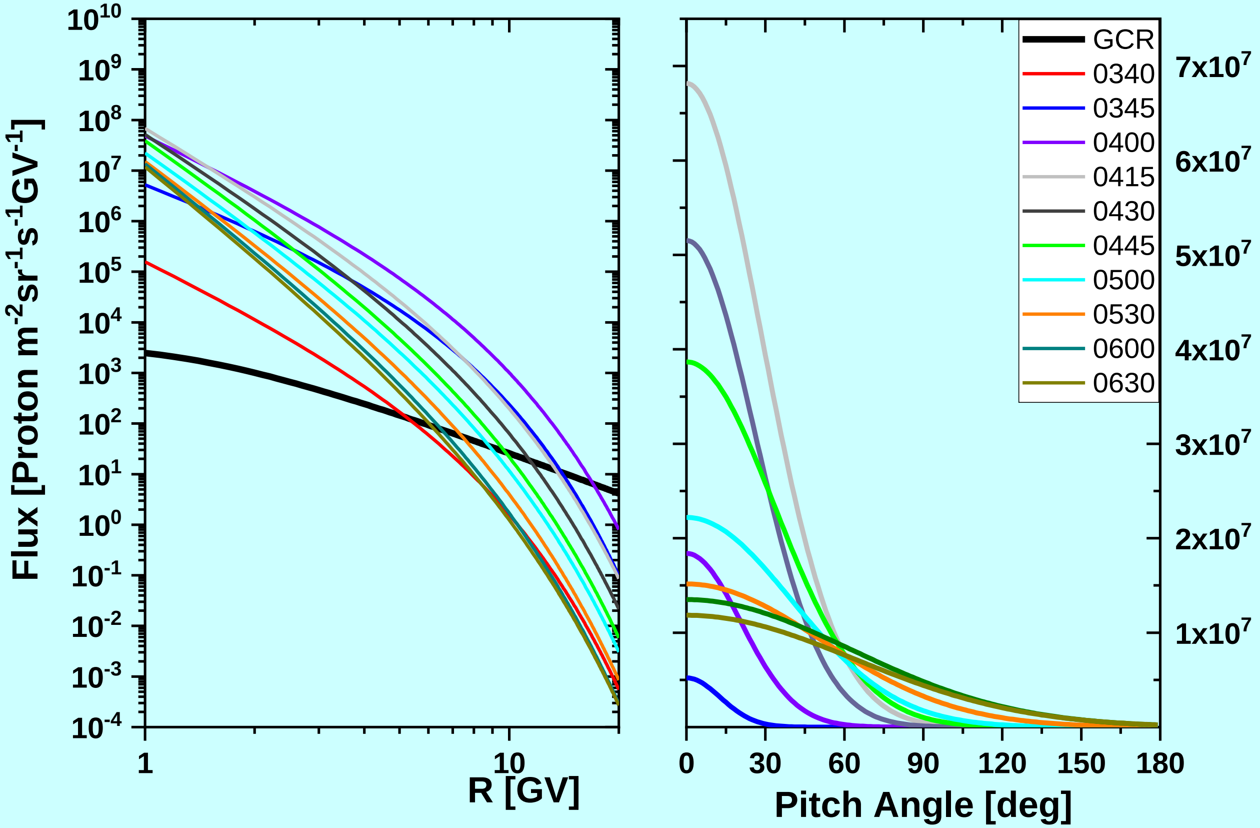
GLE analysis comparison with direct measurements



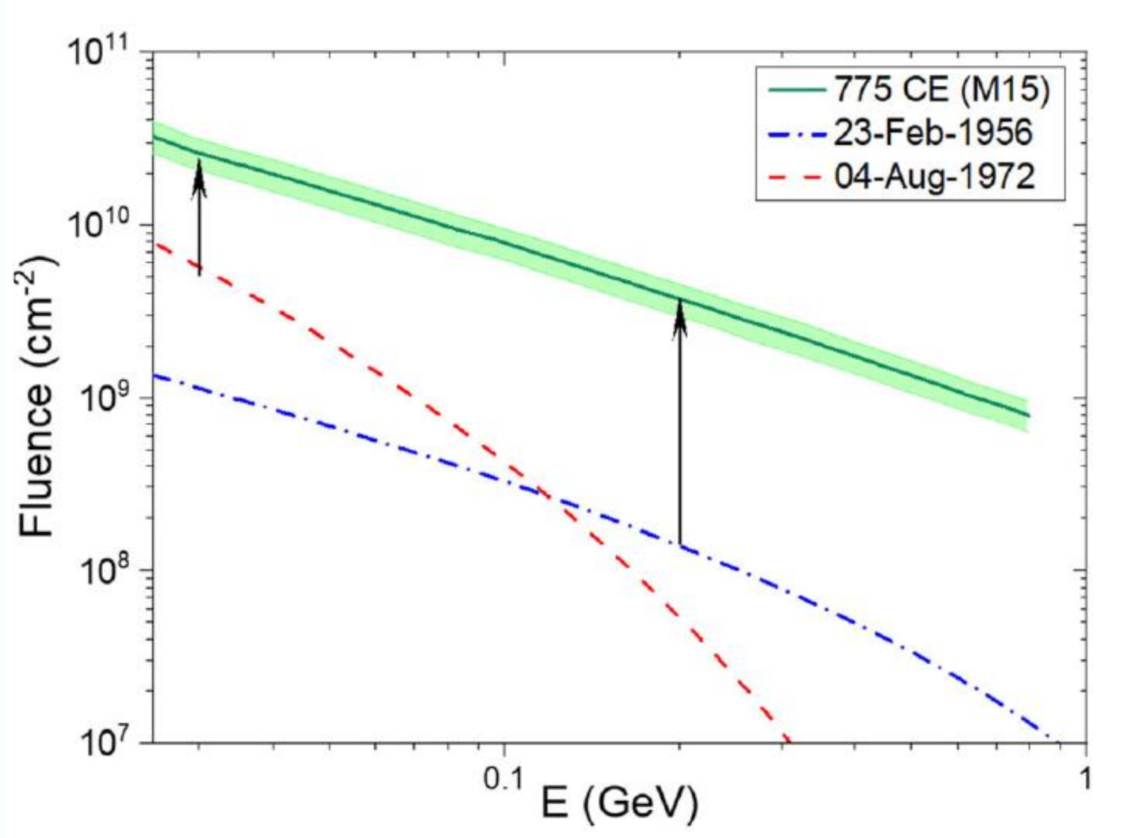
Reconstruction of the integral SEP fluence for GLE #71 (17 May 2012)
Direct measurements by the PAMELA experiment parameterized via the Ellison–Ramaty
1σ uncertainties are shown with the *filled area* (Bruno *et al.*, 2018).

Rigidity spectra and PAD during GLE #5, 23 February 1956
GLE #   73, 28 October 2021

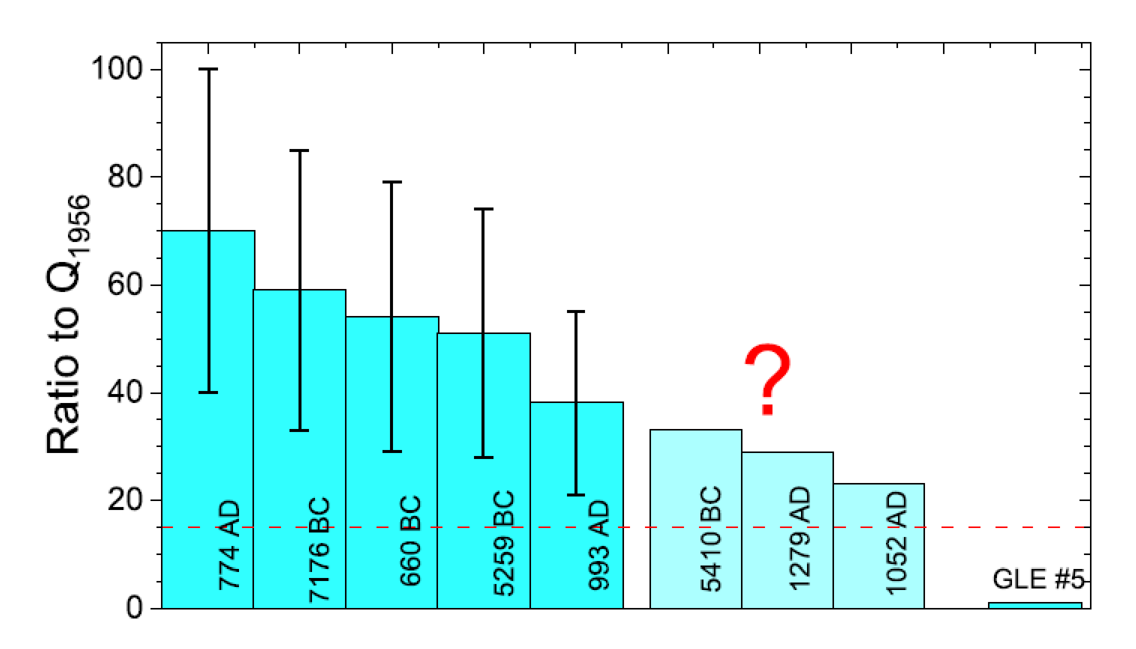




Event integrated fluence of selected events incl. 774 AD



Ratio of the modelled annual radiocarbon production Q of known (blue) and candidate (light blue) historical SEP events



774 AD (Mekhaldi et al. 2015, green line),
two major GLE: hardest (23 February 1956; blue dashed curve) and softest (4 August 1972; red dotted curve)
see (Koldobskiy et al. 2021); for details see Cliver et al., LRSP 2022

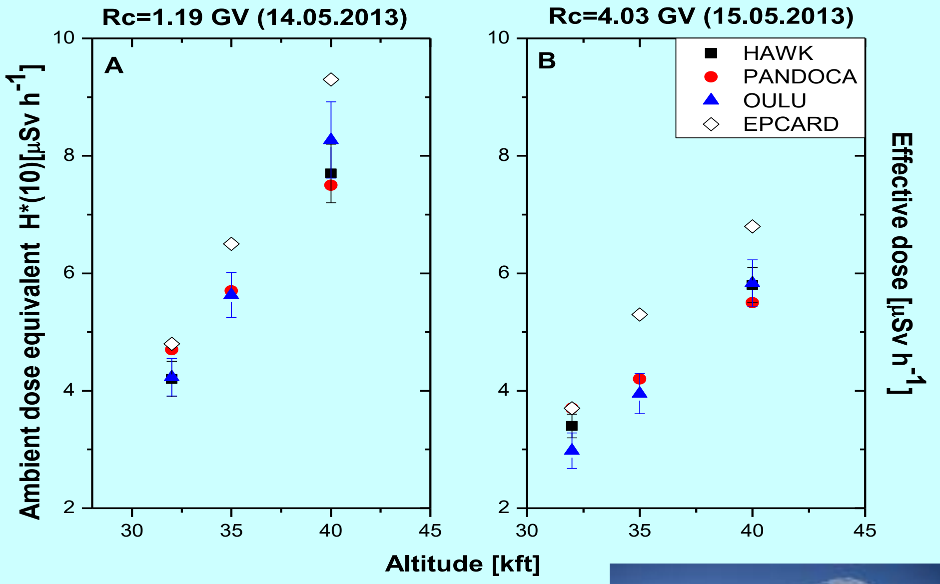
Model for computation of exposure to radiation at aviation altitudes

Effective and/or
ambient dose equivalent dose rate

$$E(h, R_c, \theta, \varphi) = \sum_i \int_{E_{cut,i}(R_c)}^{\infty} \int_{\Omega} J_i(T') Y_i(T', h) d\Omega dT'$$

MC computed Yield function

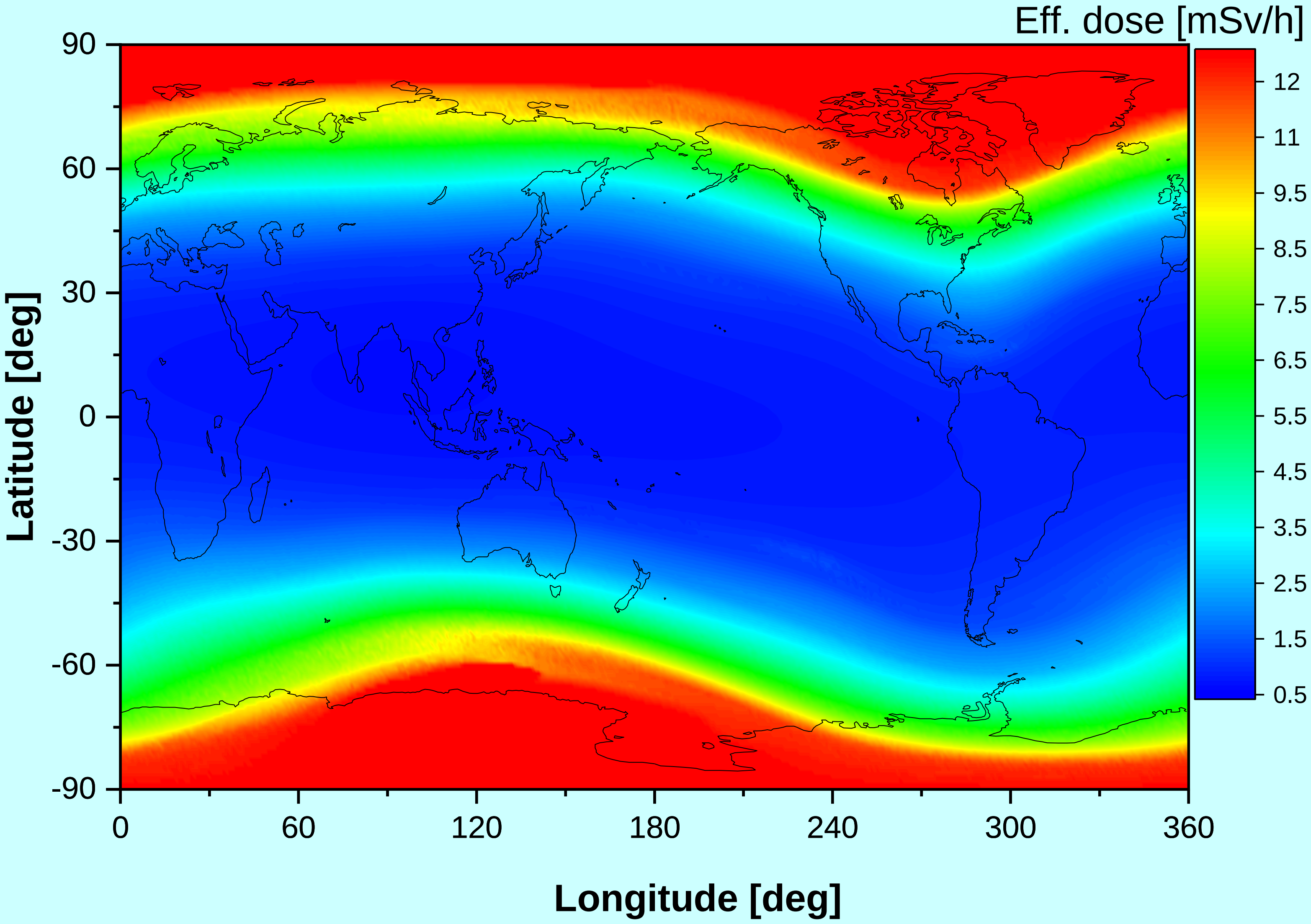
$$Y_i(T', h) = \sum_j \int_{T^*} F_{i,j}(h, T', T^*, \theta, \varphi) C_j(T^*) dT^*$$



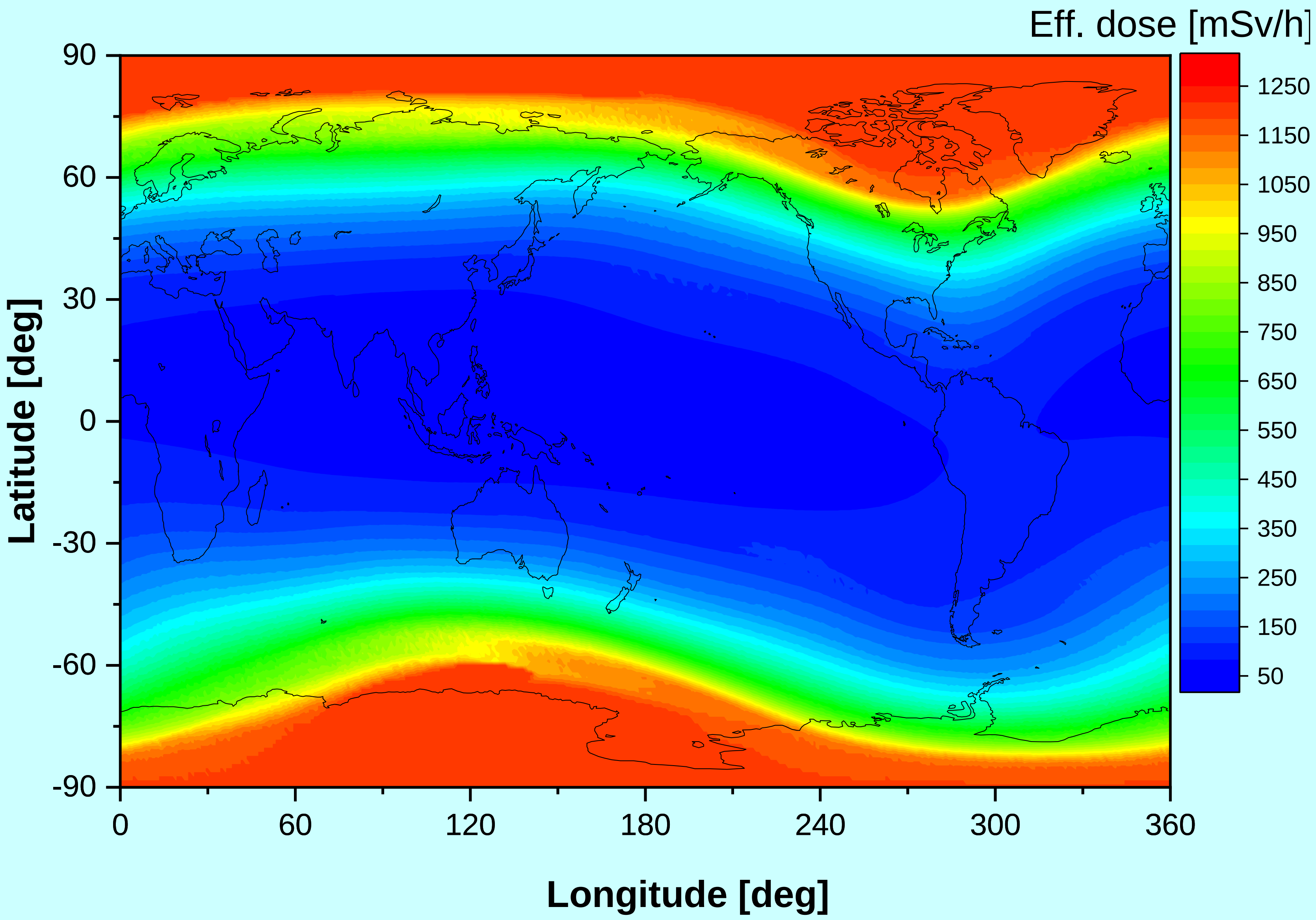
Comparison between MDU-1 Liulin measurements with Oulu dosi
spheric ionization models. Column 1–2 correspond to the altitud
respectively. Column 3 correspond to MDU-1 Liulin measurement,
modeled absorbed dose, while columns 5–6 to ion production in ai

Alt. [km]	Alt. [kft]	Dose rate [μGy/h]		Ionization [ion pairs/s cm^3]	
		Liulin	Model	Liulin	Model
3	9.85	0.37 ± 0.9	0.22 ± 0.08	16 ± 6	21 ± 5
10.7	35	2.8 ± 0.7	6.4 ± 2.0	43 ± 14	55 ± 12
15.2	50	5.2 ± 1.3	7.7 ± 2.1	57 ± 18	62 ± 14

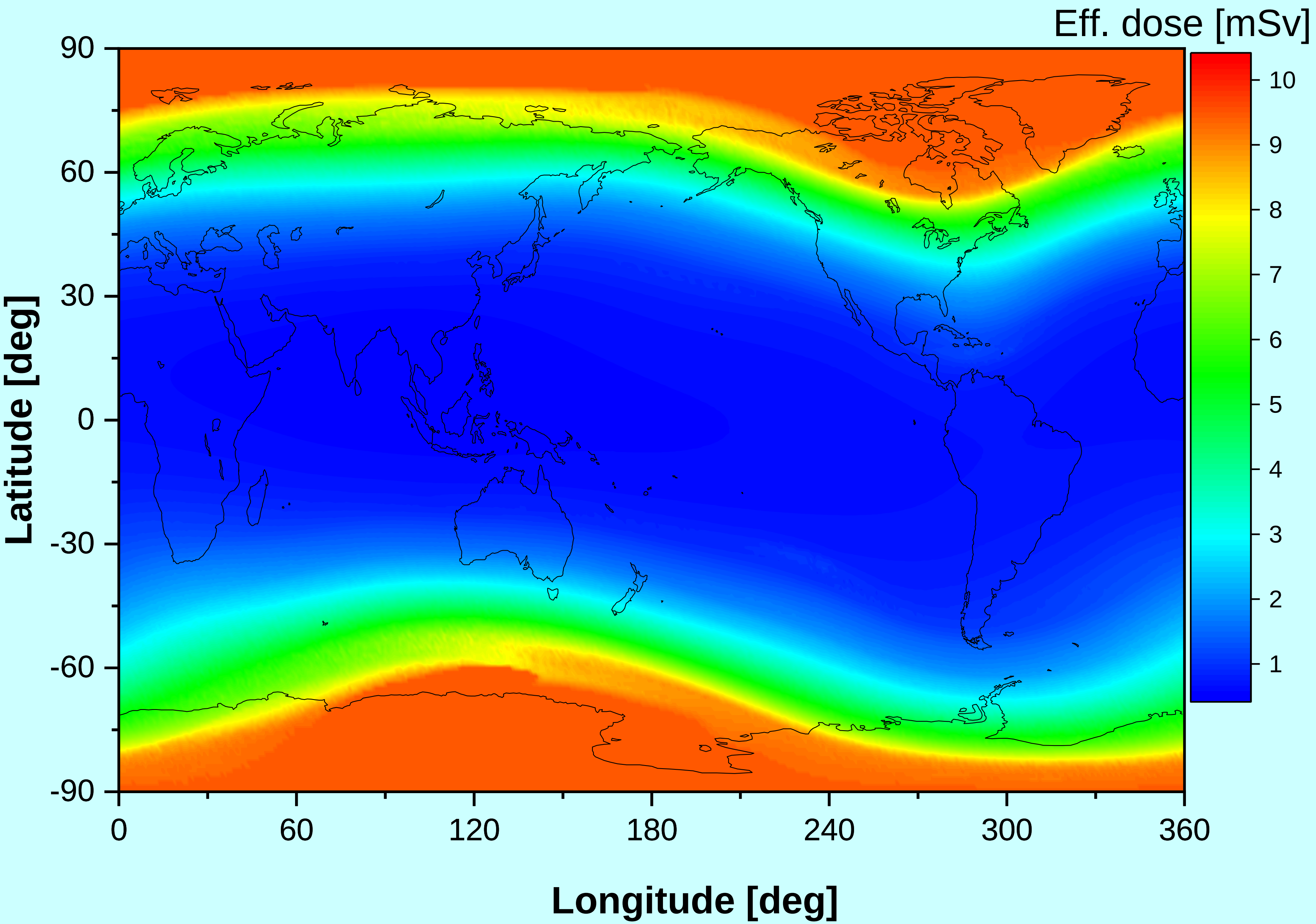
Peak effective dose at level 050 during GLE #5, 23 February 1956



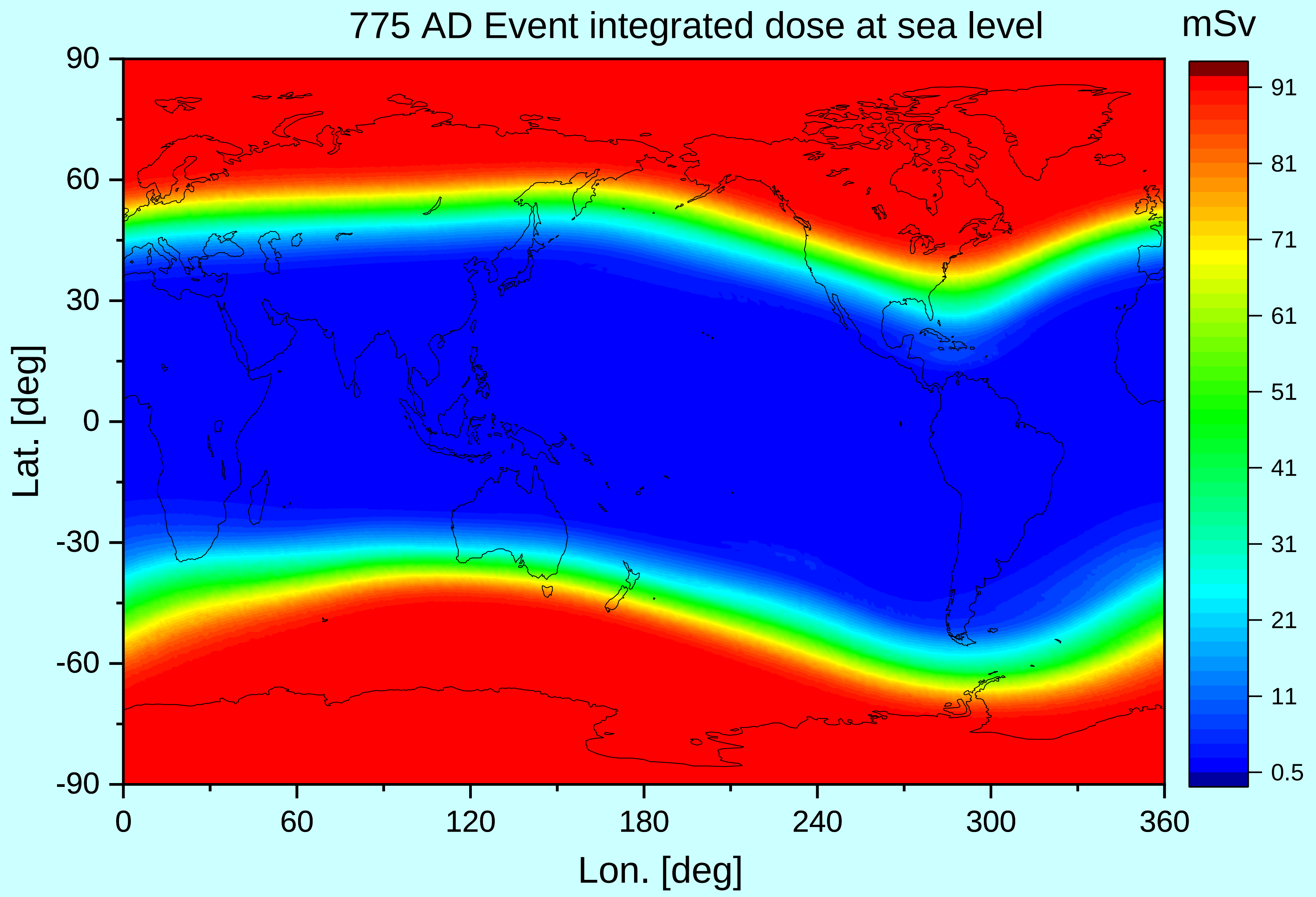
Peak effective dose at level 050 during 774 AD event



Integrated exposure during the first 4h of GLE# 5 at L040



Event integrated effective dose at sea level during 774 AD event

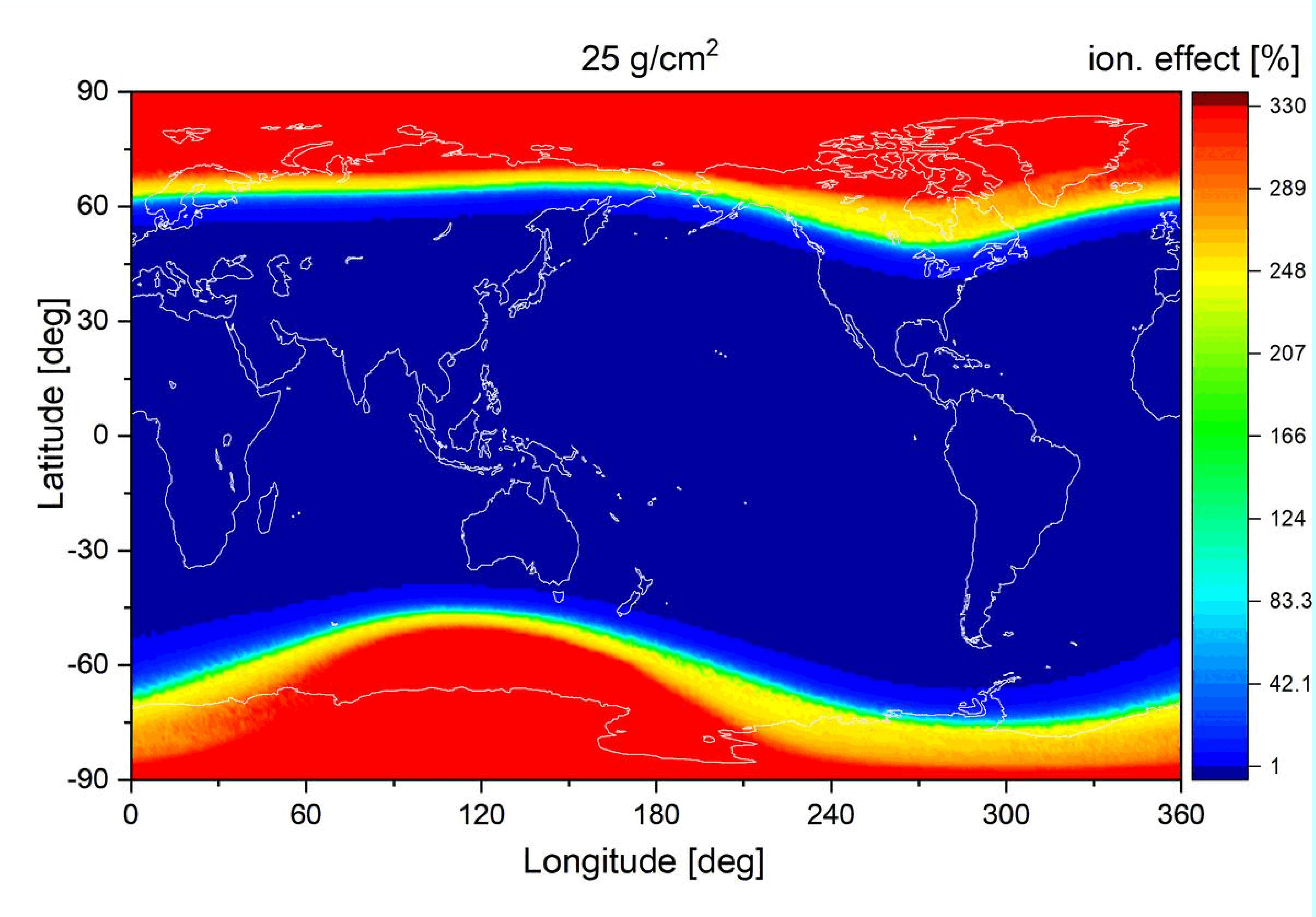


Atmospheric ionization

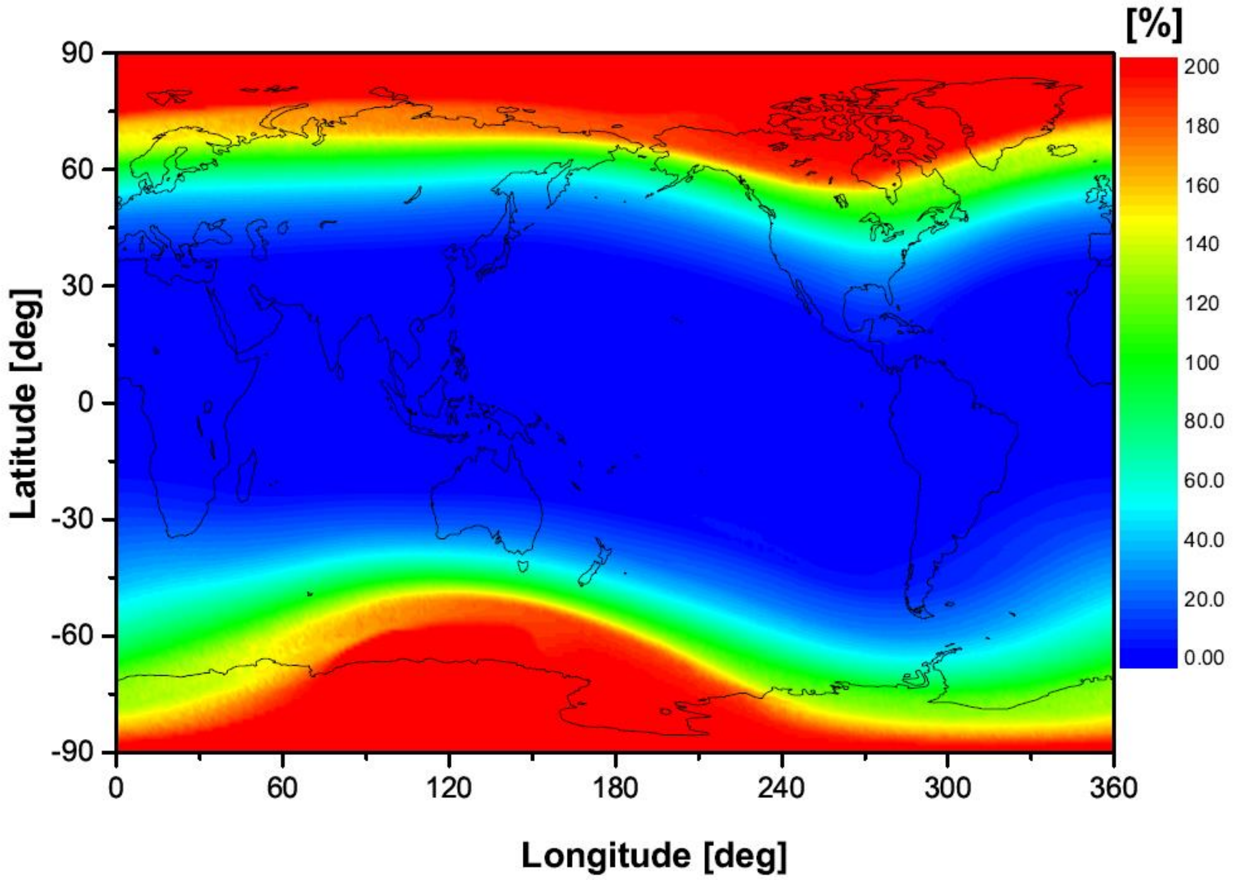
$$q(h,E) = \frac{1}{E_{ion}} \sum_i \int_{E_{cut}(R_c)}^{\infty} \int_{\Omega} D_i(E) \frac{\partial E(h,E)}{\partial h} \rho(h) dE d\Omega$$

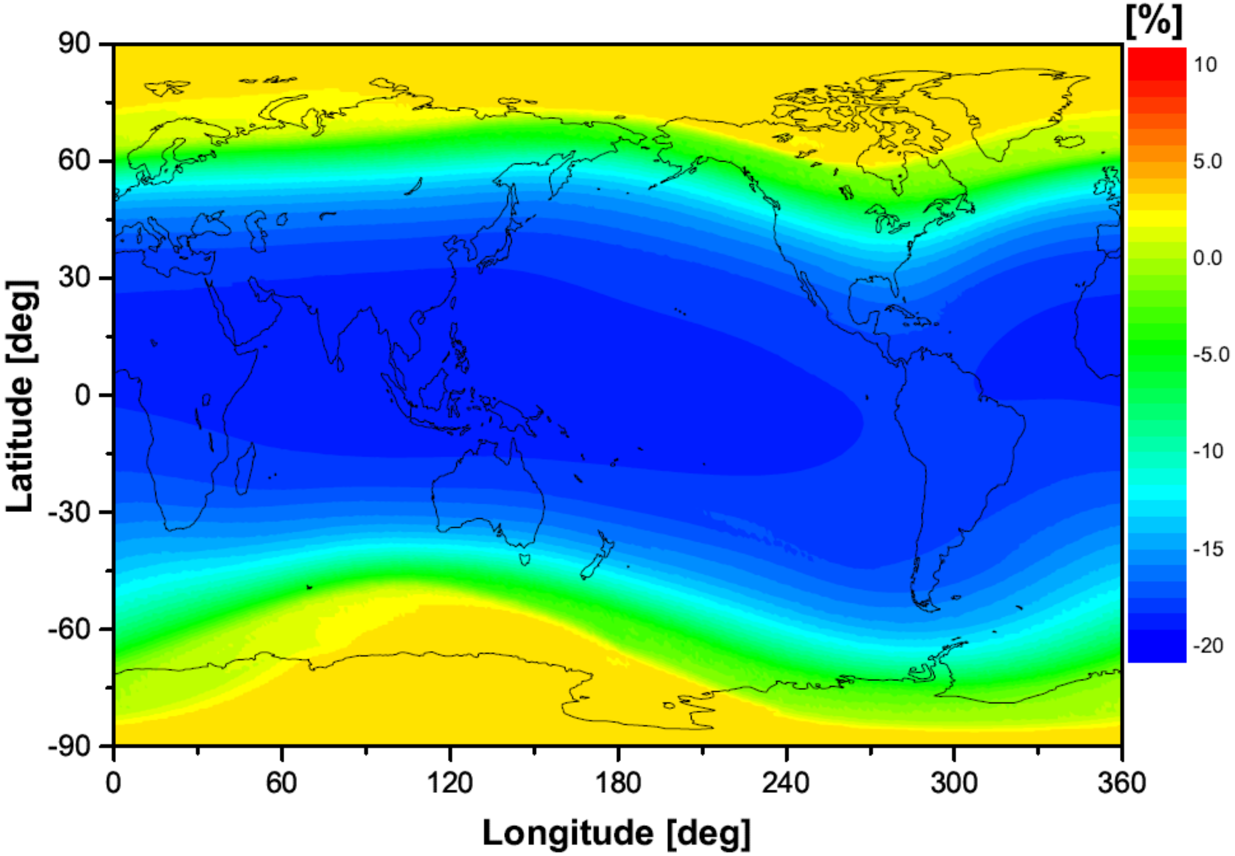
where δE is the deposited energy in an atmospheric layer δh , h is the air overburden (air mass) above a given altitude in the atmosphere expressed in g/cm^2 or altitude a.s.l., Di(E) is the differential cosmic ray spectrum for a given component i: protons p, Helium (-particles), the latter representative for heavier nuclei with atomic number Z > 2, is the atmospheric density in $g.cm^{-3}$, E is the initial energy of the incoming primary nuclei on the top of the atmosphere, is a solid angle and Eion = 35 eV is the average energy necessary for creation of an ion pair in air.

24h integrated ionization effect vs. altitude during GLE # 73



24h integrated ionization effect at R-P maximum during GLE # 65 and 66





Conclusion

1. Using verified NM yield function & verified method for GLE analysis based on NM data

2. Spectra of selected GLEs, scaling of GLE # 5 to 774 AD

3. Assessment of space weather & terrestrial effects, inluding 774 AD


THANK YOU