Which are the relevant energies and measurements for Space Radioprotection?

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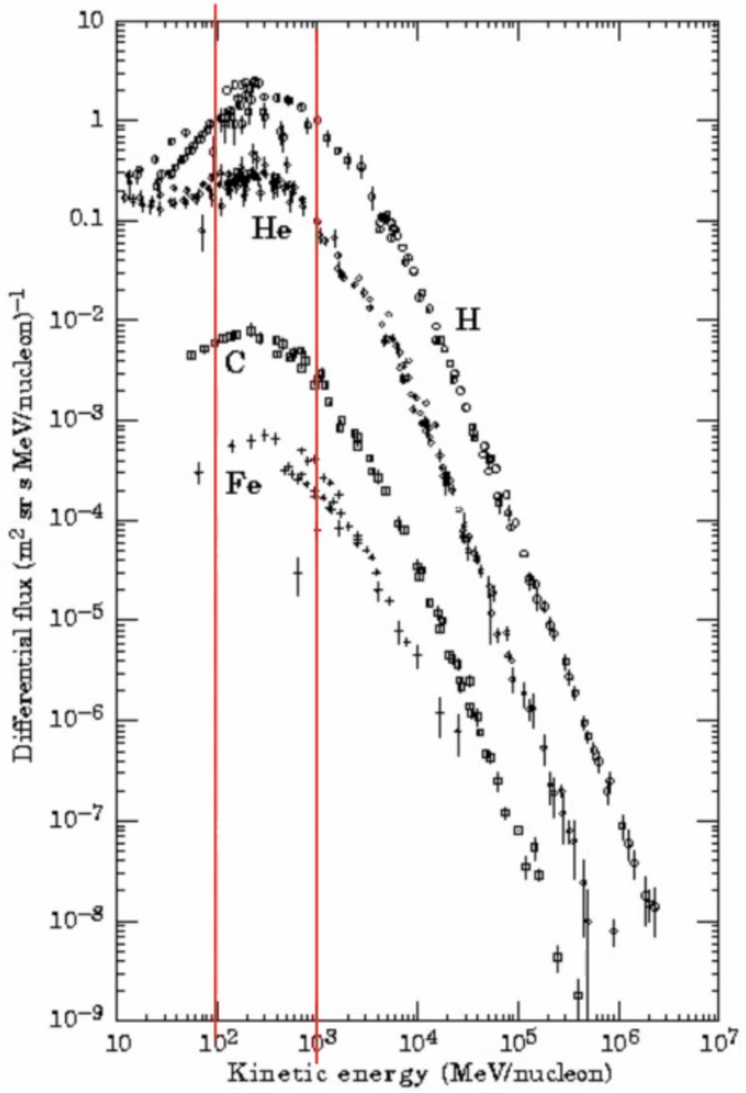
Introduction

During the FOOT Coll. Meeting in June 2023 some discussion has started about the relevant energies for measurements of interest for Space Radioprotection

In this presentation we aim to clarify a few aspects and propose some discussion about the future programme of FOOT in this topic

The galactic cosmic ray spectrum



Reminded by M. Toppi during the FOOT general meeting
Here the spectrum is given as a function of energy/nucleon

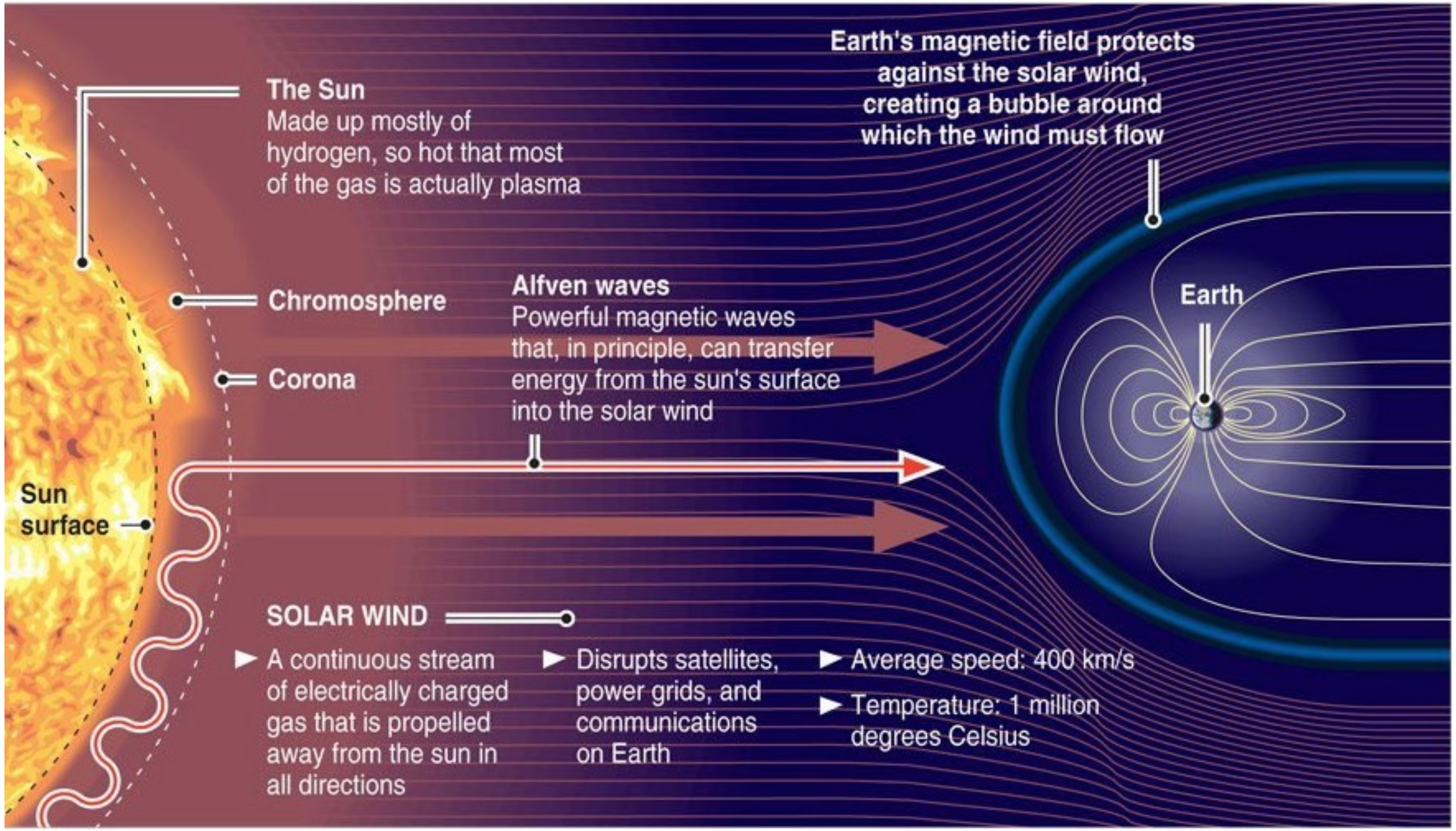
In GCR you can find all nuclei from H to Fe (and also something beyond Fe)
Above a few GeV/nucleon all energy spectra exhibit a power law behaviour ~$E^{-\gamma}$, where γ~2.7 (somewhat depending on nuclear species)

However in this (old) plot some very important facts do not appear
As we are going to show in the following,
the energy region below 1 GeV/nucleon is strongly affected by:

- Solar Modulation (in the whole solar system)
- Earth Magnetic field (coordinate dependent, relevant for all missions in Low Earth Orbit, e.g. on the International Space Station)

The role of solar modulation

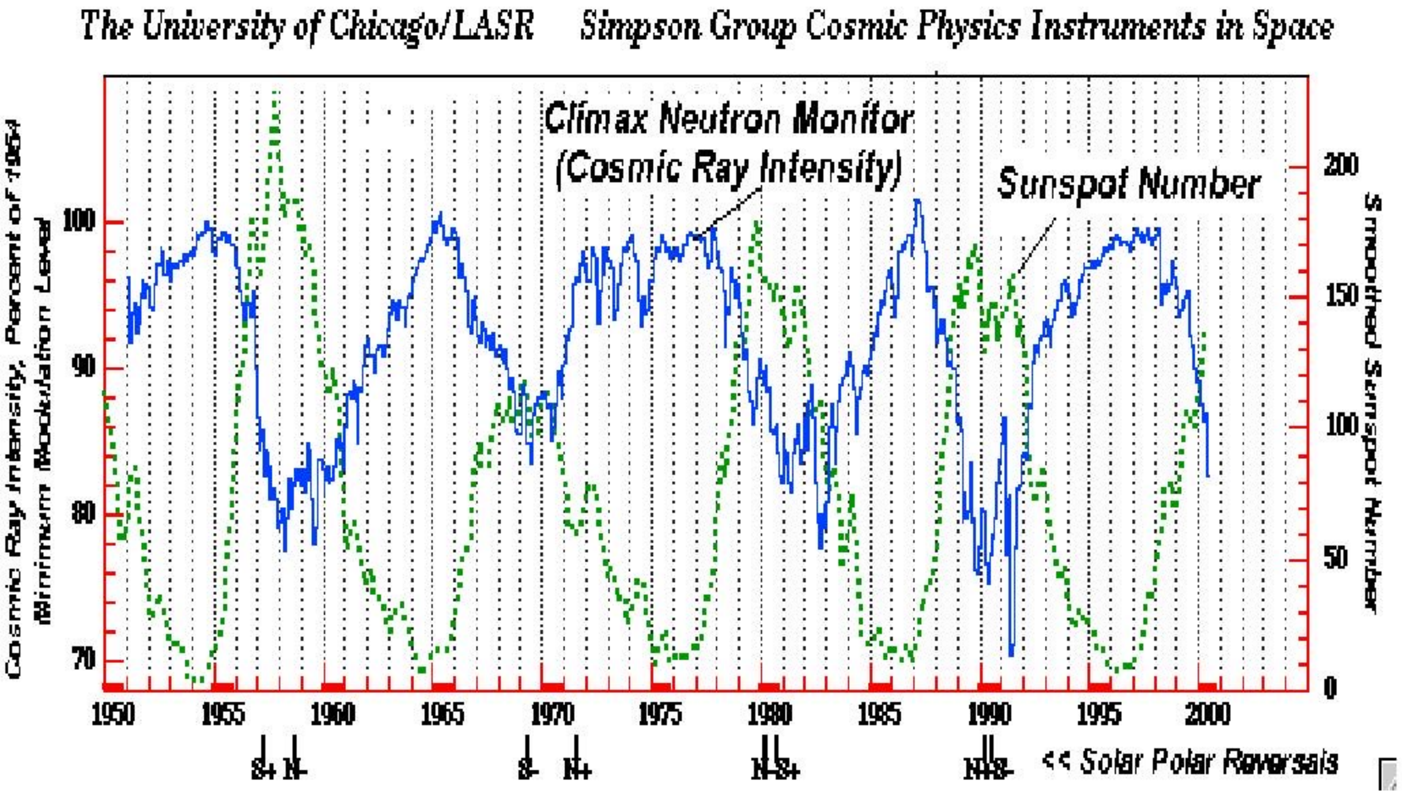
Heliosphere is the region surrounding the Sun and the solar system that is **filled with the solar magnetic field** and the protons and electrons of the **solar wind**. The solar wind is a gas of charged particles known as plasma.



The solar wind particles, even when enhanced due to higher solar activities, do not contribute to the radiation burden to astronauts due to their relative low energy and hence their absorption in already very thin shielding thicknesses.

The role of solar modulation

Cosmic ray fluxes in the heliosphere are modulated by solar wind.
The solar activity changes with a period of ~11 year, and this is the main reason for the observed 11-year variations of cosmic ray fluxes.
Predictions are based on sunspot number (SSN) and is anticorrelated with the neutron flux monitors at the Earth surface.



Besides this, the directions of magnetic fields in solar polar regions and in the heliosphere change to the opposite direction every ~11-years. This causes, in addition, the presence of another 22-year solar magnetic cycle and contributes features to the known ~11-cycle

The role of solar modulation

During phases of higher solar activity the cosmic-ray flux is decreased by a factor from 3 to 4 against phases during minimum solar activity.
This is the reason why travels to moon and Mars are planned for 2024 and 2035 respectively.

However, the probability of Solar Particle Events (SPE) is higher during solar maximum.

Solar modulation affects the GCR spectrum mostly in the energy region <1 GeV/n

fundamental impact on the radiation risk assessment:

not only intensity, but also relevant energies change

The Badhwar & O’Neill (BON) model of GCR spectra adopted by NASA

The BON model (first published in 1996) provides a description of the “Local Interstellar Energy Spectrum” (LIS) for all ions from Z=1 to Z=28. It starts from the existing set of experimental data and makes use of a magneto-hydrodynamic model to take into account solar modulation in the heliosphere

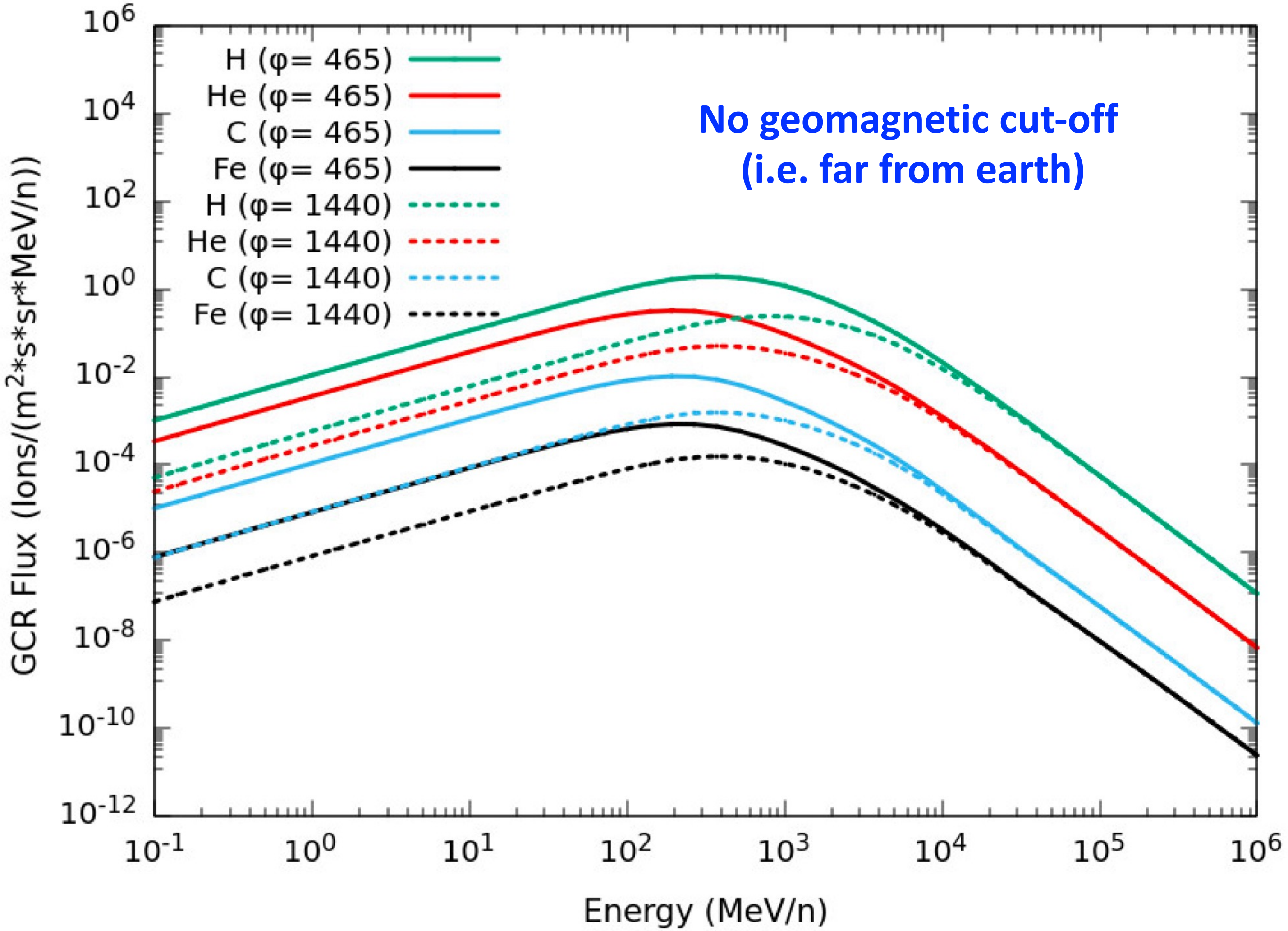
LIS are parametrized as: $f_{\mathrm{LIS}}(T) = j_0 \beta^{\delta} (T + m)^{-\gamma}$ T = Kinetic energy/nucleon

LIS spectra are then brought to local spectra, at any distance from the Sun and time, according to the state of the heliosphere by means of a diffusion equation where the main parameter is a “solar modulation potential” ϕ.

ϕ values at a given time can be estimated using the cosmic ray neutron monitors, correlated to the sunspot number (i.e. to solar activity)

(for bibliography and details see Appendix)

A few Z spectra for 2 values of solar modulation potential representing typical solar max and solar min conditions



When moving **from solar min to solar max**:

- the change (increase) in peak energy
- the change (decrease) of flux intensities for E<1GeV/u:

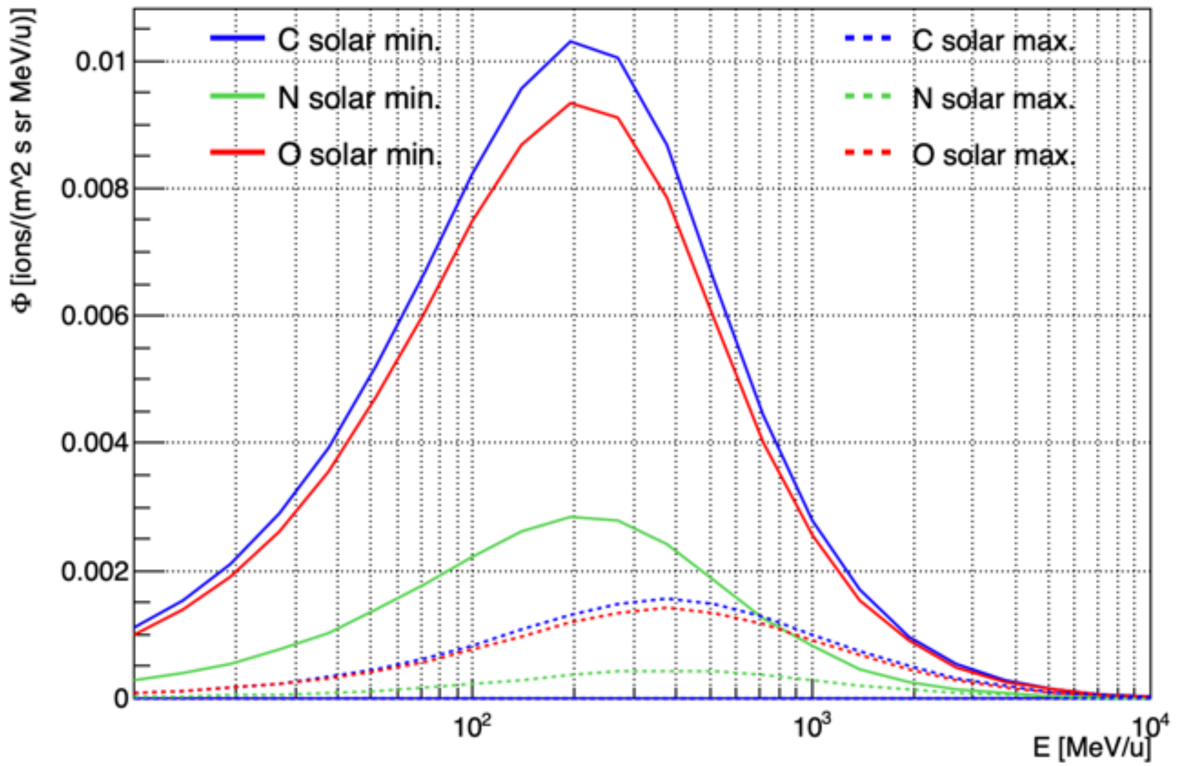
The change in intensity is significant, don't be confused by the log scale:

Up to ¾ of the total GCRs flux is lost!

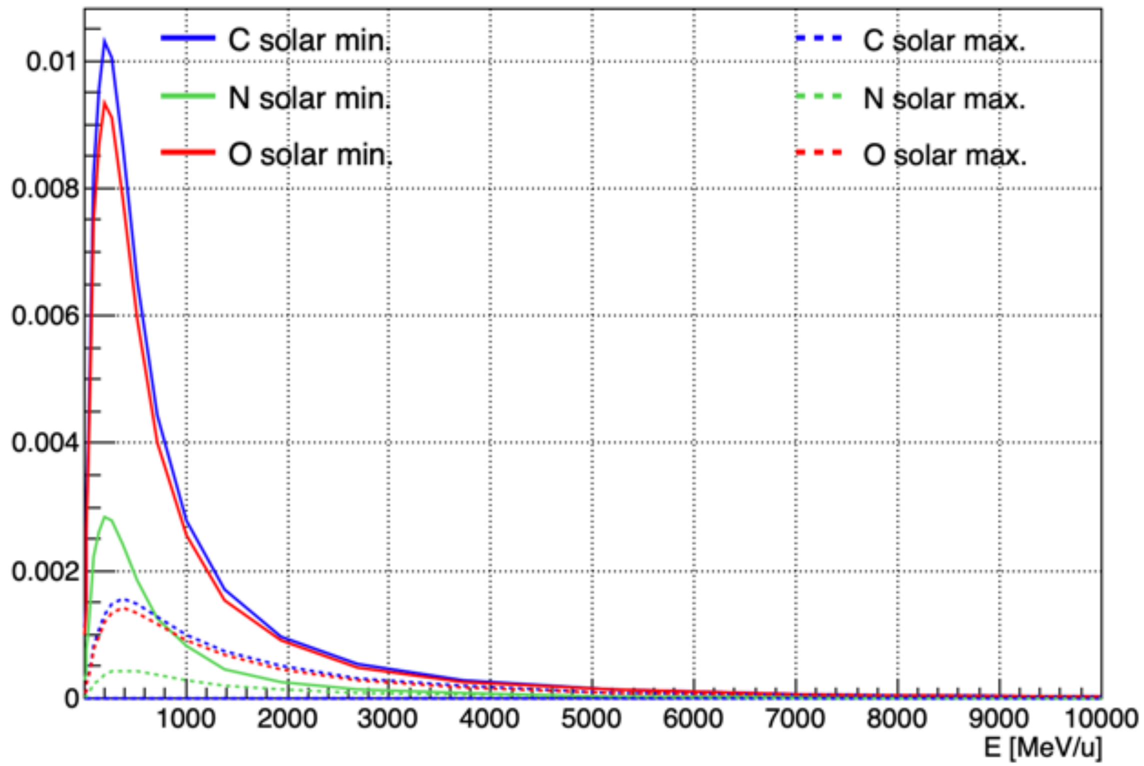
Example for C,N,O spectra

No geomagnetic cut-off (i.e. far from earth)

Lin-Log scale



Lin-Lin scale



Notice for example that peak energy for C,O moves from ~300 MeV/u at solar min to ~500 MeV/u at solar max

It is also evident that, from the point of view of radiation protection, solar max is a safer condition with respect to solar min as far as GCR are concerned, but…

BON GCR spectra are included in FLUKA

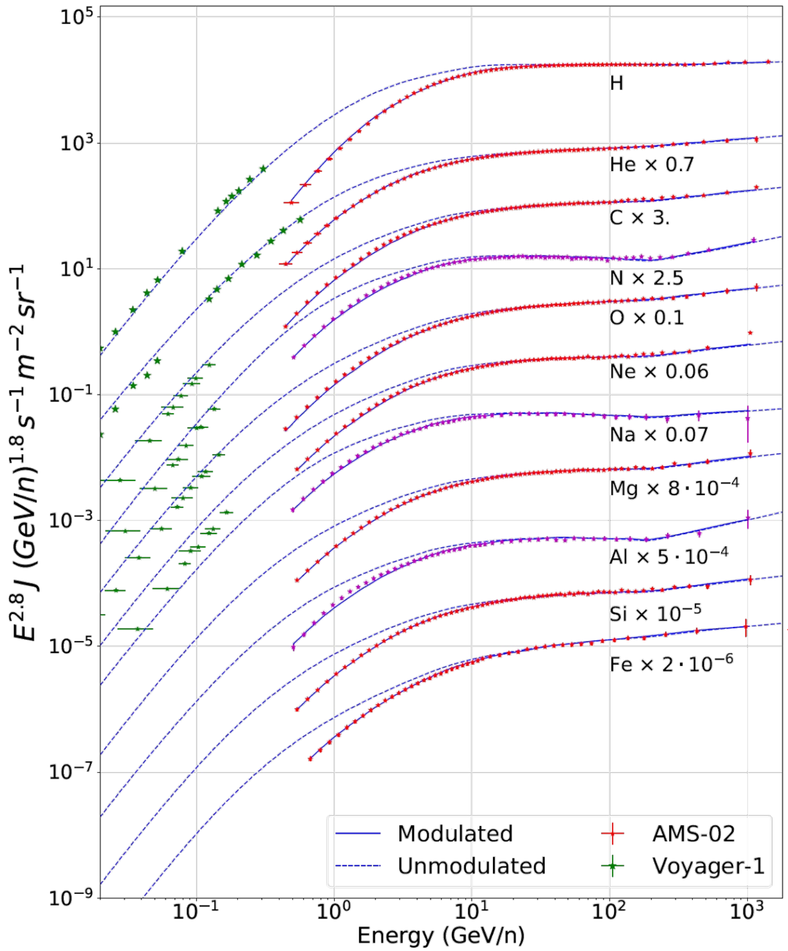


Figure 4. Spectra of the CRs injected in the simulations, compared to AMS-02 and Voyager-1 data (available up to Ne). Modulated spectra (see the text for the details in the Fisk potential used for the data collected in different periods) are shown as a solid line and the unmodulated spectra as a dashed line. Voyager data is shown in green, AMS-02 data corresponding to CR species with a significant secondary contribution (namely N, Na and Al) is shown in magenta and AMS-02 for the main primary CR nuclei is shown in red.

FLUKA has included BON GCR spectra useful for several applications for 25 years .

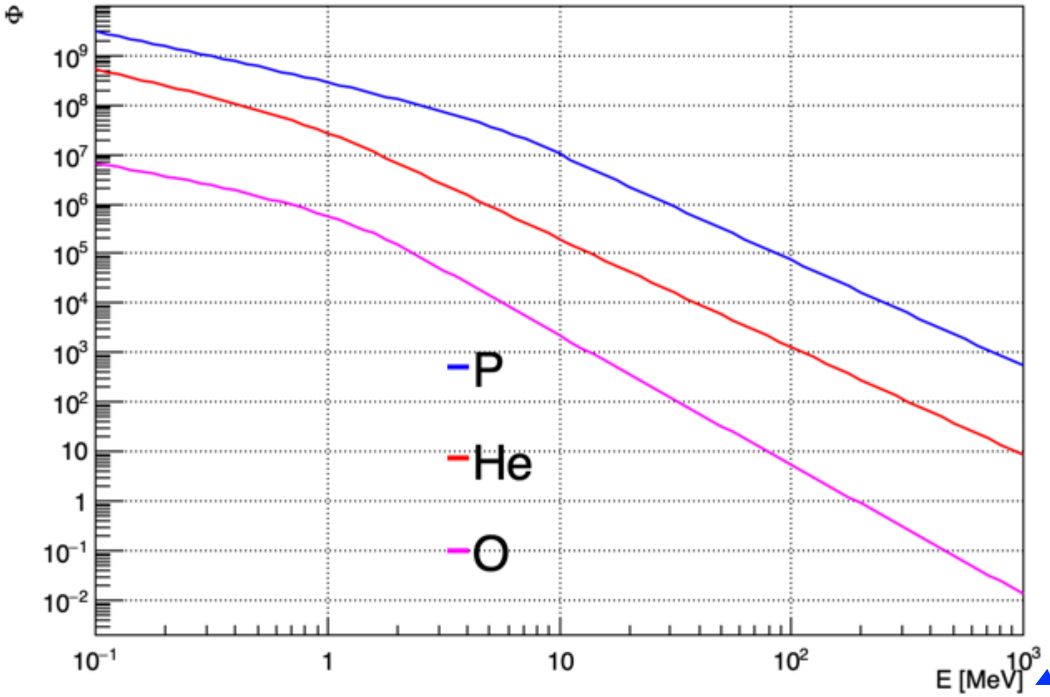
The latest update will be available in the next 2023 release

In this plot fluxes are weigthed by $E^{2.8}$

Pro and Con of the Solar Maximum choice

From the point of view of radiation risk, Solar Max is taken as the preferred choice for Far From Earth missions. This is true from the point of view of dose from GCR

However, during Solar Max periods, the frequency of Solar Particle Events (SPE) is significantly higher



Example:
energy spectra from SPE of 20 Jan 2005

Mostly low energy protons

Warning: this is total kinetic energy

Countermeasurements to be taken by astronauts

A ~fast warning of SPE is possible: ~ 1 hour in advance

https://www.youtube.com/watch?v=70GrihLXmSs

At present astronanuts can take shelter under their baggages in the cargo bay

Courtesy of F. Ballarini (Pv)

Other possible countermeasurements against SPE and GCR

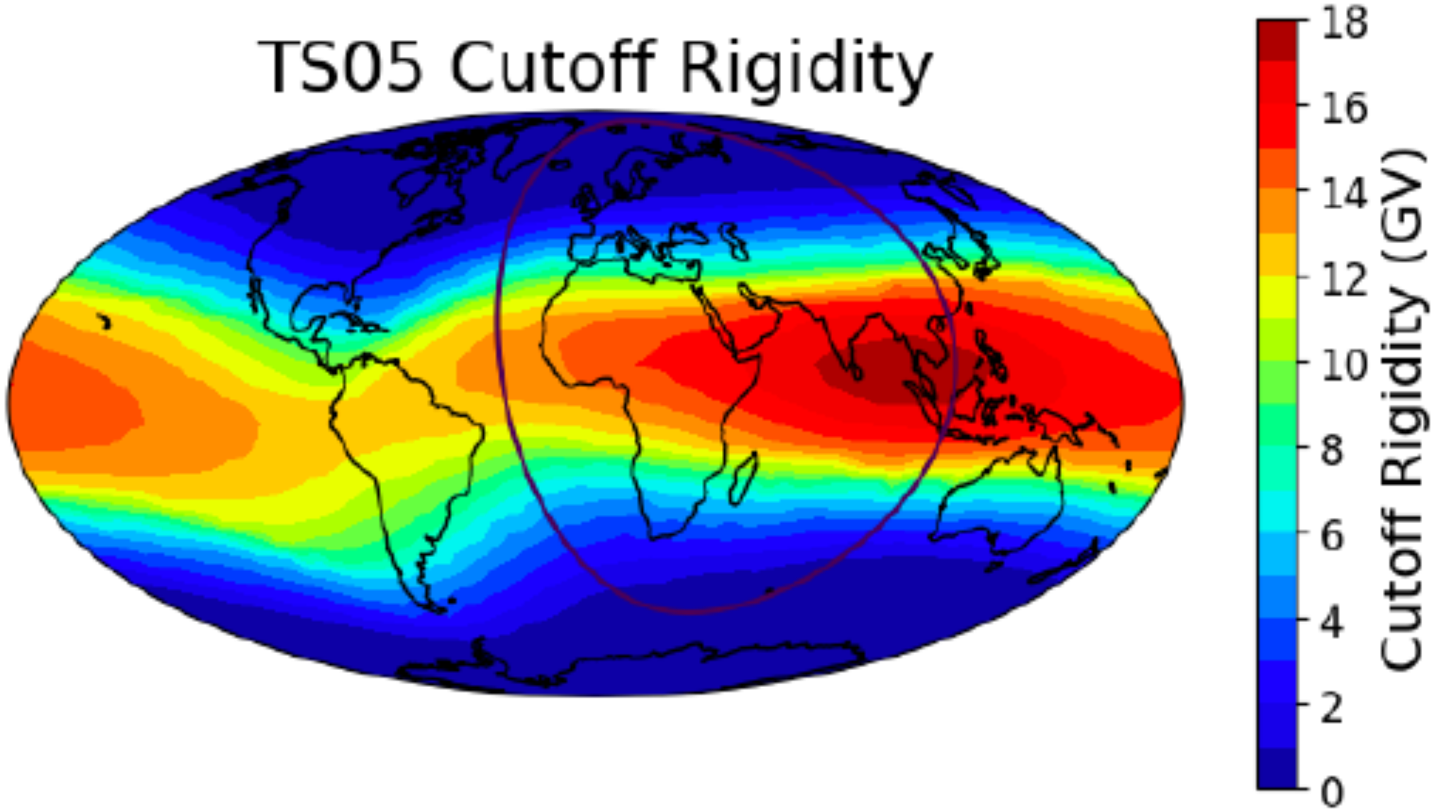
Beyond the choice of Solar Max periods as favourite period for travelling:

- Active (magnetic field) shielding *(research)*
- R&D to improve SPE forecasting and alert
- R&D to reduce travel time *(research on nuclear propulsion...)*
- Anti-oxydant rich diet
- Ibernation during travel *(research: it's not the science fiction cryogenic one…)*

About Solar Min periods: both on the Moon and Mars underground shelters have to be considered

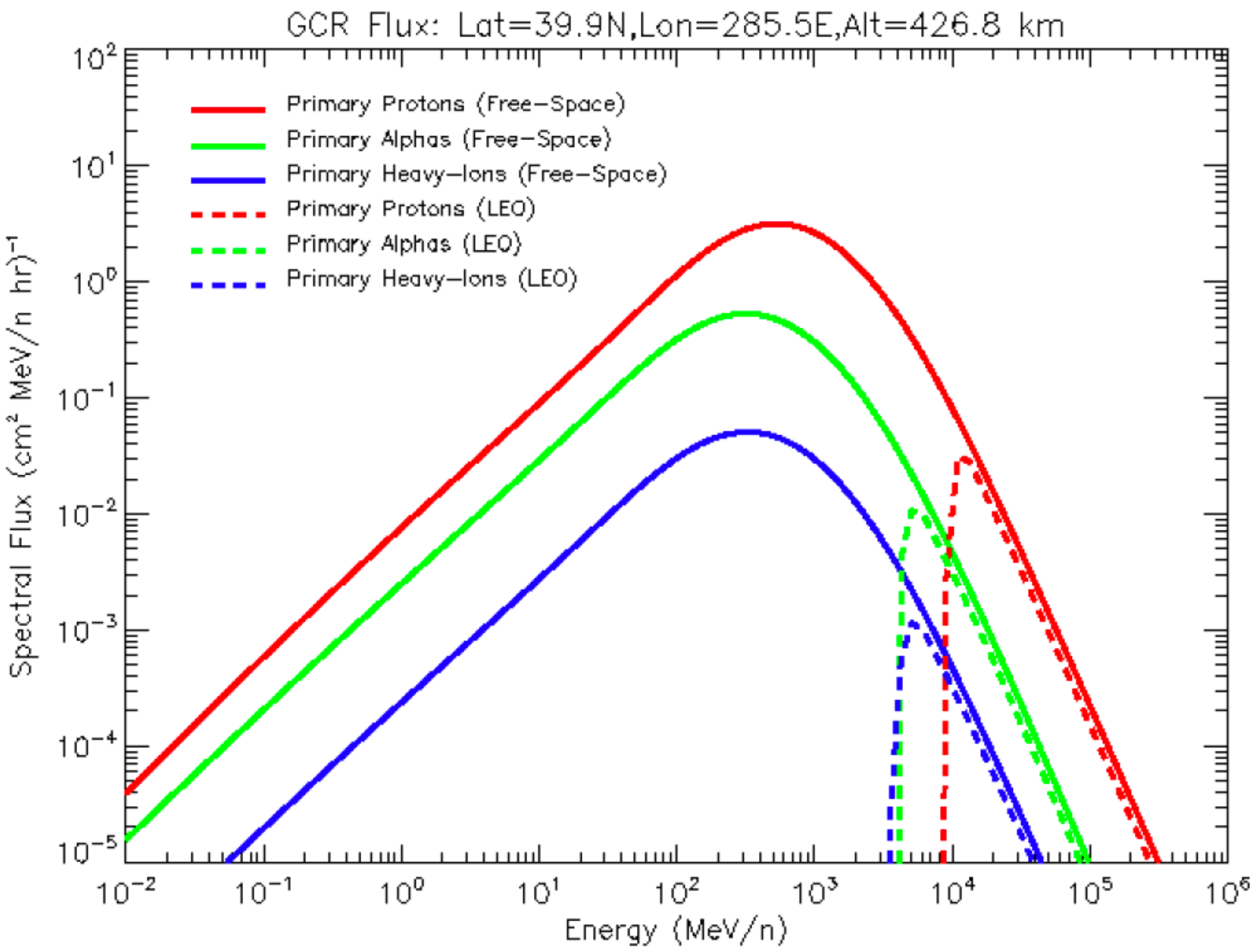
In case of long periods in an orbiting station around the Moon, Solar Minimum is however an issue

The case of Low Earth Orbit (LEO): the geomagnetic cutoff



In LEO astronauts are protected by the magnetosphere which limits the exposure to solar energetic particles far below the limit causing acute radiation effects in man.
SPE are, therefore, mostly an issue for exploratory-class missions.

Effect of high geomagnetic rigidity cut



Through the Earth's magnetic field and an atmospheric thickness of about 1 kg/cm^2 thickness, the exposure to cosmic radiation on the Earth's surface is reduced to a nearly zero level.

Leaving Earth astronauts are shielded by the structure of the spacecraft.

For the ISS the interior is shielded on average by 20 g/cm^2, a shielding close to that of the Martian atmosphere.

Which ions and which energies are relevant?

There are 2 completely different, but complementary, evaluations to be carried out:

- The radiation damage directly produced by primary GCR. This can be of relevance for Extra Vehicular Activity or for activity on the surface of the Moon or Mars. Both these activities are of limited time duration
- The radiation damage produced by primary GCR and their secondaries produced in the shielding of the spacecraft. This is usually considered the most crucial contribution for long duration space travels

Direct contribution from GCR

There is a very recent work on this subject:

Space Weather, 21, e2022SW003285 (2023)

Astronaut Radiation Dose Calculation With a New Galactic Cosmic Ray Model and the AMS-02 Data

Xuemei Chen[1,2], Songying Xu[1,2], Xiaojian Song[2], Ran Huo[2], and Xi Luo[2]

[1]University of Jinan, UJN, Jinan, China, [2]Shandong Institute of Advanced Technology, SDIAT, Jinan, China

They claim to be able to reduce uncertainty with respect to the BON model 2010,2011 and 2014

Materials: LET dependent | Effective Z and LET dependent

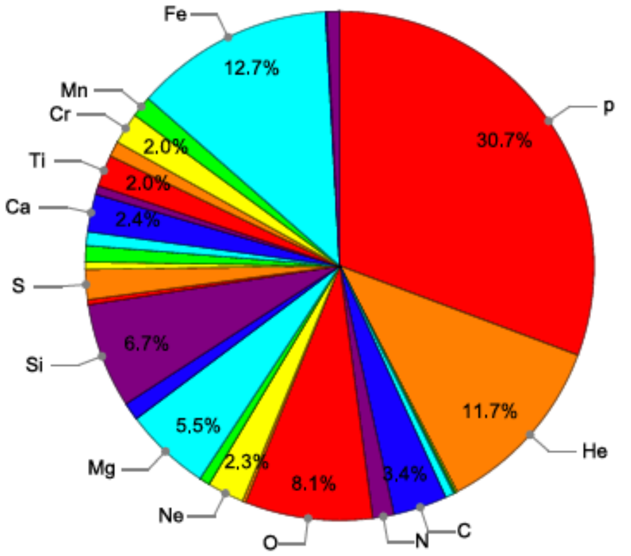
Analytical model

ICRP60 quality factors (1990) or NASA quality factors (2011)

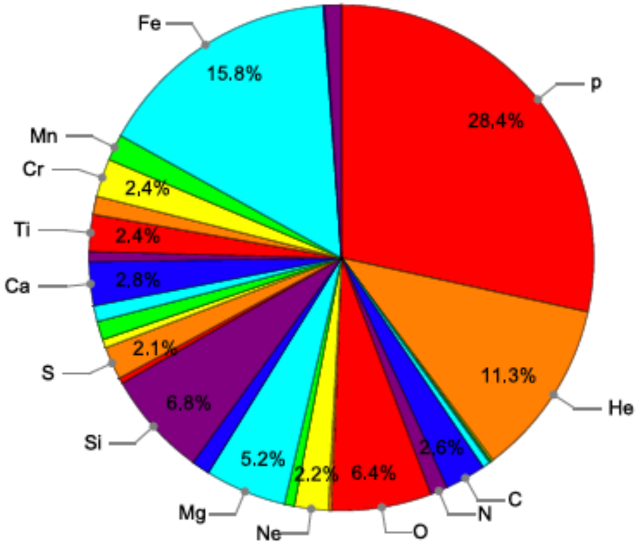
ICRP103 tissue weights (2007)

ICRP110 Adult Reference Computational Phantoms (2009)

They analyze the contribution due to the different ions, but integrating on the whole energy spectrum



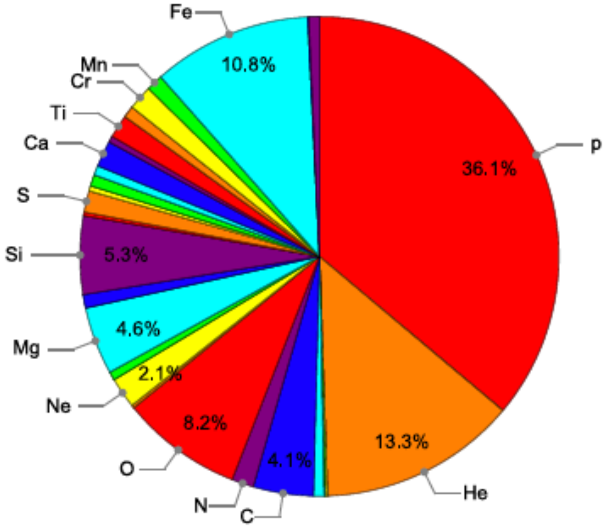
Solar Min of Jan 2010
Q_{ICRP60}, 55.8 cSv/yr



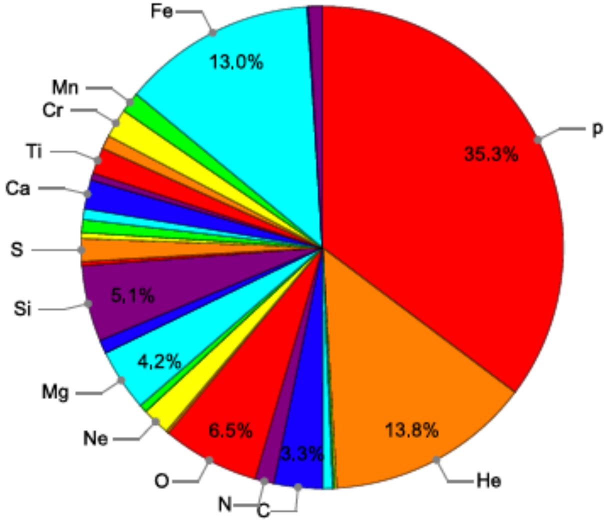
Solar Max of Feb 2014
Q_{ICRP60}, 26.3 cSv/yr

Solar Min: ~ 56 – 58 cSv/yr
Solar Max: ~26 cSv/yr

For a 650 days mission (1.8 yr, travel to Mars) it's ~1 Sv



Solar Min of Jan 2010
Q_{NASA}, 58.3 cSv/yr



Solar Max of Feb 2014
Q_{NASA}, 26.5 cSv/yr

Composite GCR contribution and Exposure limits for astronauts

Expected effective dose (total body) for a typical mission to Mars of 650 days (Ramos et al 2023 Int J Mol Sci)

Solar Min

Al Thickness (g/cm^2)	Equivalent Dose (mSv)
0	986.7
0.3	904.5
1	812.1
2	770.4
5	729.0
10	681.6
20	708.5

Solar Max

Al Thickness (g/cm^2)	Equivalent Dose (mSv)
0	240.9
0.3	249.2
1	279.5
2	319.6
5	254.1
10	227.6
20	266.4

Limits for the whole career

ESA/RSA: 1 Sv

NASA: 0.6 Sv (!)

JAXA: 0.5-1 Sv

age- and sex-dependent

This is one of the main reasons why there are efforts to try to go back on the Moon at the end of 2024 and to go to Mars in 2035: **Solar Max!!!**

Courtesy of F. Ballarini (Pv)

The conclusions of a first investigation about the relevance of different energy regions of GCR (composite contribution)

Space Weather (2014) 12, 217–224, doi:10.1002/2013SW001025.

GCR environmental models I: Sensitivity analysis for GCR environments

Tony C. Slaba[1] and Steve R. Blattnig[1]

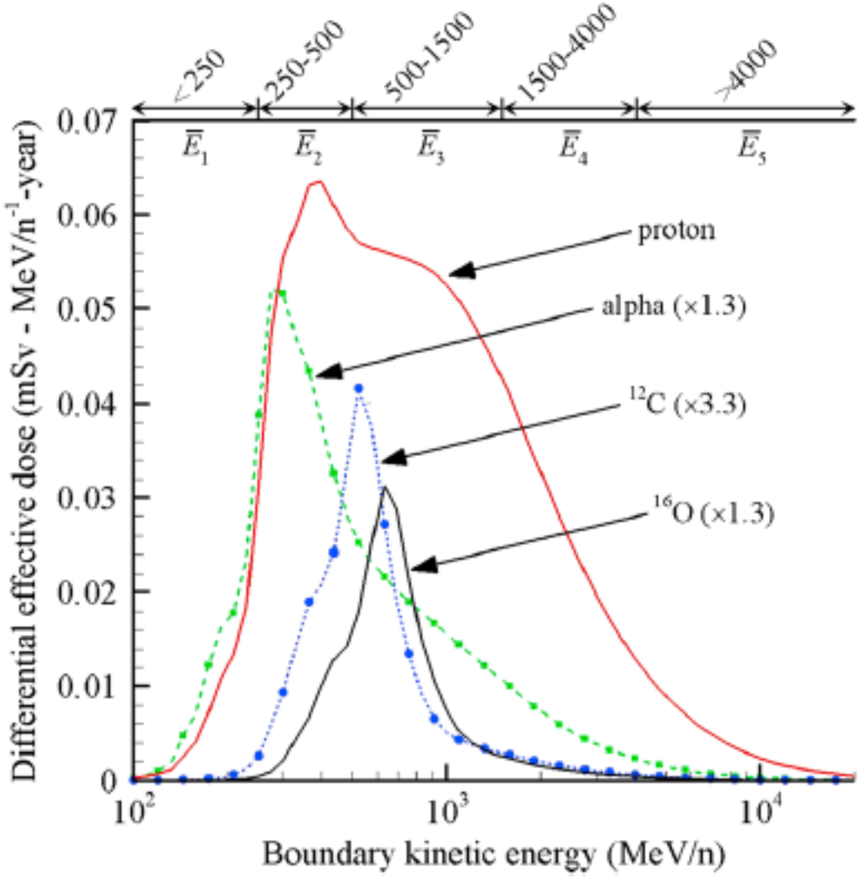
[1]NASA Langley Research Center, Hampton, Virginia, USA

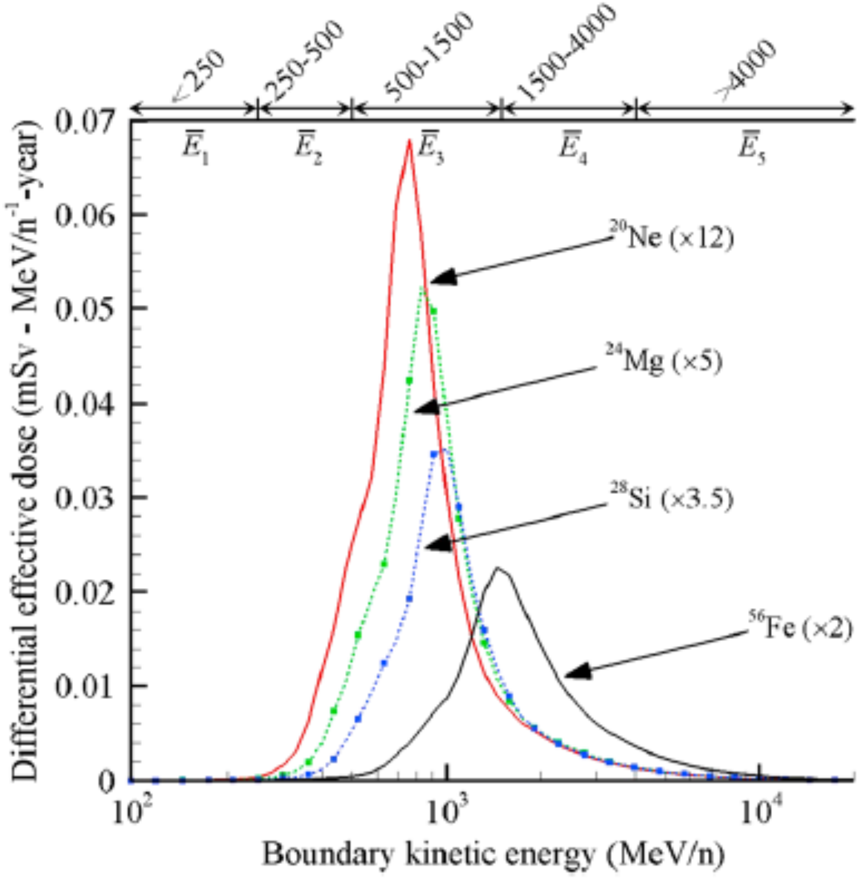
Investigation of the relevance of different energy regions and different ions to dose contribution from GCR on the basis of BON spectra (2010 update)

Materials:
1-d NASA code HEZTRN-p/EM code for a few thickess values of shielding
ICRP60 quality factors (1990)
ICRP103 tissue weights (2007)
FAX (Female Adult Voxel) human phantom.

Not yet a detailed 3dim MC simulation

Solar Minimum





Differential effective dose as a function of incident kinetic energy behind 20 g/cm2 of Aluminium exposed to solar minimum conditions described by BON2010 model. Results for specific ions have been scaled to improve plot clarity.

GCR spectrum 90% effective dose > 500 MeV/n

E_1: $<$ 250 MeV/n
E_2: 250-500 MeV/n
E_3: 500-1500 MeV/n
E_4: 1500-4000 MeV/n
E_5: $>$ 4000MeV/n

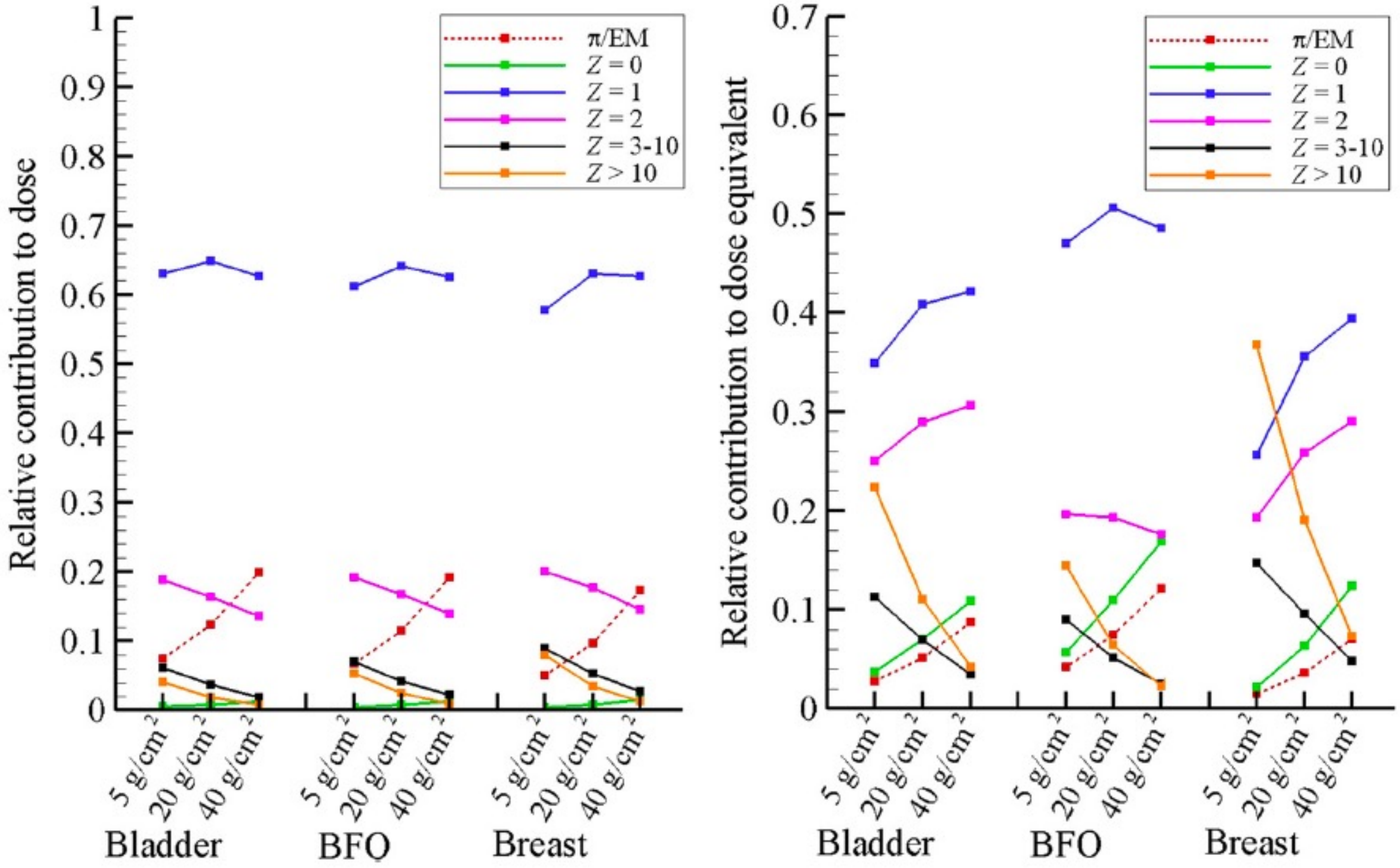
Solar Minimum	$\bar{E}_1$	$\bar{E}_2$	$\bar{E}_3$	$\bar{E}_4$	$\bar{E}_5$	Total
$Z = 1$	1.2	5.4	18.2	18.4	14.8	58.1
$Z = 2$	1.2	2.2	4.1	2.9	1.7	12.2
$Z = 3\text{-}10$	0.0	3.3	3.8	1.3	0.8	9.1
$Z = 11\text{-}20$	0.0	0.2	6.6	2.0	1.1	10.0
$Z = 21\text{-}28$	0.0	0.0	4.7	3.8	2.1	10.6
Totals	2.5	11.1	37.4	28.4	20.5	100.0

$E_3 + E_4 + E_5 = 86\%$ $E_4 + E_5 = 49\%$

Relative contribution (×100) of GCR boundary energy and charge groups to effective dose with **20 g/cm²** aluminium shielding. A value of 0.0 indicates that the relative contribution is less than 0.1%.

For **40 g/cm²**: $E_3 + E_4 + E_5 = 91\%$ $E_4 + E_5 = 57\%$

Percent contribution to dose equivalent by charge group



Blood Forming Organs

Slaba, Blattnig, Norbury, Rusek, La Tessa
LSSR 8, 52, 2018

Dose equivalent is dominated by Light Ions and Neutrons

The 2020 paper by J. Norbury et al.

Are Further Cross Section Measurements Necessary for Space Radiation Protection or Ion Therapy Applications? Helium Projectiles

John W. Norbury[1]*, Giuseppe Battistoni[2], Judith Besuglow[3,4], Luca Bocchini[5], Daria Boscolo[6], Alexander Botvina[7], Martha Clowdsley[1], Wouter de Wet[8], Marco Durante[6,9], Martina Giraudo[5], Thomas Haberer[10], Lawrence Heilbronn[11], Felix Horst[6], Michael Krämer[6], Chiara La Tessa[12,13], Francesca Luoni[6,9], Andrea Mairani[10], Silvia Muraro[2], Ryan B. Norman[1], Vincenzo Patera[14], Giovanni Santin[15,16], Christoph Schuy[6], Lembit Sihver[17,18], Tony C. Slaba[1], Nikolai Sobolevsky[7], Albana Topi[6], Uli Weber[6], Charles M. Werneth[1] and Cary Zeitlin[19]

Front. Phys. 8:565954.
doi: 10.3389/fphy.2020.565954

Here the role of FOOT has been emphasized

Main remarks from this paper - 1

- Neutrons and light ion fragments dominate dose equivalent for realistic spacecraft shield thicknesses (≥ 20 g/cm2).
- Because they have small charge and mass, neutrons and light ion fragments are scattered at large angles, and therefore require full 3-dimensional transport methods (as opposed to 1-dimensional straight-ahead scattering approximations)
- Full 3-dimensional transport methods, in turn, require nuclear physics double differential cross sections as input.
- Existing MC codes exhibit large differences for light ion fragment production. The disagreements are mainly due to inaccurate light ion nuclear physics models and lack of experimental data to be used to improve these models.
- Light ion cross sections represent the largest physics uncertainty in space radiation, but light ion cross section measurements represent the largest gap in the cross section databases
- Future experimental programs should focus on measuring double differential cross-section data sets as completely as possible (covering all angles, energies, and fragments including neutrons) to be able to cross-check them against measured total and single differential cross sections.

Main remarks from this paper - 2

- Detailed analysis of He data below 3 GeV/n reveals significant problems and flaws with the data, leading to the conclusion that there is almost no high quality double differential data for helium projectiles over the entire energy region
- No double differential cross section data exist for light ion fragment production from He projectiles above 3 GeV/n.
- No double differential cross section data exist for light ion fragment production from O projectiles above the pion threshold (>280 MeV/n).
- No double differential cross section data exist for light ion fragment production from silicon (Si) projectiles in any energy region.
- No double differential cross section data exist for light ion fragment production from iron (Fe) projectiles in any energy region. This is particularly surprising, given the prominent role of Fe projectiles in space radiation biophysical studies

Main recommendation from this paper:

- A new set of inclusive, isotopic, double differential cross sections should be measured for a complete set of neutron and light ion fragments for the reactions

$$^{4}\text{He} \quad + \quad \text{H, C, O, Ca, Al, [Fe]} \quad \rightarrow \quad \text{n}, {}^{1,2,3}\text{H}, {}^{3,4}\text{He} \quad + \quad \text{X}$$

for projectile kinetic energies ranging over 50 MeV/n – 50 GeV/n and fragment angles ranging over 0–180^{o}

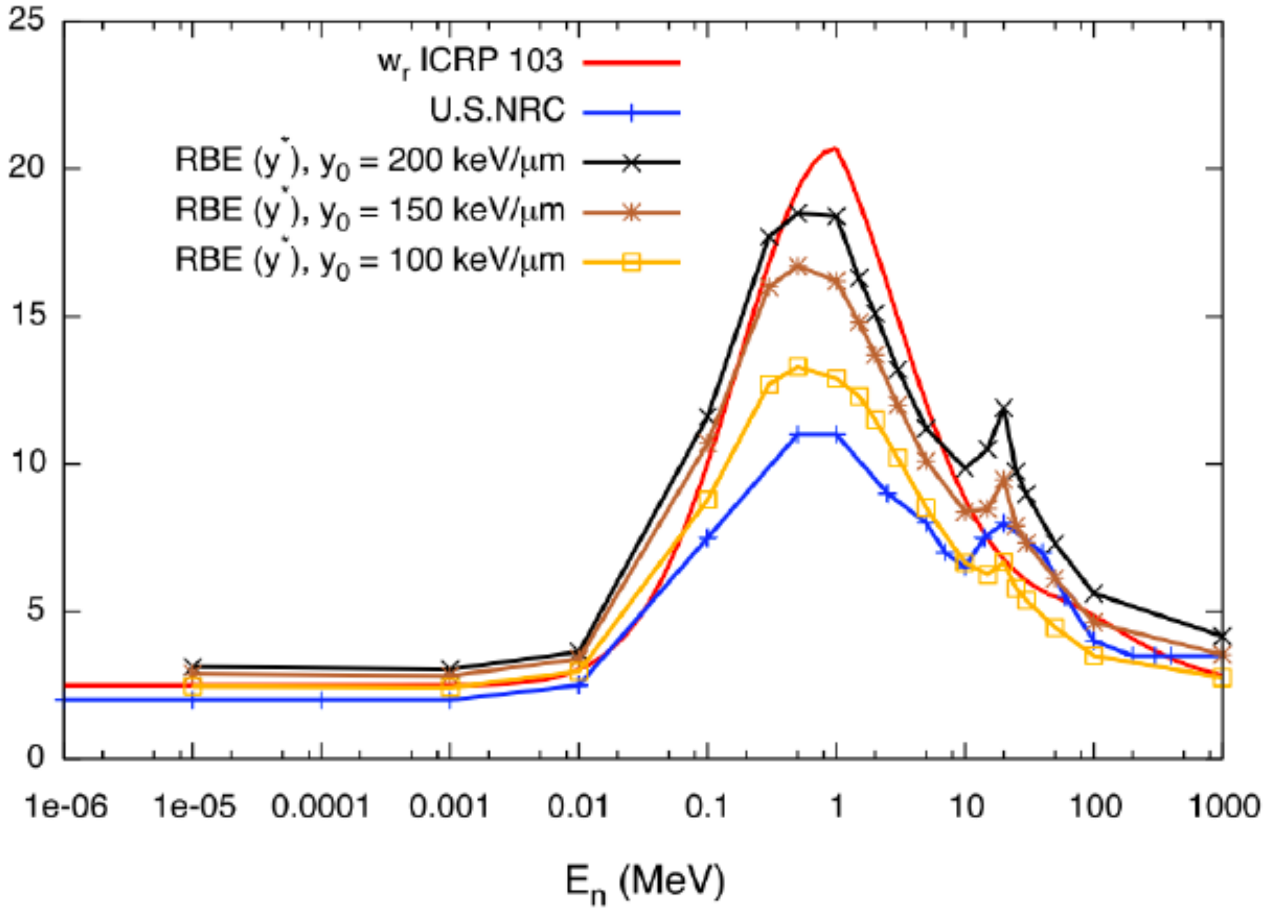
- Those experiments should be accompanied by measurements of total reaction and single differential fragment production cross sections for ^{4}He projectiles, in particular for targets heavier than oxygen in the energy range between 50 MeV/n – 50 GeV/n

Conclusions: a summary of possible considerations and suggestions for FOOT - 1

- The peak energy of GCR spectrum is not the most relevant energy for dose evaluation, even for solar minimum
- Energies > 500 MeV/u have to be considered in any case, better if up to 1500 MeV/u. This is not possible in general at hadrontherapy facilities: measurements at the energies accessed by FOOT seem to be of partial interest.
- Most important projectiles: He, O, Si, Fe
- Most important targets: H, C, O, Ca, Al, [Fe] (secondary production in shielding is important)
- Priority has to be given to the double diff cross sections for the production of light fragments
- It could be instructive to repeat the work of Slaba et al. using a full MC 3D simulation

Conclusions: a summary of possible considerations and suggestions for FOOT - 2

Which could be the interesting neutrons?



Neutrons' RBE as a function of their energies. In red, is the RBE declared by ICRP in the report ICRP 103. Other curves are derived from MC simulations with the PHITS method using microdosimetric functions to assess biological damage
(G. Baiocco et al., 'The origin of neutron biological effectiveness as a function of energy', Sci Rep, vol. 6, 2016)

Most dangerous are those in the range 0.1-10 MeV, below the energy of fast neutrons that was recently considered for a possible upgrade of FOOT

A new review paper just appeared:

Nuclear data for space exploration

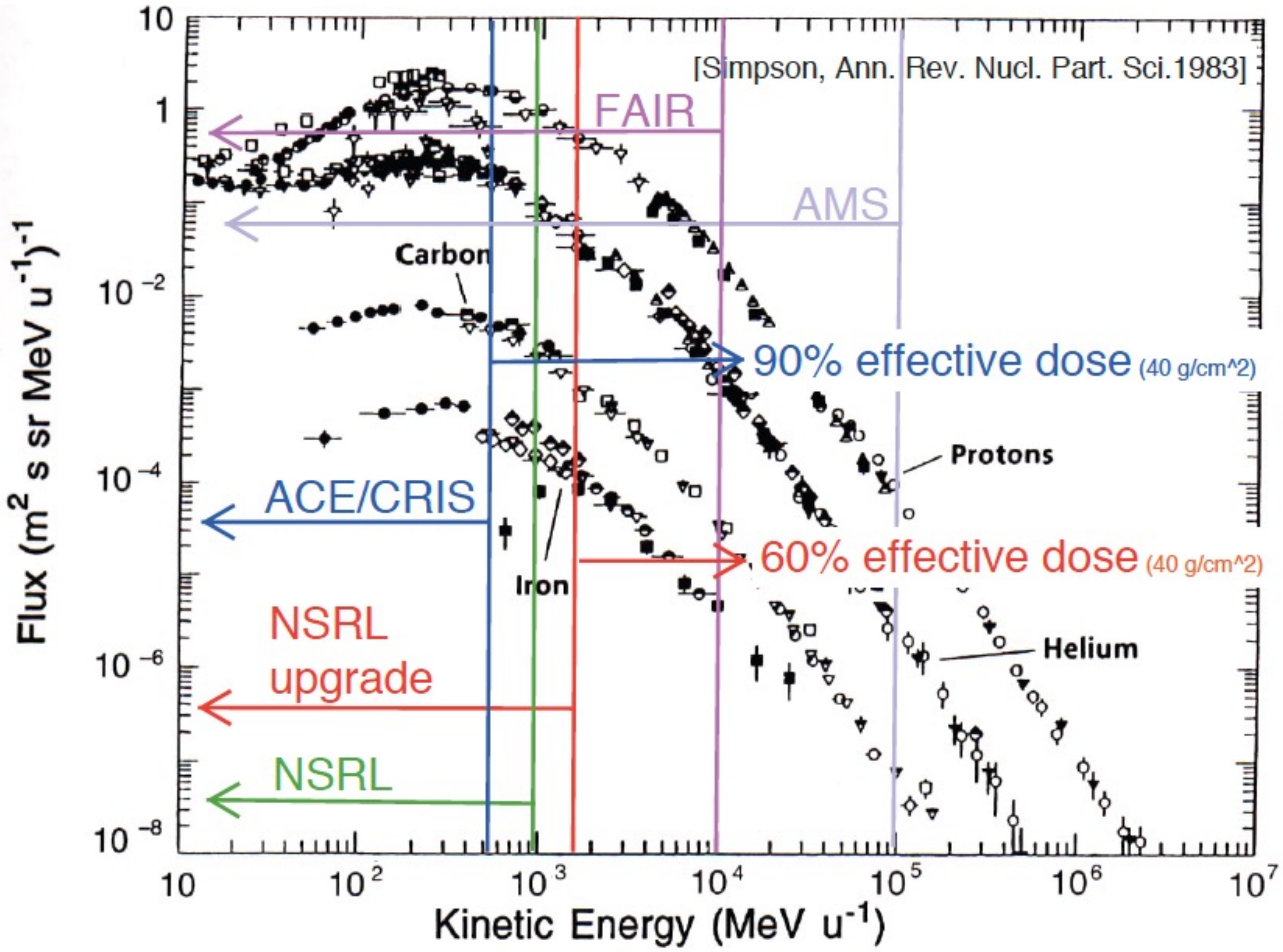
Michael S. Smith[1]*, Ramona L. Vogt[2,3] and Kenneth A. LaBel[4]

[1]Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN, United States, [2]Nuclear and Chemical Sciences Division, Lawrence Livermore National Laboratory, Livermore, CA, United States, [3]Department of Physics and Astronomy, University of California, Davis, Davis, CA, United States, [4]Johns Hopkins Applied Physics Laboratory, Laurel, MD, United States

Front. Astron. Space Sci. 10:1228901.
doi: 10.3389/fspas.2023.1228901

Here the emphasis is put on the measurement at high energy (multi GeV), suggesting in particular the use of the STAR experiment at RICH (USA)

Effective dose and range accessible to experiments:



(Norbury et al.)

ACE = Advanced Composition Explorer
CRIS = Cosmic Ray Isotope Spectrometer

NSRL = NASA Space Radiation Laboratory (A joint Brookhaven Lab/NASA facility to study the effects of cosmic radiation)

Ion	Max En (MeV/u)
4He	1000
12C	1000
16O	1000
28Si	1000
56Fe	1000

Backup Slides

Bibliography on BON Model

G. D. Badhwar, P. M. O'Neill, Long-term modulation of galactic cosmic radiation and its model for space exploration., Advances in Space Research, vol. 14, no. 10, pp. 749-757, 1994.

G. D. Badhwar, P. O'Neill, Galactic cosmic radiation model and its applications," Advances in Space Research, vol. 17, no. 2, pp. 7-17, 1996.

P. O'Neill, Badhwar-O'Neill 2010 Galactic Cosmic Ray Flux Model Revised, Nuclear Science, IEEE Transactions on, vol. 57, pp. 3148-3153, 2010

P. M. O'Neill, C. C. Foster, Badhwar-ONeill 2011 Galactic Cosmic Ray Flux Model Description, Tech. Rep. NASA/TP-2013-217376, 2013.

P. M. O'Neill, S. Golge, T. C. Slaba, The Badhwar-O'Neill 2014 GCR flux model description. Tech. Rep. NASA/TP-2015-218569, 2015

T. C., Slaba, K. Whitman, The Badhwar-O'Neill 2020 GCR model. Space Weather, 18, e2020SW002456, 2020

Exp. Data used to build the last update of BON model (2020)

Table 1
Summary of Collected Measurements

Name	Flight	Time	Ions (Z)	Energy (GeV/n)	Data points	Median error
ACE/CRIS[a]	Satellite	1998-present	5-28	0.05–0.5	12446	9%
AMS[b]	STS-91	1998	1, 2	0.1–200	58	11%
AMS-02[c]	ISS	2011-2017	1-9	0.4–10[c]	7170	3%
ATIC-2[d]	Balloon	2002	1, 2, 6, 8, 10, ...,14, 26	4.6–10[c]	61	33%
BESS[e]	Balloon	1997-2000, 2002, 2004, 2007	1, 2	0.2–22	479	11%
CAPRICE[f]	Balloon	1994, 1998	1, 2	0.15–350	93	6%
CREAM-II[g]	Balloon	2005	6-8, 10, 12, 14, 26	18–10[c]	42	25%
HEAO-3[h]	Satellite	1979	4-28	0.62 – 35	332	9%
IMAX[i]	Balloon	1992	1, 2	0.18–208	56	18%
MASS[j]	Balloon	1991	1, 2	1.6–100	41	9%
PAMELA[k]	Satellite	2006-2009	1, 2	0.08–10[c]	6614	5%
TRACER[l]	Balloon	2003	8, 10, 12, ...,20, 26	0.8–10[c]	60	10%
Garcia-Munoz[m]	Satellite	1974	6, 8, 10, 12, 14	0.05–1	57	27%
Lezniak[n]	Balloon	1974	4-14, 16, 20, 26	0.35–52	114	11%
Minagawa[o]	Balloon	1975	26, 28	1.3–10	16	8%
Simon[p]	Balloon	1976	5-8	2.5 – 10[c]	46	32%

[a](Stone et al., 1998). [b](Alcaraz et al., 2000a, 2000b). [c](Aguilar et al., 2015a, 2015b, 2017, 2018a, 2018b, 2018c). [d](Panov et al., 2009). [e](Abe et al., 2016; Shikaze et al., 2008). [f](Boezio et al., 1999; Boezio et al., 2003). [g](Ahn et al., 2009). [h](Engelmann et al., 1990). [i](Menn et al., 2000). [j](Bellotti et al., 1999). [k](Adriani et al., 2011, 2013, 2017; Martuicci et al. 2018). [l](Ave et al., 2008). [m](Garcia-Munoz et al., 1977). [n](Lezniak & Webber, 1978). [o](Minagawa, 1981). [p](Simon et al., 1980).

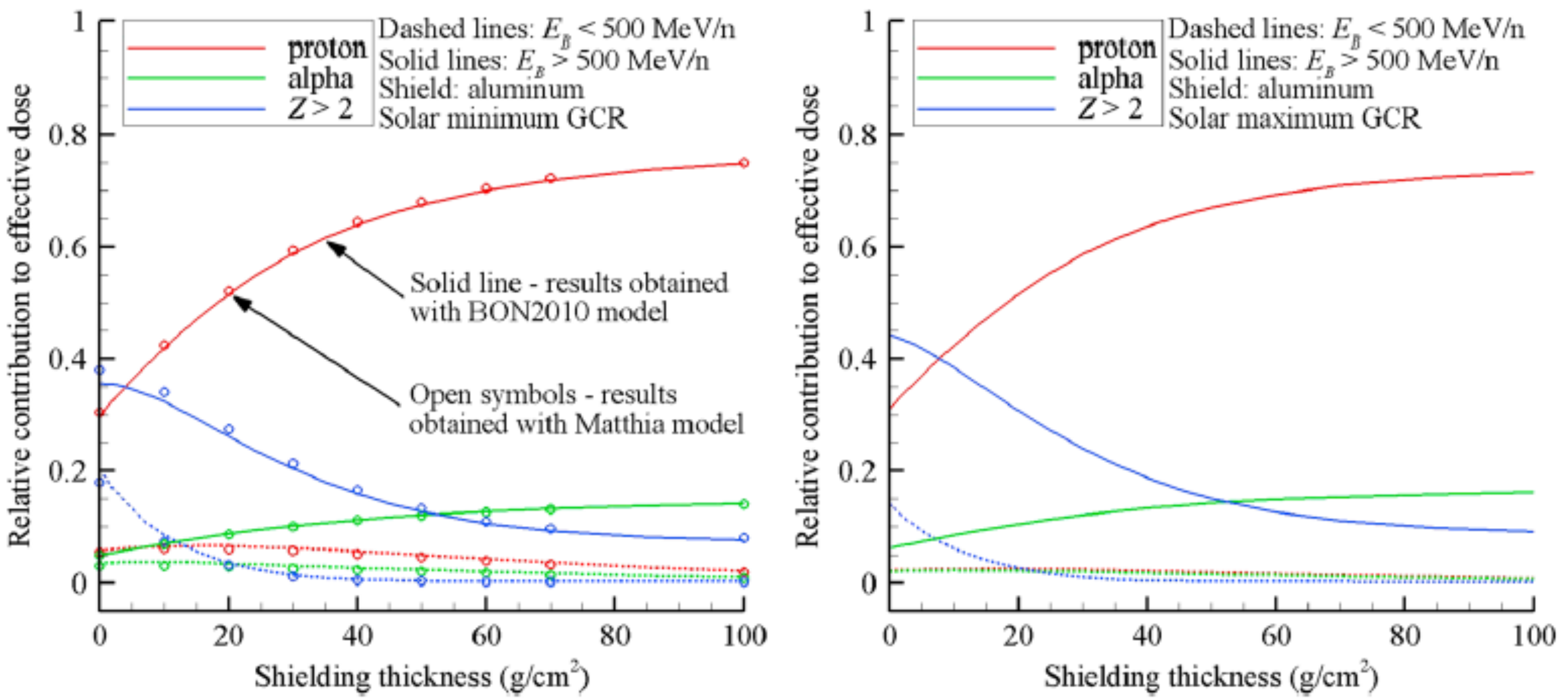
Parameter values for all unmodulated LIS spectra (1≤Z ≤ 28)

$$f_{\mathrm{LIS}}(T) = j_0 \beta^{\delta} (T + m)^{-\gamma}$$

Table B1
LIS Parameters (j_0, γ, δ) for Each Ion

Z	j_0	γ	δ	Z	j_0	γ	δ
1	9.35958×10^{-4}	2.80583	2.12	15	7.00114×10^{-9}	3.07083	1.76
2	5.31867×10^{-5}	2.78079	-2.04	16	5.86173×10^{-8}	2.70070	-1.74
3	1.60292×10^{-7}	3.11530	1.86	17	6.09709×10^{-9}	3.10022	0.78
4	9.40500×10^{-8}	3.04829	1.95	18	1.32512×10^{-8}	3.00133	2.75
5	2.19596×10^{-7}	3.05504	0.78	19	8.60410×10^{-9}	3.06630	0.29
6	1.65248×10^{-6}	2.72725	-1.40	20	3.14380×10^{-8}	2.73290	-1.88
7	3.15343×10^{-7}	2.89393	-1.66	21	4.02263×10^{-9}	3.05437	-1.18
8	1.78878×10^{-6}	2.69771	-1.95	22	1.26982×10^{-8}	3.03093	-1.10
9	1.89162×10^{-8}	3.02882	0.26	23	6.53956×10^{-9}	3.01542	-1.39
10	2.47948×10^{-7}	2.73606	-1.25	24	1.69119×10^{-8}	2.91752	-1.21
11	4.00947×10^{-8}	2.78163	-1.95	25	1.39910×10^{-8}	2.79527	-0.88
12	2.86573×10^{-7}	2.74120	-1.57	26	1.91393×10^{-7}	2.61473	-2.68
13	4.88895×10^{-8}	2.79137	-1.20	27	9.70709×10^{-10}	2.65139	-2.98
14	2.71499×10^{-7}	2.65875	-1.80	28	1.18883×10^{-8}	2.53385	-3.71

Solar Minimum Solar Maximum

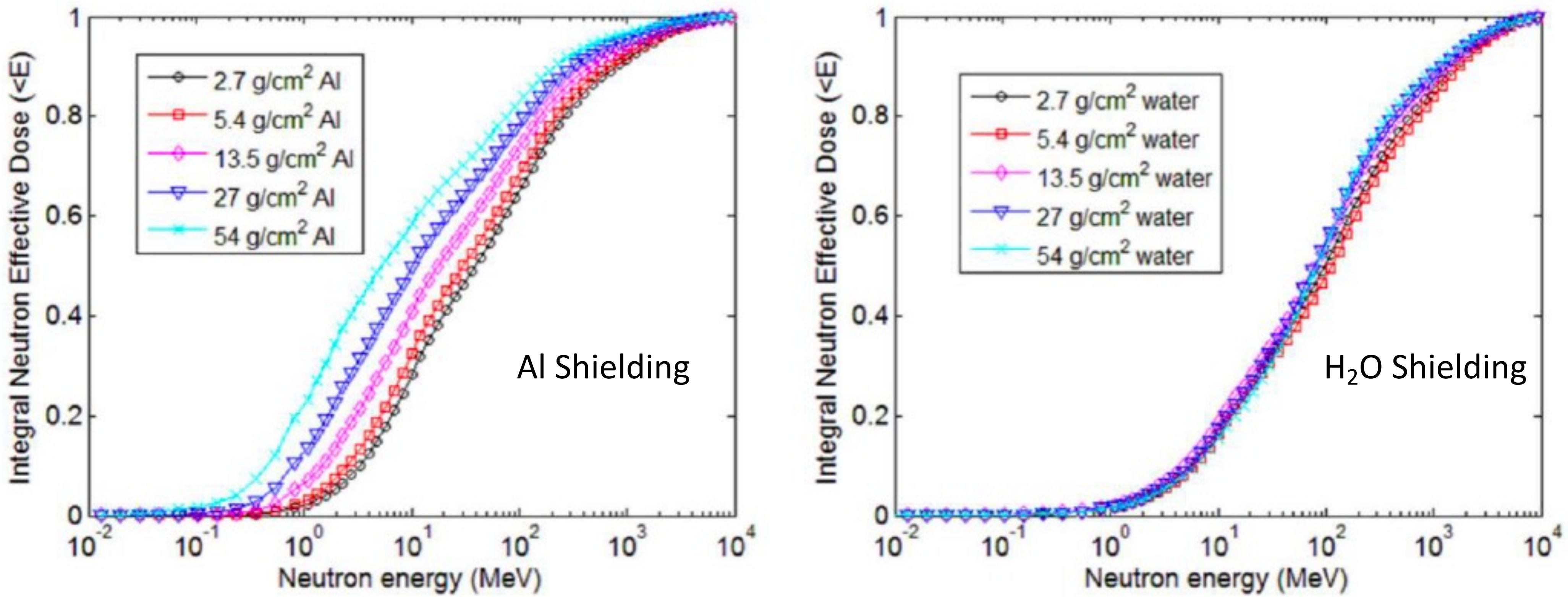


Fractional contribution to effective dose as a function of Al shield thickness for (left) solar minimum and (right) solar maximum conditions.

a) the importance of E>500 MeV/u;

b) Z>2 ions effectiveness decreases for increasing thickness, while this is not true for Z=1,2.

This increase is primarily associated with secondary target fragments and neutrons produced by nuclear collisions between the protons and the shielding material. These target fragments generally have an increased biological risk as compared to the primary protons.



Integral neutron effective dose VS neutron energy

L. H. Heilbronn et al., 'Neutron yields and effective doses produced by Galactic Cosmic Ray interactions in shielded environments in space', *Life Sci Space Res,* vol. 7, pp. 90–99, 2015