GCR Methods in Radiation Transport

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Overview

- CRÈME used in HZETRN and other codes 1986-1992
- Badhwar and O'Neill Model developed for HZETRN applications in 1993
  - Elemental spectra for H, He, C, O, Si, Fe
  - Crème formula for other elements
- New version by Pat O'Neill in 2004 fit to ACE and includes LSS spectra
  - Elemental spectra for all elements
- Isotopic composition integrated into HZETRN in 2005 using historical data including Ulysses

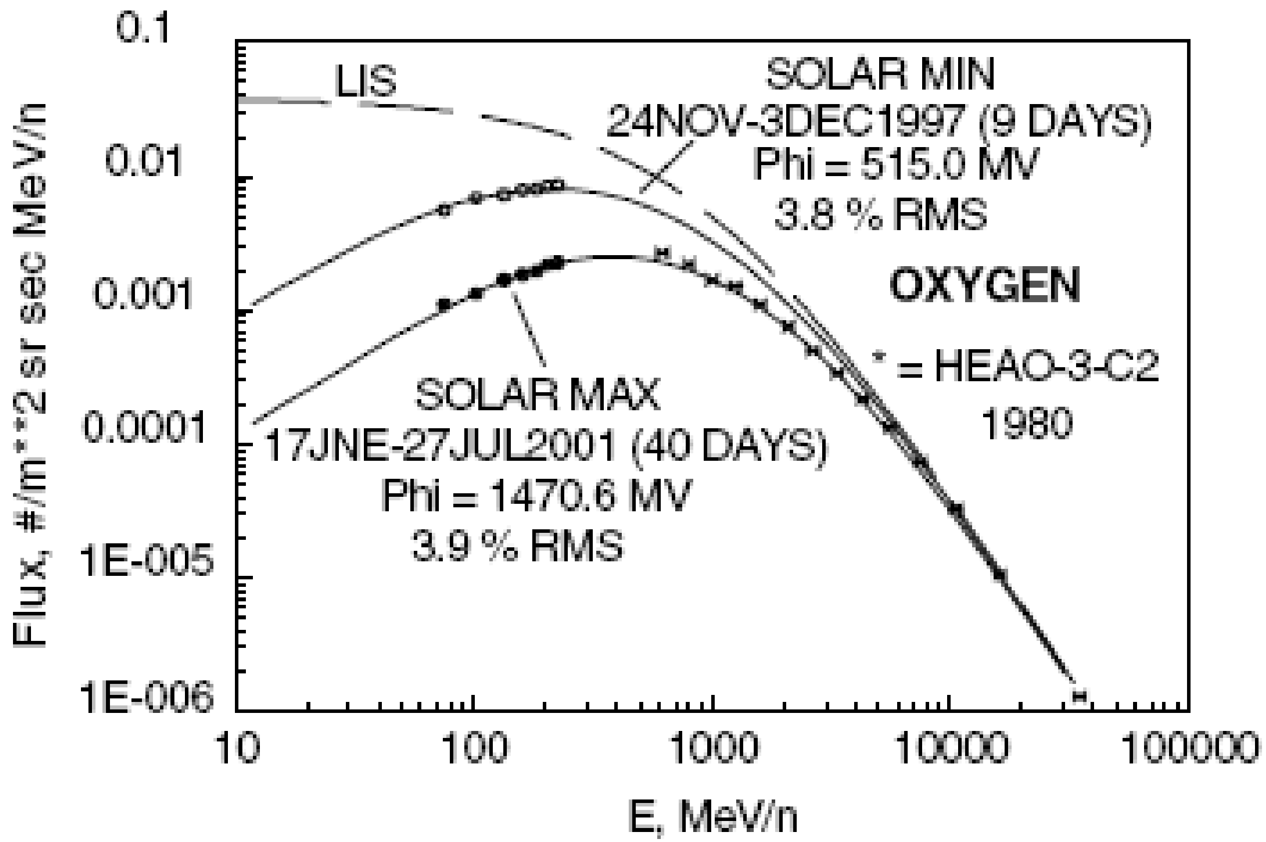


Fig. 1. Badhwar–O'Neill Model fit of ACE CRIS oxygen energy spectra measurements near solar minimum and near solar maximum.

A single diffusion coefficient, Eq. (1), describes the effect of the sun's magnetic field on particles entering the heliosphere.

$$k(r,t) = (k_0/V_{SW})\beta P[1 + (r/r_0)^2]/\Phi(t), \quad (1)$$

where V_{SW} is the constant solar wind speed (400 km/s), r is distance from the sun in AU, t is time in years, k_0 is constant, β is particle speed relative to the speed of light, P is particle rigidity in MV.

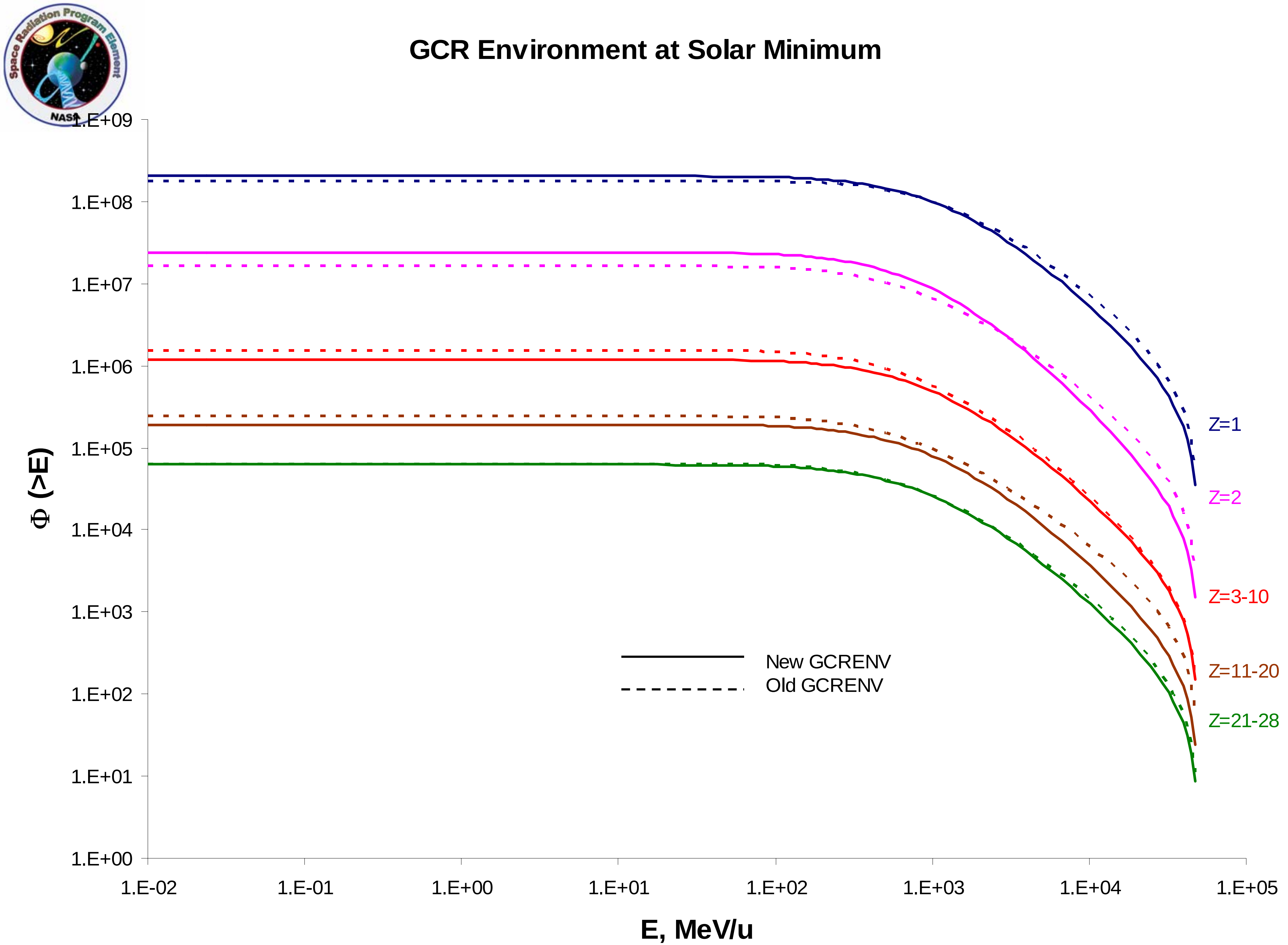
The diffusion coefficient describes the effect of: (1) stronger magnetic field; (2) more magnetic disturbances; and (3) an expanding magnetic field. Therefore it is closely related to solar activity. Note that *larger* values of the diffusion coefficient allow *easier flow* of particles – less magnetic hindrance to flow. Therefore, we expect it to *increase* during solar *minimum*.

Table 1
LIS parameters and average model RMS error in % for elements

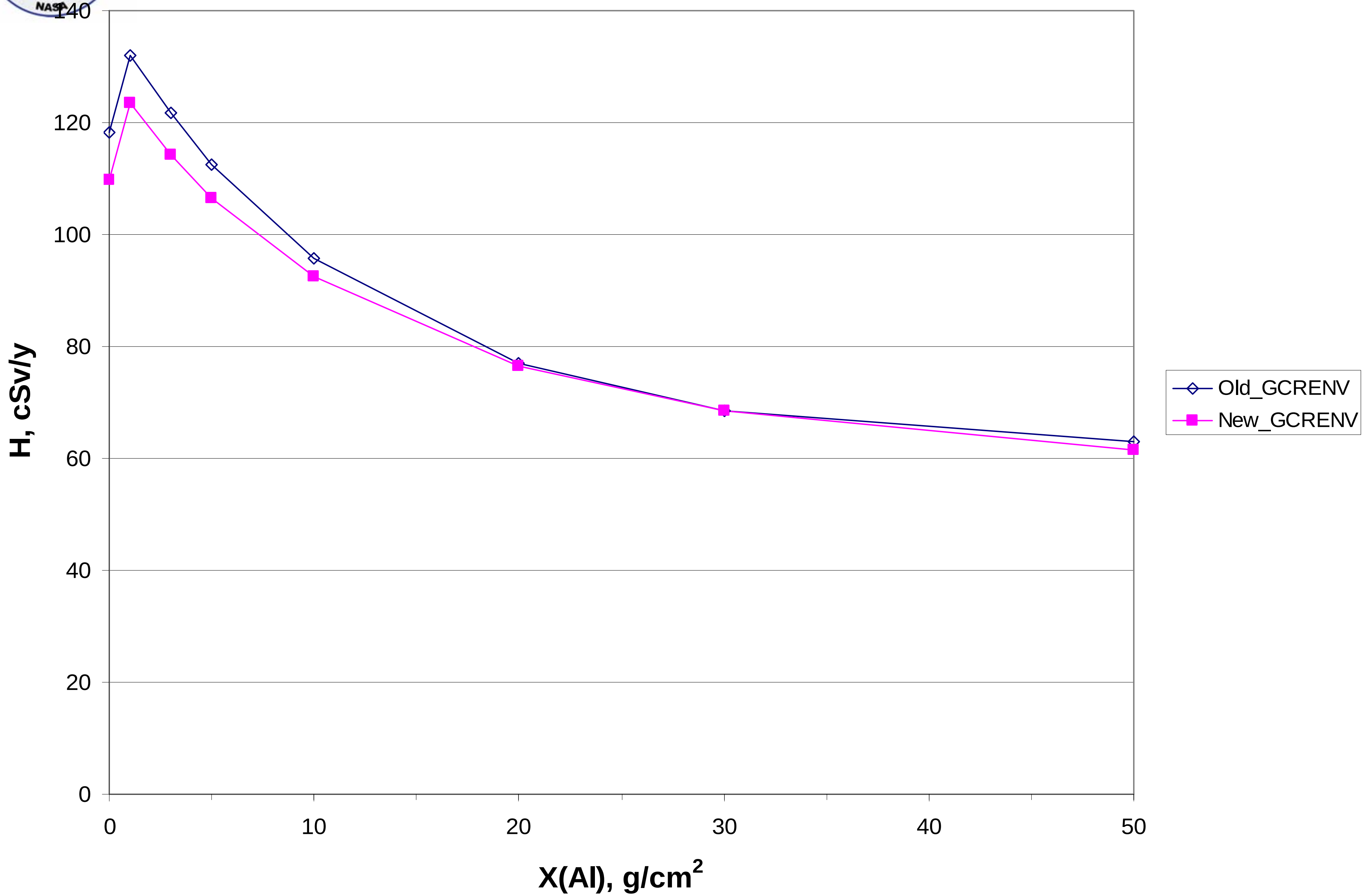
Z	Element	γ	δ	J_0	#ION	#Days	% Error	
							Φ_{ACE}	Φ_{CLI}
1	Hydrogen	2.765	0.0	1.2500E − 3	1000	7	9.3	12.0
2	Helium	3.053	0.0	4.0000E − 5	1000	21	9.9	11.3
3	Lithium	2.704	0.887	2.8000E − 7	N/A	365	5.6	5.9
4	Beryllium	2.776	1.196	1.4000E − 7	N/A	365	8.9	7.5
5	Boron	3.040	0.369	1.8000E − 7	1000	48	7.6	9.5
6	Carbon	2.835	0.0	1.3000E − 6	2000	21	4.9	7.8
7	Nitrogen	2.973	0.250	2.2500E − 7	1000	35	6.8	8.7
8	Oxygen	2.800	0.0	1.4000E − 6	2000	18	4.5	7.3
9	Fluorine	2.882	0.816	2.2000E − 8	200	74	11.6	13.6
10	Neon	2.823	0.0	1.8700E − 7	1000	43	5.9	8.2
11	Sodium	2.803	0.0	3.8094E − 8	500	79	6.2	7.5
12	Magnesium	2.826	0.0	2.4841E − 7	1000	28	5.5	7.4
13	Aluminum	2.903	0.472	3.3718E − 8	300	49	8.3	9.7
14	Silicon	2.823	0.0	1.8340E − 7	1000	32	5.3	7.1
15	Phosphorus	2.991	1.399	5.3011E − 9	100	95	12.5	14.2
16	Sulphur	2.838	0.690	3.7502E − 8	300	54	8.7	9.5
17	Chlorine	3.041	1.929	5.0000E − 9	100	101	16.8	16.7
18	Argon	2.918	1.291	1.3000E − 8	100	43	13.0	11.6
19	Potassium	3.169	1.827	5.8000E − 9	100	52	15.0	16.7
20	Calcium	2.910	0.996	2.8000E − 8	200	36	9.5	10.3
21	Scandium	2.926	1.267	5.8351E − 9	100	73	13.0	12.3
22	Titanium	2.790	0.532	2.4982E − 8	200	45	10.8	11.4
23	Vanadium	3.028	0.617	5.6000E − 9	100	48	13.1	13.5
24	Chromium	2.945	0.582	1.4400E − 8	200	43	10.2	11.1
25	Manganese	2.794	0.0	1.2000E − 8	200	66	11.7	12.5
26	Iron	2.770	0.0	1.4000E − 7	1000	32	6.1	6.7
27	Cobalt	2.764	0.0	9.4052E − 10	30	94	22.5	21.5
28	Nickel	2.712	0.0	8.3950E − 9	100	64	13.7	14.2

#ION is the minimum # of ions per channel collected to define the interval data point. #Days is the average collection time. % ACE is the average model – ACE % error from solar minimum (1997.6) to solar maximum (2000.9) using the value of $\Phi_{ACE}(t)$ determined from the ACE CRIS oxygen fit. % CLI is the average model – ACE error with the value of $\Phi_{CLI}(t)$ determined from the CLIMAX Neutron Monitor used instead of that from the oxygen fit.

GCR Environment at Solar Minimum



Free Space at Solar Minimum



Isotopic Composition

- Historical data used to re-distribute Badhwar-O'Neill elemental flux into isotopic fractions

$$\phi(Z, E) = \sum_{A_j} f_j(A_j, Z)\phi(A_j, Z, E),$$

- Energy-independent

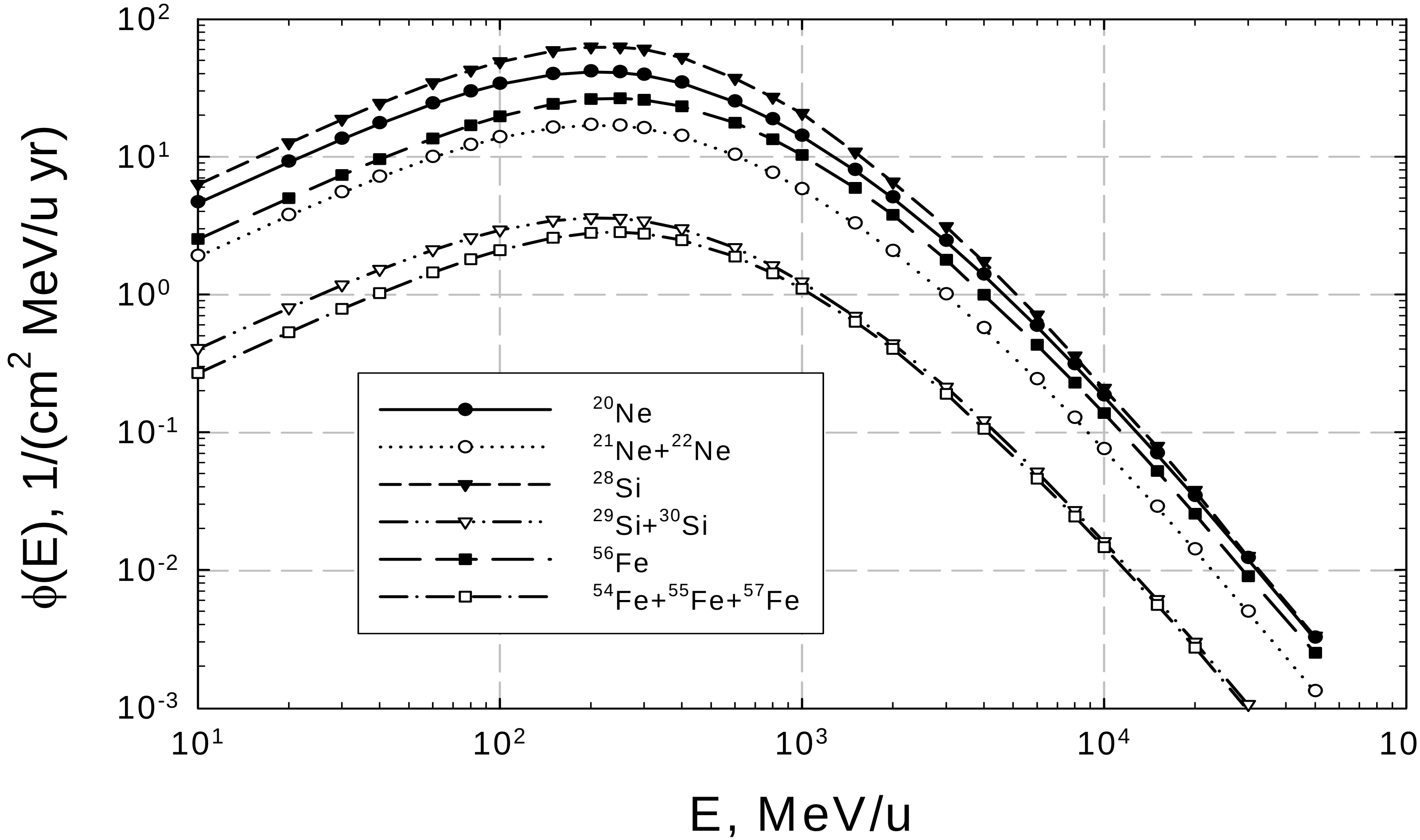
Table 1a: Isotopic Composition of GCR Elements *Z*=3 to 12.

Isotope	*Near-Earth Fraction*	*Source Fraction*
	Z=3	
^{6}Li*	0.5	0.5
^{7}Li	0.5	0.5
	Z=4	
^{7}Be*	0.5	0.5
^{9}Be	0.35	0.35
^{10}Be	0.15	0.15
	Z=5	
^{10}B	0.31	0.2
^{11}B	0.69	0.8
	Z=6	
^{12}C	0.92	0.999
^{13}C	0.08	0.001
	Z=7	
^{14}N	0.48	0.78
^{15}N	*0.57*	0.22
	Z=8	
^{16}O	0.946	0.985
^{17}O	0.027	0.008
^{18}O	0.027	0.007
	Z=10	
^{20}Ne	0.55	0.68
^{21}Ne	0.10	0.0
^{22}Ne	0.35	0.32
	Z=12	
^{24}Mg	0.64	0.74
^{25}Mg	0.18	0.14
^{26}Mg	0.18	0.13

*Data on solar modulation was not found and thus near-Earth and source composition are set equal.

Table 1b: Isotopic Composition of GCR Elements *Z*=13 to 20.

Isotope	*Near-Earth Fraction*	*Source Fraction*
	Z=13	
^{26}Al	0.02	0.0
^{27}Al	0.98	1.0
	Z=14	
^{28}Si	0.84	0.902
^{29}Si	0.08	0.054
^{30}Si	0.08	0.044
	Z=16	
^{32}S	0.69	0.96
^{33}S	0.15	0.02
^{34}S	0.16	0.02
	Z=17	
^{35}Cl	0.52	1.0
^{36}Cl	0.41	0.0
^{37}Cl	0.26	0.0
	Z=18	
^{36}Ar	0.64	1.0
^{37}Ar	0.03	0.0
^{38}Ar	0.30	0.0
^{40}Ar	0.03	0.0
	Z=20	
^{40}Ca	0.4	1.0
^{41}Ca	0.2	0.0
^{42}Ca	0.2	0.0
^{43}Ca	0.2	0.0
^{44}Ca	0.2	0.0


10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^1
10^2
10^3
10^4
10^5
$\phi(E)$, 1/(cm^2 MeV/u yr)
E, MeV/u
^{20}Ne
$^{21}Ne + ^{22}Ne$
^{28}Si
$^{29}Si + ^{30}Si$
^{56}Fe
$^{54}Fe + ^{55}Fe + ^{57}Fe$

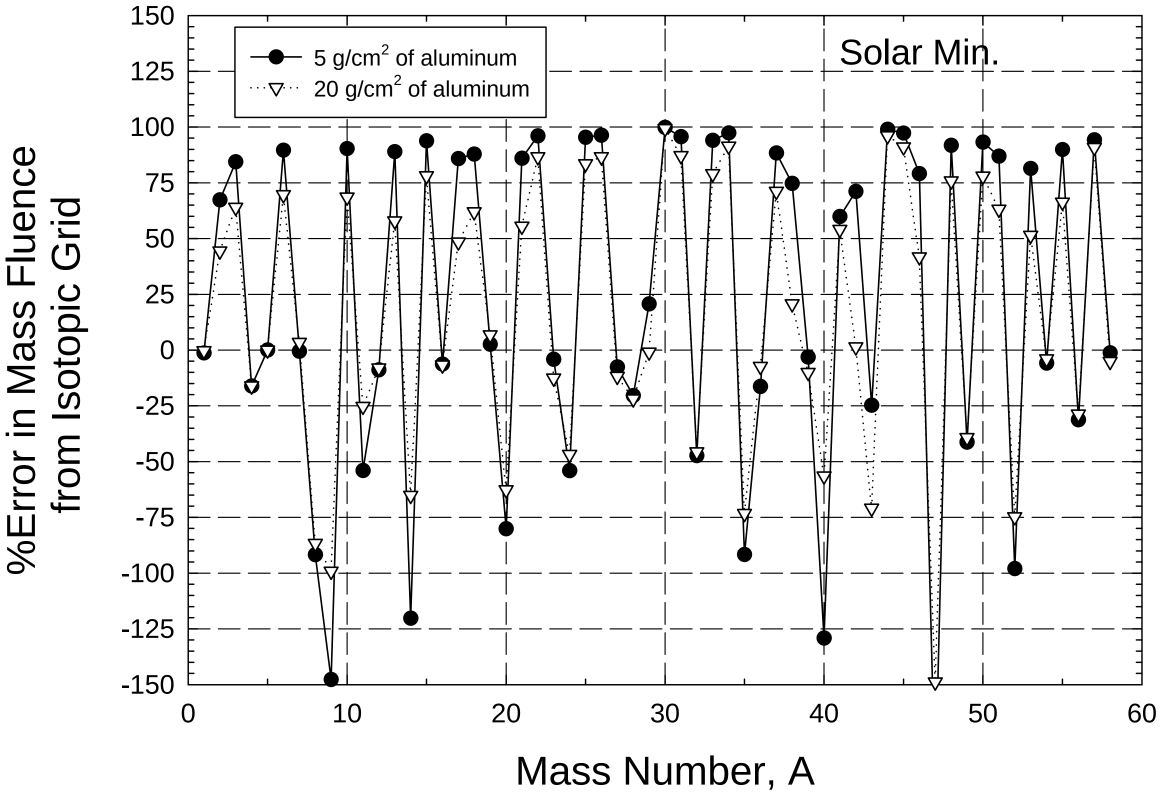


Figure 10a: Comparisons of the error that results from the HZETRN Code for the mass fluence distribution near solar minimum when using a reduced 59-isotope grid compared to transport with a 170-isotope grid

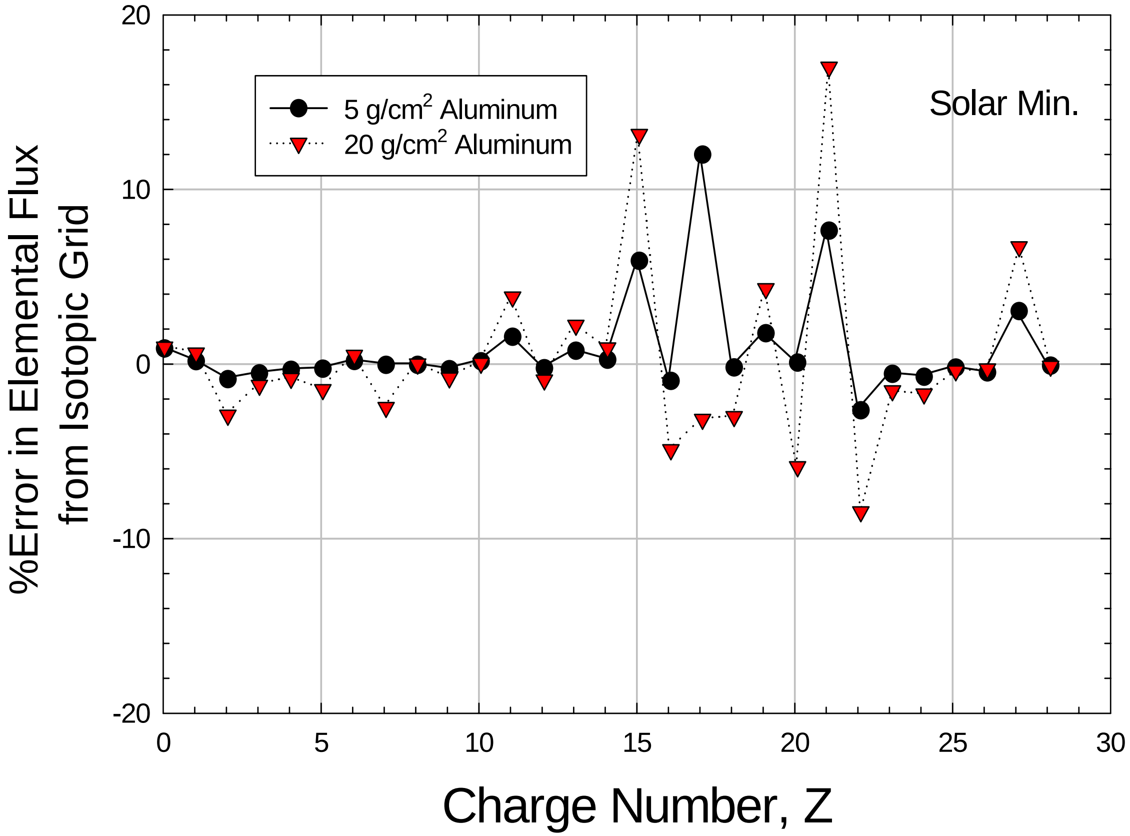


Figure 10b: Comparisons of the error that results from the HZETRN Code for the elemental fluence distribution near solar minimum when using a reduced 59-isotope grid compared to transport with a 170-isotope grid.

Table 3b: Elemental (Z) and Neutron excess (Y) dependence on GCR dose equivalent behind 5 g/cm^2 of Aluminum Shielding.

GCR Dose Equivalent per Year near Solar Minimum							
Z	Y<0	Y=0	Y=1	Y=2	Y=3	Y>3	Total-Z
0	0.00	0.00	0.65	0.00	0.00	0.00	0.65
1	15.03	2.56	1.74	0.00	0.00	0.00	19.33
2	2.48	15.60	0.00	0.00	0.00	0.00	18.08
3	0.00	0.04	0.04	0.00	0.00	0.00	0.09
4	0.05	0.00	0.04	0.02	0.00	0.00	0.12
5	0.00	0.23	0.34	0.00	0.00	0.00	0.58
6	0.03	3.14	0.29	0.01	0.00	0.00	3.47
7	0.01	0.62	0.83	0.01	0.00	0.00	1.48
8	0.07	8.67	0.27	0.27	0.00	0.00	9.28
9	0.01	0.03	0.31	0.01	0.01	0.00	0.37
10	0.03	1.69	0.37	1.10	0.01	0.00	3.20
11	0.01	0.06	0.99	0.04	0.01	0.00	1.11
12	0.05	4.71	1.33	1.34	0.01	0.00	7.44
13	0.01	0.15	1.66	0.03	0.01	0.00	1.87
14	0.06	7.46	0.77	0.75	0.01	0.00	9.06
15	0.00	0.02	0.60	0.04	0.02	0.01	0.70
16	0.02	1.86	0.42	0.48	0.02	0.01	2.82
17	0.00	0.02	0.38	0.32	0.21	0.01	0.93
18	0.01	0.89	0.08	0.51	0.04	0.06	1.59
19	0.00	0.02	1.12	0.04	0.04	0.04	1.27
20	0.01	1.03	0.03	0.58	0.57	0.58	2.81
21	0.00	0.00	0.02	0.05	0.70	0.08	0.85
22	0.00	0.01	0.03	0.72	0.81	1.12	2.69
23	0.00	0.00	0.02	0.05	0.71	0.66	1.44
24	0.00	0.00	0.03	0.68	0.73	1.33	2.77
25	0.00	0.00	0.02	0.05	0.88	1.23	2.18
26	0.00	0.00	0.03	1.34	1.50	13.90	16.77
27	0.00	0.00	0.00	0.01	0.06	0.00	0.08
28	0.00	0.00	0.01	0.87	0.00	0.00	0.88
Total-Y	17.88	48.84	12.45	9.35	6.37	19.03	113.88

Solar Modulation of GCR

- Badhwar and O'Neill use self-consistent solution to transport Local Intersteller source (LIS) for each element using Fokker-Plank radial diffusion equation based on Parker (1965)
  - Neutron monitor counts
  - Sun-spot number
- Kim et al. use a statistical model to predict probability distribution for level of future GCR modulation

Future GCR Modulation- Approach

- Sunspot number is well correlated with many observable space quantities and represents variation in the space radiation environment. A solar cycle statistical model[1-3] was developed based on the accumulating cycle sunspot data.

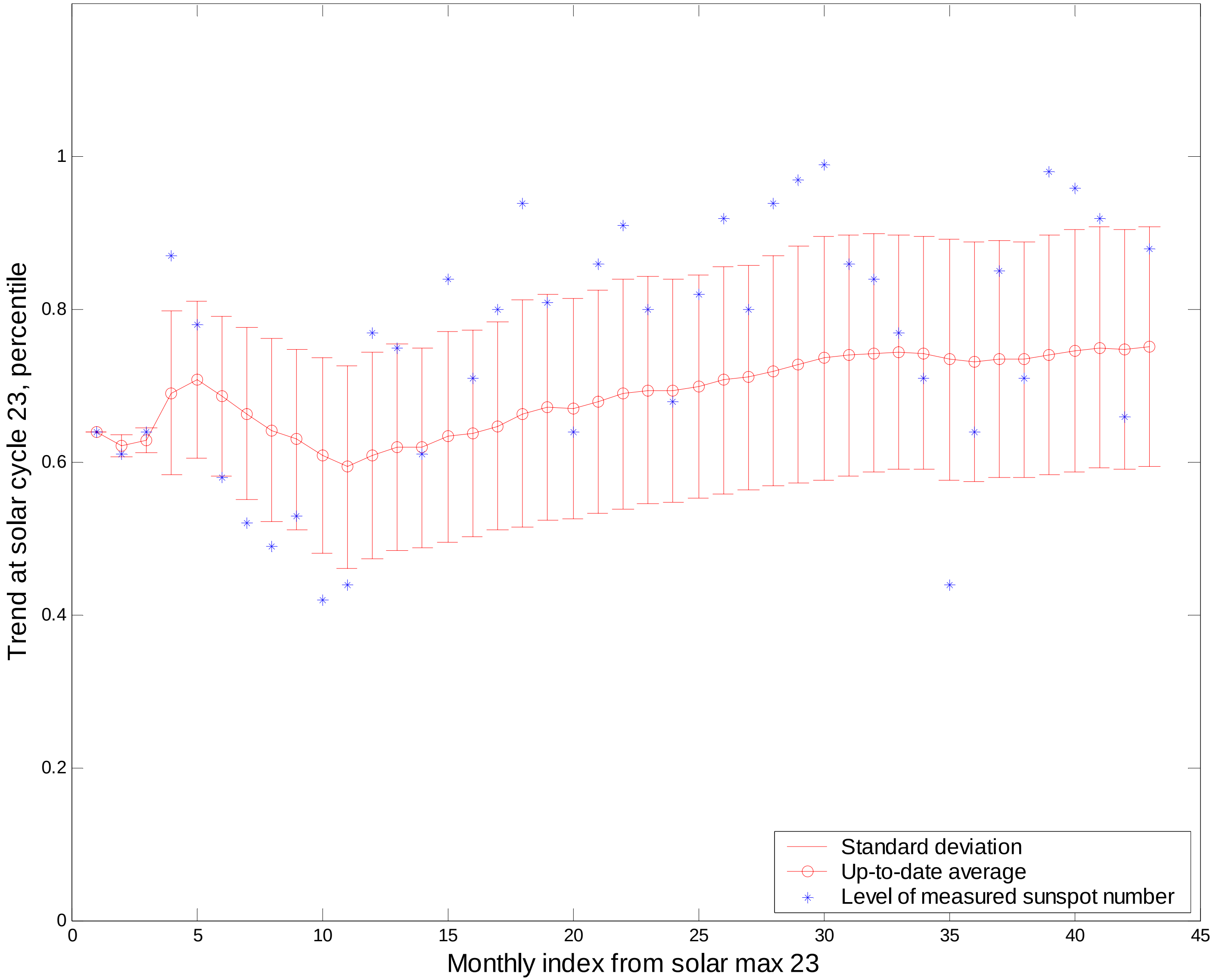
- A predictive model for GCR radiation environment[4,5] represented by GCR deceleration potential (ϕ) was derived from GCR flux and ground-based Climax neutron monitor rate measurements over the last four decades.

$\Rightarrow$ Prediction of radiation environments and doses for future space exploration missions.

- Relationship between large SPE occurrence and ϕ

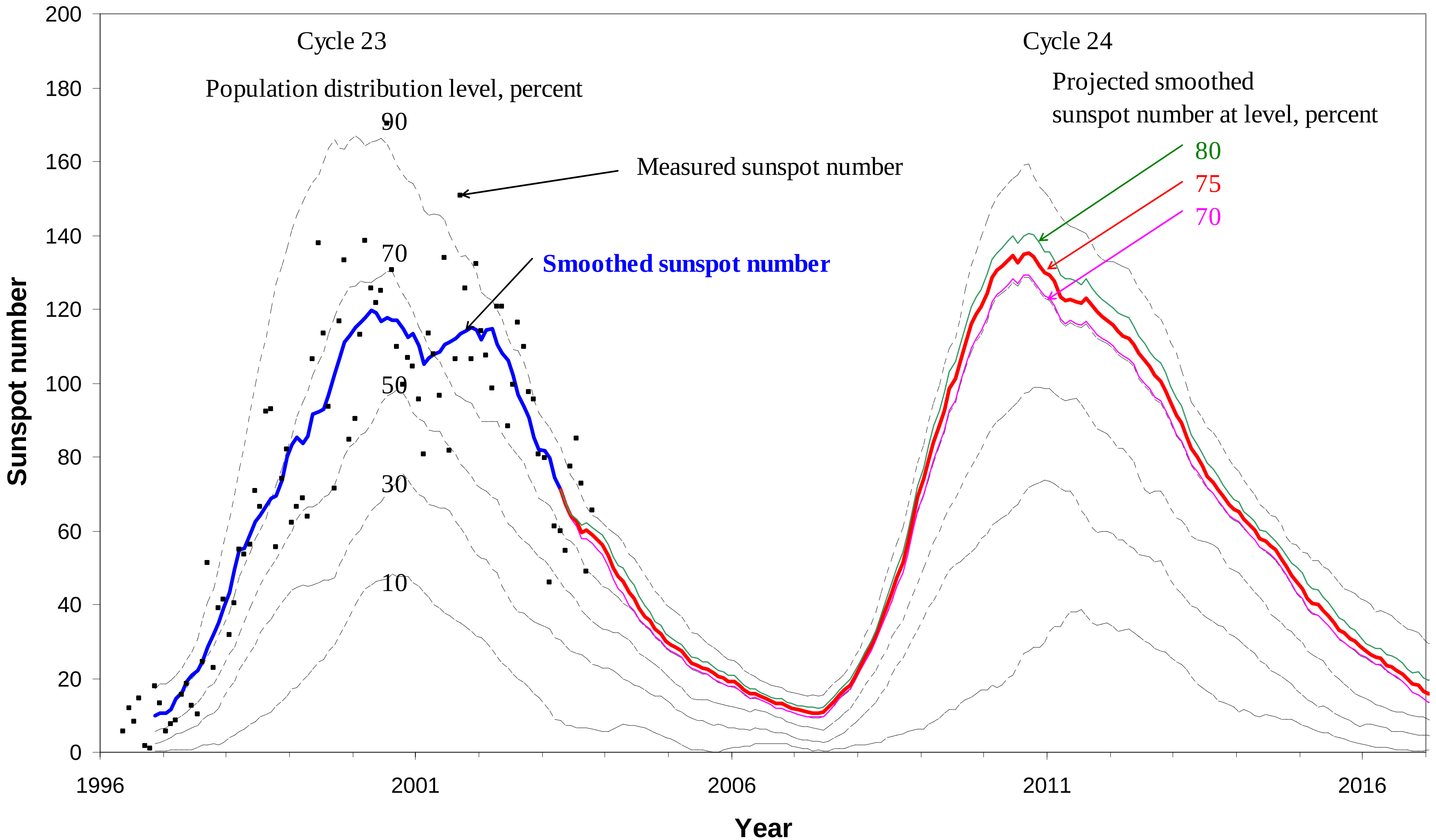
$\Rightarrow$ A probability of SPE in mission period.

Population Group of Declining Phase of Cycle 23 (Cumulative Mean Value and Statistical Fluctuation)

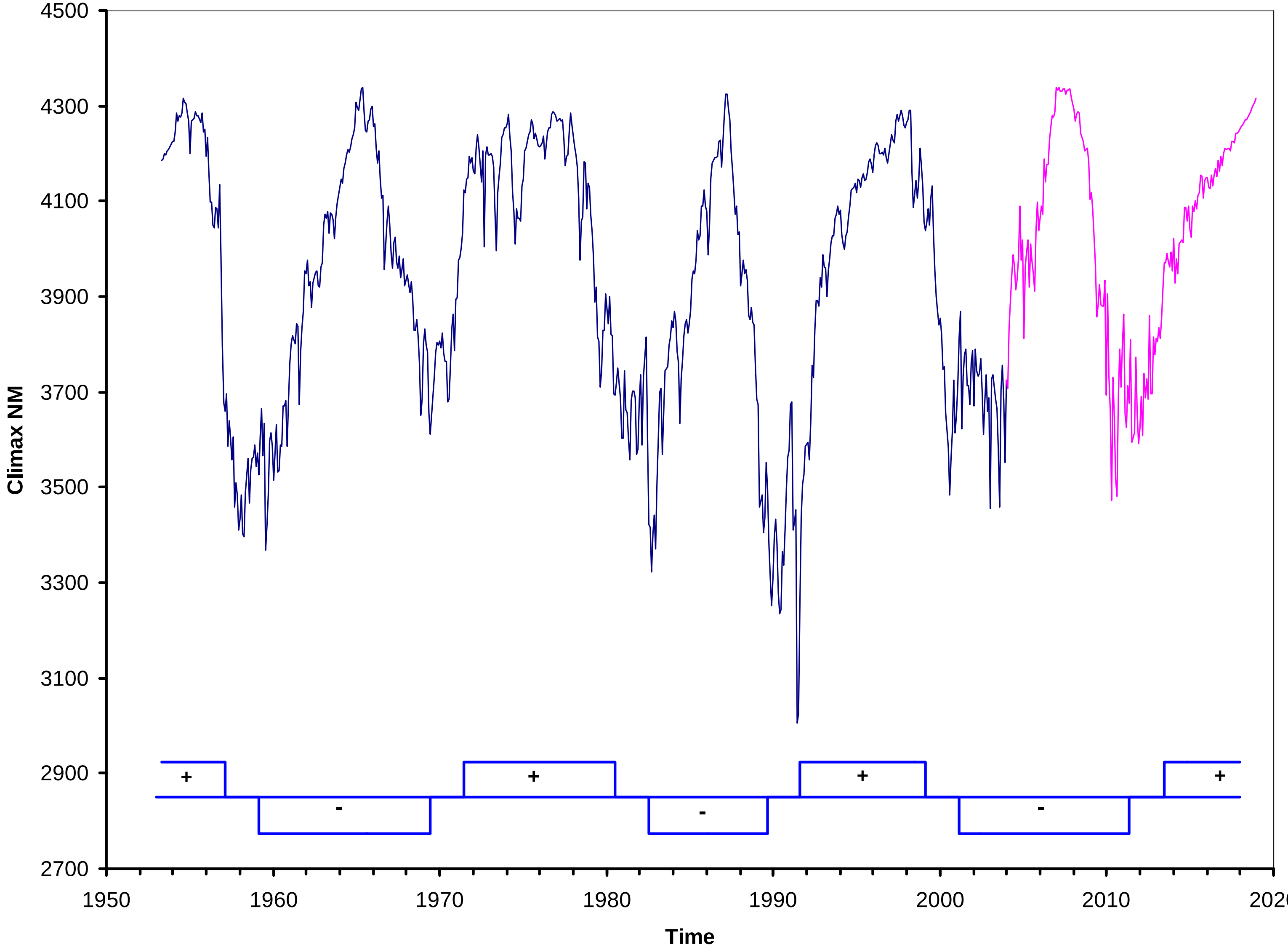


Projections of Solar Cycles 23 and 24

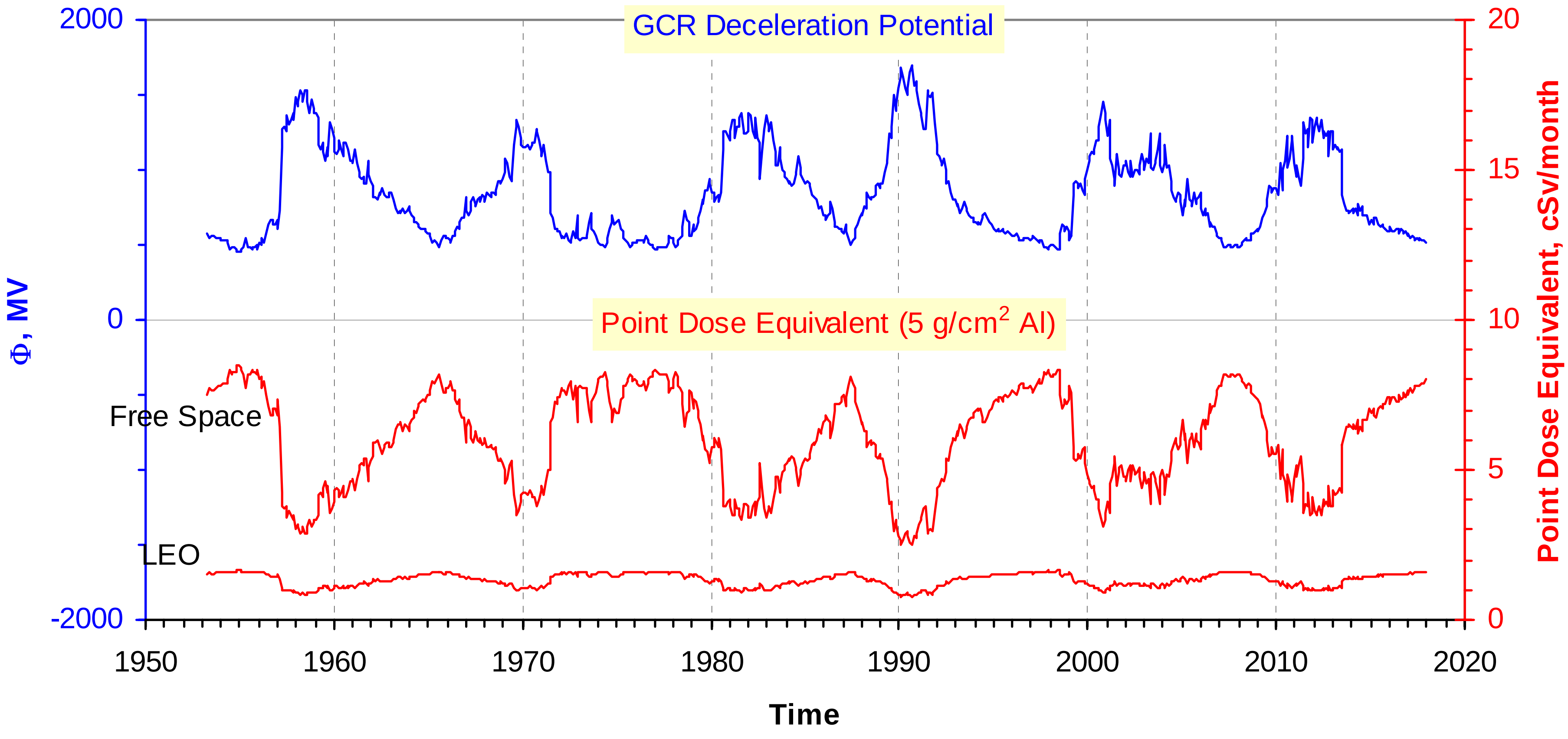
A basis for estimating of exposure in future space missions



Climax Neutron Monitor Rate Measurements and Projection to Solar Cycles 23 and 24



GCR Environments
and
Point Dose Equivalents inside Spacecraft



$$\lambda(\Phi, R) = \lambda_{\text{Inter-stellar}} + \lambda_{\text{Inter-planetary}}(\Phi, R), \tag{2}$$

where Φ is the solar modulation parameter and R (in A.U.) is the radial distance from the sun. It then follows that the amount of fragmentation in the inter-planetary media and the isotopic abundances are dependent on the modulation parameter and radial distance. Based on the results of Lukasiak et al. (1993) the following formula is used to describe the dependence of the isotopic ratio (near-Earth) on the solar cycle including a dependence on the modulation parameter Φ(MV)

$$f(A, Z) = f_{\text{Source}}(A, Z) + [\exp(\gamma\sqrt{\Phi}) - 1], \tag{3}$$