

BADHWAR – O’NEILL GALACTIC COSMIC RAY MODEL UPDATE BASED ON ADVANCED COMPOSITION EXPLORER (ACE) ENERGY SPECTRA FROM 1997 TO PRESENT

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ABSTRACT

Accurate knowledge of the interplanetary Galactic Cosmic Ray (GCR) environment is critical to planning and operating manned space flight to the moon and beyond. In the early 1990’s Badhwar and O’Neill developed a GCR model based on balloon and satellite data from 1954 to 1992. Since August 1997 the Advanced Composition Explorer (ACE) has provided significantly more accurate GCR energy spectra due to its much larger collection power. The original Badhwar – O’Neill Model, updated with the new ACE data, should provide interplanetary mission planners with highly accurate GCR environment data for radiation protection for astronauts and radiation hardness assurance for electronic equipment.

INTRODUCTION

The Advanced Composition Explorer (ACE) is stationed at the Earth-Sun L1 libration point (about 1.5 million km from earth). One of the primary instruments onboard ACE, the Cosmic Ray Isotope Spectrometer (CRIS), provides “quiet time” energy spectra for elements from lithium ($z=3$) through nickel ($z=28$). The energy spectra are in the range of highest modulation from roughly 50 to 500 MeV / nucleon. The ACE CRIS geometric factor is $250 \text{ cm}^2 - \text{sr}$. Collecting continuously since 1997, the collection power of CRIS is much larger than any of the previous satellite or balloon GCR instruments for GCR measurements in the 50 – 500 MeV/n range.

Most of the previous satellite instruments were $< 10 \text{ cm}^2 - \text{sr}$. The IMP-3 through 8 satellite instruments had geometric factors around $2 \text{ cm}^2 - \text{sr}$. The balloon instruments were somewhat larger however; their total collection power was limited by their float-at-altitude times, which were a few days at most. IMAX (Menn et al., 2000), launched in Canada in 1992 with a geometric factor of $142 \text{ cm}^2 - \text{sr}$ measured proton and helium spectra in a 16 hour flight - but no heavy ion spectra. Collection at higher energies required much larger geometric factors. HEAO-3-C2 (Engelmann et al., 1990) had $413 \text{ cm}^2 - \text{sr}$ collecting continuously for 8 months mid-way between solar minimum to maximum for energies between 1 and 35 GeV/n and provides the best high-energy spectra to this day.

Since ACE CRIS has operated continuously since 1997, its total collection power provides a unique opportunity to refine our GCR models. Davis et al. (2001) estimates the residual systematic uncertainty of the spectra measured by CRIS to be less than 5%.

This new data was used to update the original Badhwar – O’Neill Model (Badhwar and O’Neill, 1991, 1992, 1993, 1994, 1996) and greatly improves the interplanetary GCR prediction accuracy. When the new – highly precise ACE CRIS data was analyzed it became obvious that the LIS spectrum for each element precisely fit a very simple analytical energy, velocity power-law.

This model accurately accounts for solar modulation of each element (hydrogen – nickel) by propagating the Local Interplanetary Spectrum (LIS) of each element through the heliosphere by solving the Fokker – Planck diffusion, convection, energy loss boundary value problem. A single value of the deceleration parameter, $\Phi(t)$, describes the level of solar cycle modulation and determines the GCR energy spectrum for all of the elements at a given distance from the sun.

MODEL

The intensity and energy of galactic cosmic rays entering the heliosphere is lowered as they are scattered by irregularities in the interplanetary magnetic field embedded in the solar wind. Parker (1965) showed that the steady-state, spherically symmetric Fokker-Planck equation accurately accounts for diffusion, convection, and adiabatic deceleration of these particles. The Fokker-Planck equation is readily solved numerically to propagate the Local Interstellar Spectrum (LIS) for each element to a given radius from the sun.

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 A.U., 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.

Also, since the solar magnetic field is expanding we expect the diffusion coefficient to become larger with distance from the sun. An inverse square law (for $1/k(r, t)$) for a spherical cavity seems entirely reasonable (others have assumed an exponential decay law (Fisk, 1971)). With our assumption, in order to fit each of the various elements from hydrogen to nickel with the simple analytical LIS form, the modulation cavity scaling parameter r_0 turns out to be 4.0 A.U. The physical significance of the 4 AU cavity scaling is not yet clear; the actual boundary of the cavity was set at 50 AU.

Actually, the single fit parameter that determines the level of solar modulation is $k_0/\Phi(t)$. However, customarily we set k_0 to a constant ($k_0 = 1.6 \cdot 10^{21} \text{ cm}^2/\text{s}$) and then determine the value of $\Phi(t)$ that fits the measured spectra. The solar modulation parameter, $\Phi(t)$ in MV, is related to the energy and rigidity required for interstellar particles in order to propagate through the heliosphere to the radius in question (1 AU in our case). However, since the value of k_0 was arbitrarily chosen here and is not physically significant, the actual fit values of $\Phi(t)$ in MV are not significant, they simply define the level of modulation consistent with our model and our choice of k_0 .

LOCAL INTERSTELLAR SPECTRUM (LIS)

The energy spectrum of each element at the outer heliosphere boundary has long been known to vary as a power law in total energy. However, the ACE data fit demonstrates that inclusion of β in the simple power law form of Eq. 2 allows for highly accurate agreement with ACE data for all the elements down to energies of approximately 50 MeV.

$$j_{lis}(E) = j_0 \beta^\delta / (E + E_0)^\gamma, \quad (2)$$

where $j_{lis}(E)$ is the differential LIS for an element, E is the particle's kinetic energy/nucleon and E_0 is the particle's rest energy/nucleon which is 938 MeV/n for every particle. The free parameters are γ , δ and j_0 which are determined from the ACE fit and differ for each element.

ACE CRIS DATA FIT - OXYGEN

The Advanced Composition Explorer (ACE) Cosmic Ray Isotope Spectrometer (CRIS) measurements are the foundation of this Badhwar-O'Neill Model update. The measurements are available continuously since August 1997. The daily average fluxes were readily obtained from the ACE web site (<http://www.srl.caltech.edu/ACE/>) where more detailed information regarding the precision of the instrument may also be found. The CRIS data is conveniently only available for "quiet times" and the data extends from solar minimum in 1997 to present which takes it beyond the recent solar maximum – more than sufficient to define GCR spectra.

The daily spectrum is not precise enough to accurately define the actual spectrum – even for ACE oxygen – there just aren't enough ions caught in one day. Therefore, daily oxygen data was accumulated until at least 2000 ions were collected in each energy channel. Even for oxygen this required 10 to 40 day intervals. Each interval was allowed to contain only consecutive days - periods of solar activity were excluded. Non-contiguous intervals were excluded in order to minimize proximity to solar flare data. Therefore, the good data set intervals near solar maximum were much longer and there were not as many.

The resulting ACE CRIS good data set intervals for oxygen were fit by our model and the data fit very well from 1997 – 2004 for an LIS with $\gamma = 2.80$ and $\delta = 0.0$. The high energy tail of the spectrum was chosen to be compatible with the French Danish experiment HEAO-3-C2 measurements of 1980 (Engelmann et al., 1990) which are considered to be the most accurate high energy data available.

The actual fit for oxygen is shown in Figure 1 for a good data set interval chosen near solar minimum and another near solar maximum. Each good data set interval meets the 2000 ion per channel requirement and the average model versus ACE RMS error is $< 4\%$ for both. The solar minimum data set required 9 consecutive days of data, whereas 40 days of data were needed near solar maximum.

SOLAR MODULATION PARAMETER - $\Phi_{ACE}(t)$

The ACE CRIS oxygen data was fit for each data set of consecutive days starting in August 1997 and ending in 2004 that met the >2000 ions per energy channel requirement. This defines the solar modulation parameter, $\Phi_{ACE}(t)$, as a function of time from 1997 to 2004 as shown in Figure 2. Oxygen was chosen as the reference element to define the solar modulation parameter, $\Phi_{ACE}(t)$, for its high GCR abundance and its relatively low contribution to solar flare composition.

DATA FIT – HYDROGEN TO NICKEL

With the solar modulation parameter, $\Phi_{ACE}(t)$, defined from 1997 to 2004 from the oxygen data, the values of the LIS parameters γ , δ and j_0 were determined for the remaining elements (hydrogen to nickel) by fitting the measured energy spectra. Table 1 shows the results of the fit (γ , δ and j_0) as well as the minimum # of ions per energy channel used to define the data set, the average # of days required to collect the data set, and the average RMS error of the model from 1997 to 2004.

The results of the power law fit of the free parameters (γ , δ and j_0) determined that $\delta = 0$ for about one third of the elements. The non-zero values for δ mainly occur for the odd elements from $z = 5$ to 15 and all the elements from $z = 15$ to 24. These tend to be the less abundant elements. Also, γ ranges from 2.7 to about 3.2.

The accuracy of the model is best seen in the differential flux energy spectra graphs in Figure 3 and 4. The model and measurements are in very good agreement for the more abundant elements such as carbon and iron (2000 and 1000 ions / channel minimum respectively) in Figure 3. The model and measurements are in overall agreement for

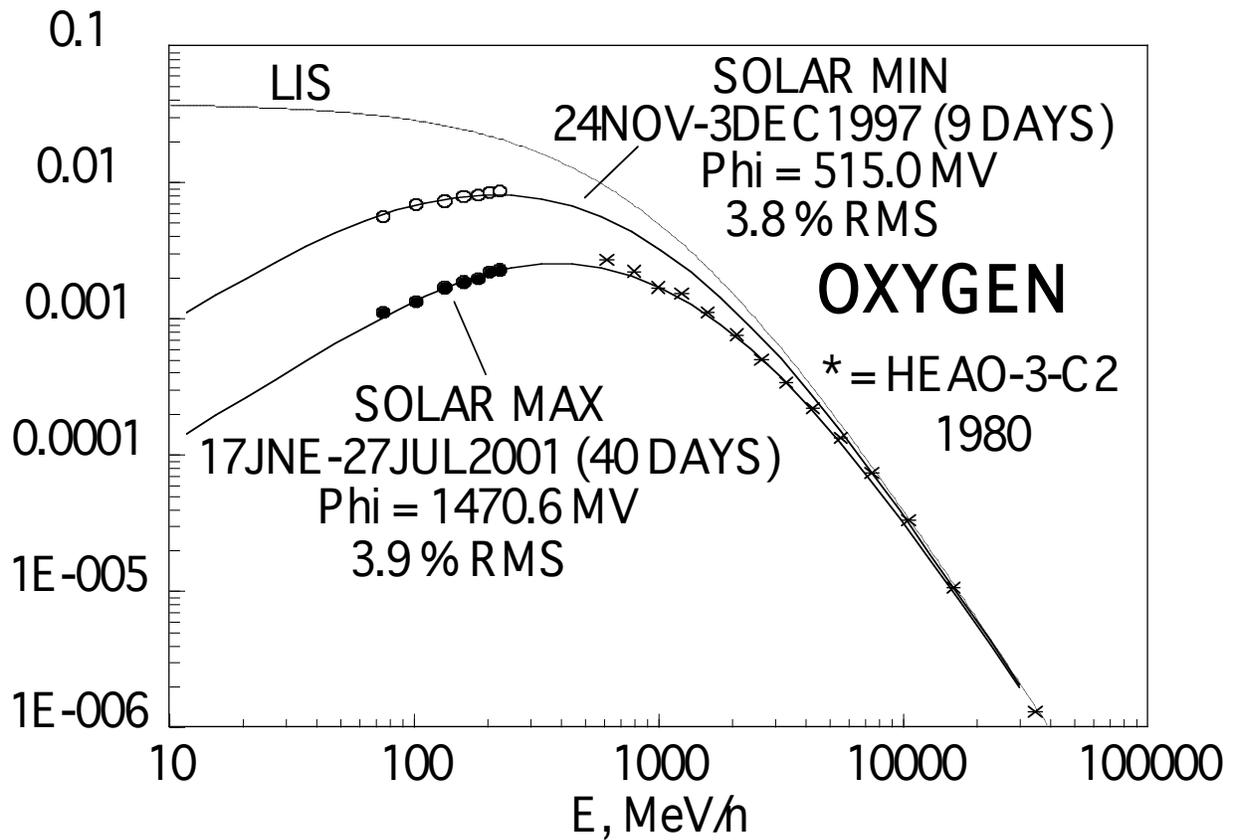


Fig. 1. Badwar-O'Neill Model fit of ACE CRIS oxygen energy spectra measurements near solar minimum and near solar maximum.

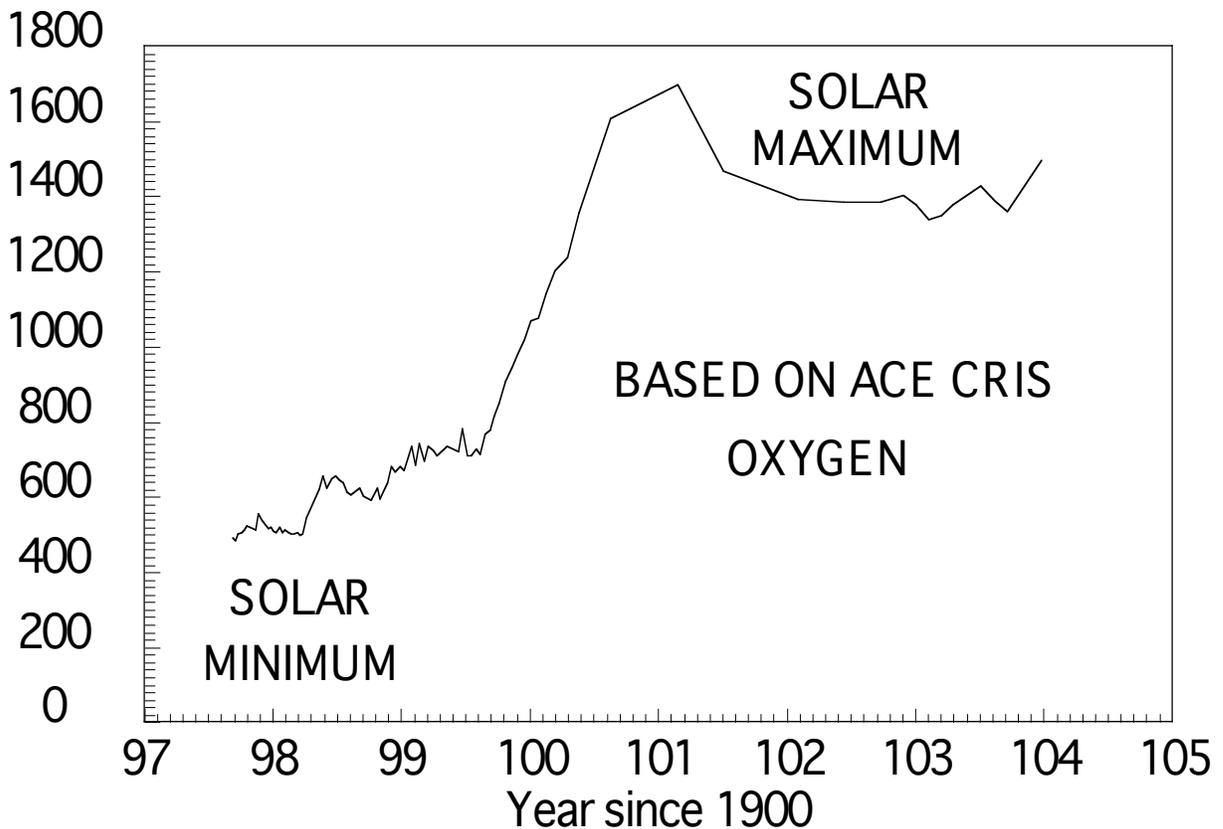


Fig. 2. Solar modulation parameter, $\Phi_{ACE}(t)$, determined by fitting ACE CRIS oxygen from 1997.6 to 2004.

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

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

the less abundant elements such as fluorine and phosphorous (200 and 100 ions / channel minimum respectively) in Figure 4, however, there is much more spread in the data points.

Boron (z=5) to Nickel (z=28)

Daily ACE CRIS measurements are available online for boron (z=5) to nickel (z=28). For each of these elements, the measured energy spectrum was determined by accumulating the daily values until a specified minimum # of ions per energy channel were collected. Note that the average model RMS errors from solar minimum to solar maximum are well below 10% for all elements for which 300 or more ions / channel could be collected. For about half of the elements even ACE CRIS does not collect more than a few 100 ions / channel in a reasonable time

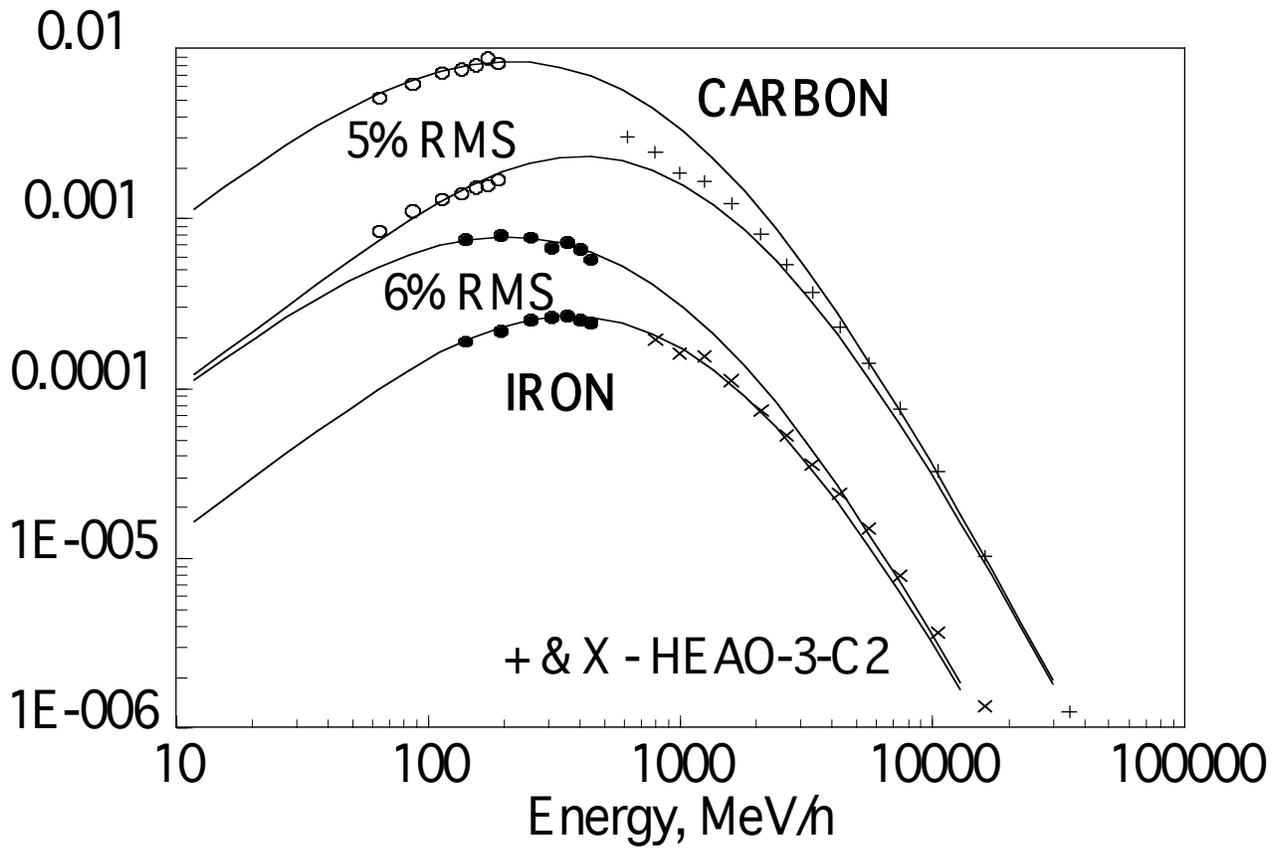


Fig. 3. Differential flux energy spectra near solar minimum and maximum for 2 of the more abundant elements, typical of the better fits.

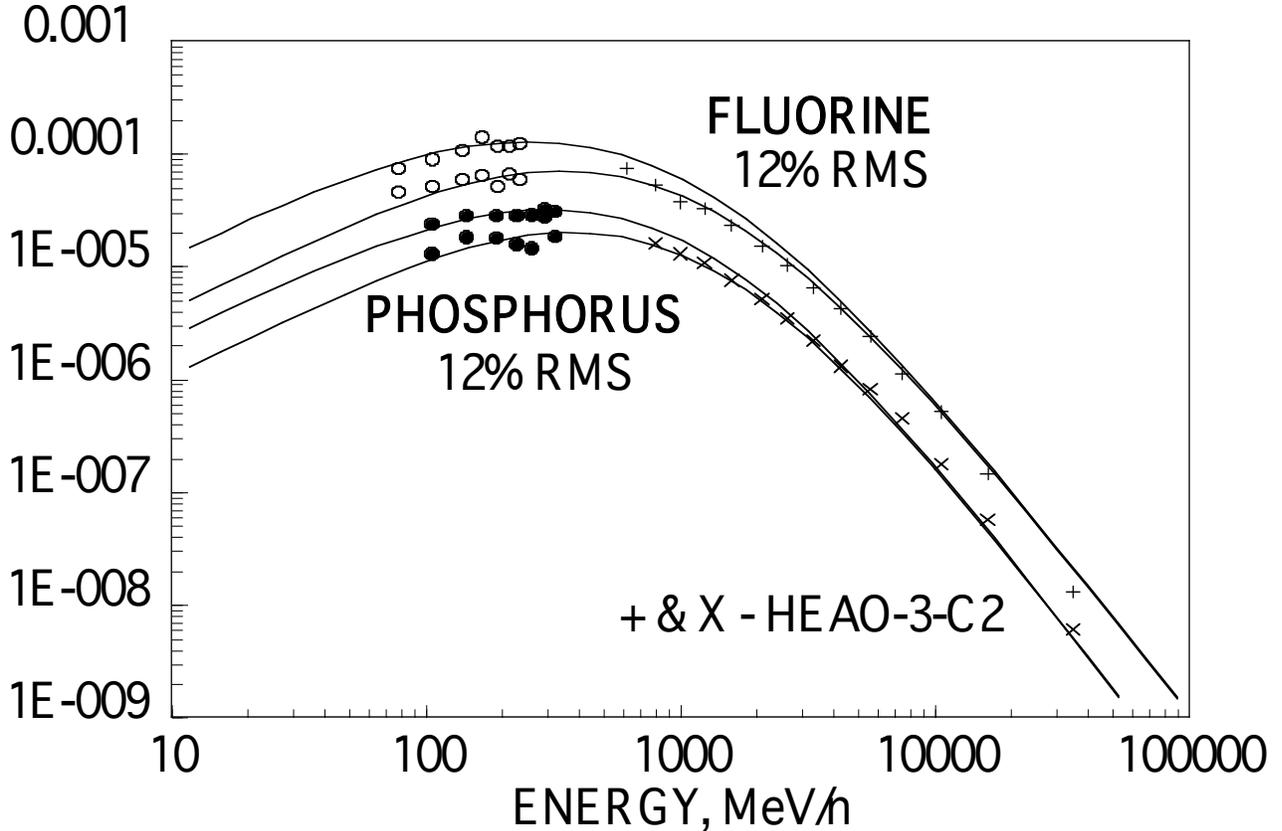


Fig. 4. Differential flux energy spectra near solar minimum and maximum for 2 of the less abundant elements, typical of the worst fits.

period (~100 days) and the errors for these elements are significantly larger – still less than 15% for most elements of any consequence.

Lithium (z=3) and Beryllium (z=4)

Daily ACE CRIS measurements for lithium (z=3) and beryllium (z=4) are not available. However, De Nolfo et al (2003) have carefully analyzed the ACE CRIS measurements and provide yearly average spectra for 2 years: 1998-1999 and 1999-2000.

For beryllium (z=4) through nickel (z=28) the high-energy tail of the spectrum was chosen to be compatible with the HEAO-3-C2 measurements of 1980 (Engelmann et al., 1990). The excellent agreement with the HEAO-3-C2 data is clearly seen in Figures 3 and 4. For lithium (z=3) the HEAO-3-C2 data was not available, so the high-energy tail of the LIS spectrum was taken to be twice that for beryllium (z=4) since this is the approximate abundance ratio (Webber and Yushak, 1979).

Hydrogen (z=1) and Helium (z=2)

IMP-8 measurements were used for hydrogen (z=1) and helium (z=2). These elements are more abundant than the elements measured by ACE CRIS; however, the IMP-8 has a collecting power of only $2.05 \text{ cm}^2 \text{ -sr}$. Also, it is especially difficult to distinguish the GCR and solar components for these elements. Fortunately, Lopate (2004) provided an extensive table defining quiet time hydrogen and helium data from IMP-8. For these elements there were not many good measurements around solar maximum and the average RMS error from 1997.6 to 1999.3 is around 10%.

For hydrogen (z=1) and helium (z=2) the high-energy tail of the spectrum was chosen to be compatible with the balloon-borne experiment Isotope Matter-Antimatter Experiment (IMAX) measurements launched from Lynn Lake, Manitoba, Canada in 1992 (Menn et al., 2000).

SOLAR MODULATION PARAMETER, $\Phi_{\text{CLI}}(t)$, FROM CLIMAX NEUTRON MONITOR

Thus far, we have defined the solar modulation parameter, $\Phi_{\text{ACE}}(t)$, only from 1997 to present based on the ACE CRIS oxygen (z=8) data. Values of $\Phi(t)$ are needed over several solar cycles and for future times. Fortunately, the Climax Neutron count is readily available on the internet (<http://ulysses.uchicago.edu/>) from 1951 to present (and beyond) and has proven long term reliability.

Since the ACE CRIS definition of $\Phi_{\text{ACE}}(t)$ is more precise for the times it is available, we must calibrate the Climax count with the ACE $\Phi_{\text{ACE}}(t)$. However, ACE CRIS currently only covers solar minimum to maximum for a solar cycle that has positive solar magnetic field for the most part.

Since Climax neutrons are the result of GCR interactions in the earth's atmosphere rather than actual GCR measurements made outside the earth's magnetosphere, the correlation is different for positive (outward solar field) solar cycles than for negative (inward solar field).

Therefore, we first calibrate the on-orbit measurements of IMP-8 that cover almost 3 solar cycles from 1973 to 2001 with the ACE CRIS $\Phi_{\text{ACE}}(t)$ for the time when both sources overlap – 1997.6 to 2001.8.

IMP-8 Solar Modulation Parameter, $\Phi_{\text{IMP-8}}(t)$

IMP-8 provides a single measurement for all ions above oxygen (z=8) at high energy that can be used to determine the solar modulation parameter. IMP-8 data is available from 1973.8 to 2001.8, almost 3 solar cycles, and has sufficient overlap to correlate with ACE CRIS. We simply treated the IMP-8 (z>8) channel 7 as if it were 200 MeV/n phosphorus. Phosphorus (z=15) is the mean ion (weighted by relative abundance) of all ions between z=9 and 28.

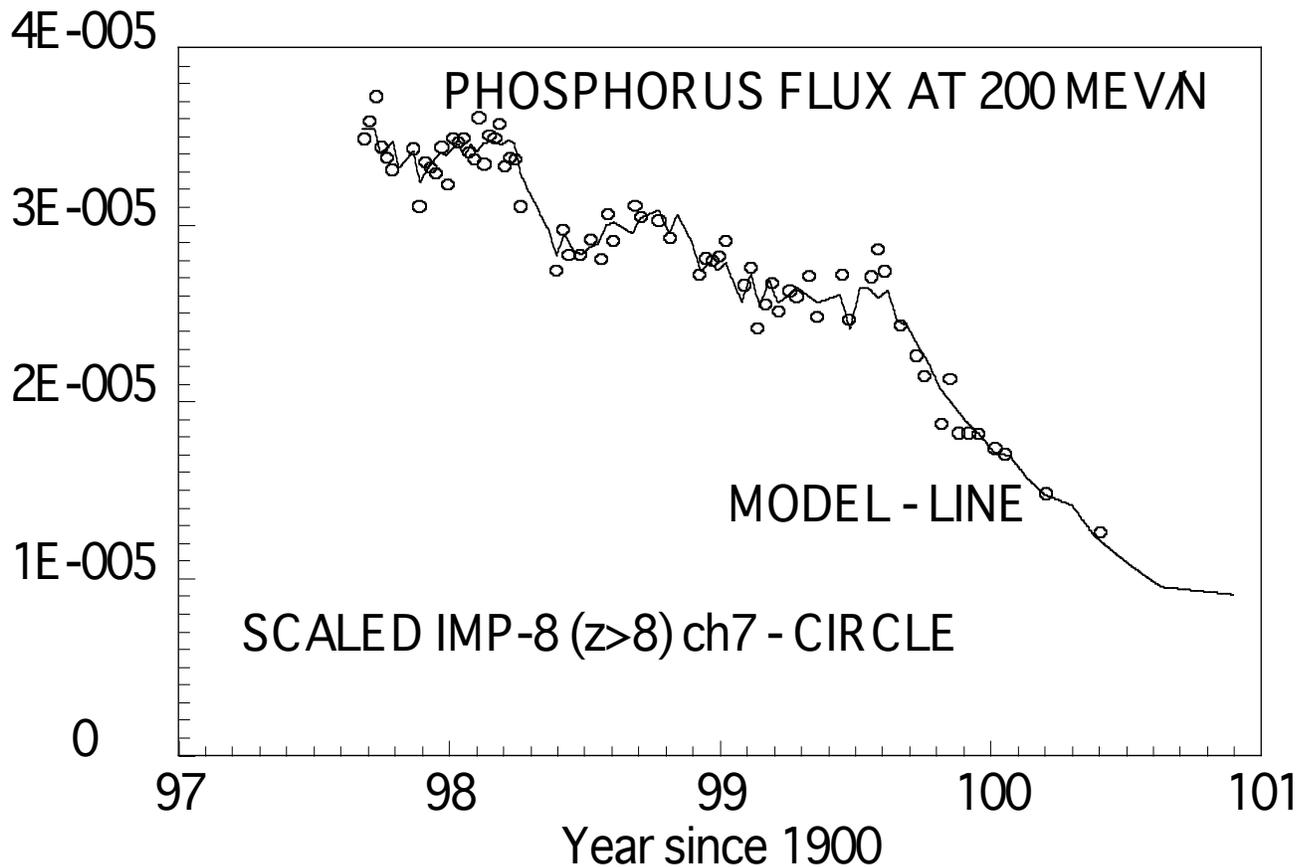


Fig. 5. Differential flux for phosphorus at 200 MeV/n based on the Badhwar - O'Neill Model (line) and from the IMP-8 high z, high energy ($z>8$) channel 7 measurement times a linear scaling factor (circle).

The IMP-8 ($z>8$) channel 7 was scaled (simply multiplied by 7803.5) to produce the phosphorus flux in Figure 5. This IMP-8 channel 7 “phosphorus flux “ was found to correlate very well with phosphorus flux predicted using the Badhwar – O’Neill Model. The correlation is 98.9% from 1997.6 to 2001.8. The IMP-8 “phosphorus” flux (Figure 5) was used to solve for the solar modulation parameter, $\Phi_{\text{IMP-8}}(t)$ which is compared to the value derived from the ACE CRIS oxygen measurements, $\Phi_{\text{ACE}}(t)$ in Figure 6.

Climax Solar Modulation Parameter, $\Phi_{\text{CLI}}(t)$

The Climax neutron count can also be used to determine the solar modulation parameter. The Climax count was compared with the IMP-8 solar modulation parameter, $\Phi_{\text{IMP-8}}(t)$ and found to correlate within 97% for the period of overlap - 1973.6 to 2001.8. The simple linear scaling formulas are given in the Figure 7 caption. Note the slight difference in scaling for positive (field outward) and negative (field inward) solar cycles and for high modulation (Climax count < 3850) when the field is actually changing sign. The solar modulation parameter, $\Phi_{\text{CLI}}(t)$ based on the Climax neutron count is shown in Figure 7.

Thus, the Badhwar – O’Neill model can now provide quiet time GCR flux for elements 1 to 28 for any time since 1951. Table 1 shows that the model RMS error is not significantly increased when the Climax solar modulation parameter, $\Phi_{\text{CLI}}(t)$ is used. The error is about 2 - 4% greater than when the more ideal solar modulation parameter derived from ACE oxygen, $\Phi_{\text{ACE}}(t)$, is used.

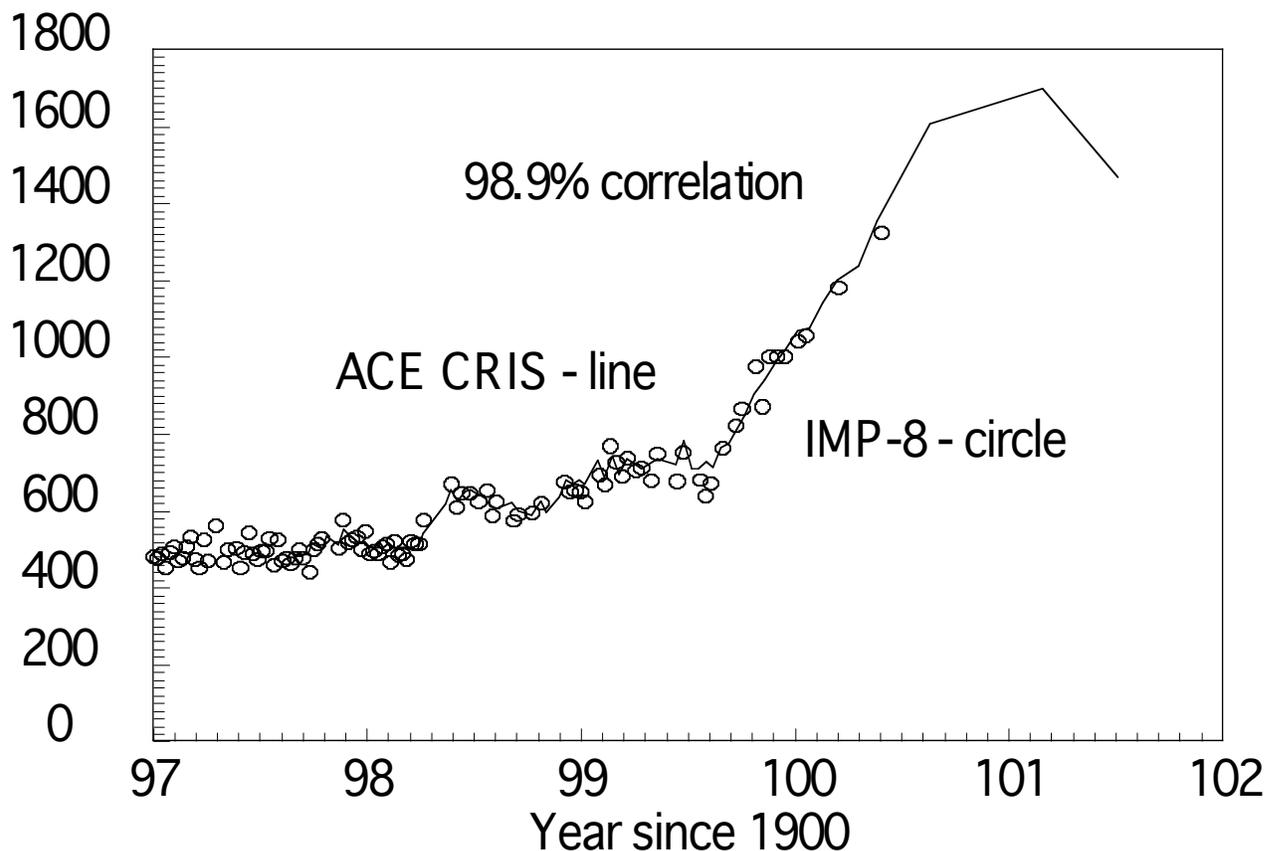


Fig. 6. Solar modulation parameter derived from ACE CRIS oxygen measurements (line) and that derived from the IMP-8 ($z>8$) channel 7 measurement (circle).

SOLAR MINIMUM VERSUS MAXIMUM

For deep space missions cosmic ray intensities at solar minimum pose the greatest threat to crew safety (Townsend, 1992 and Badhwar, Cucinotta et al. 1993). However, knowledge of the intensity at solar maximum is also important to assess the degree of mitigation that may be achieved by planning missions during the time when the flux is reduced.

Table 2 shows the average difference between the model and the ACE flux measurements for the more abundant heavy ion elements for periods at solar minimum and at solar maximum. When the ACE solar modulation parameter is used the error is around 5%. In general, flux measurements at the energies considered here are more accurate at solar minimum than at maximum. This is partly because there are more ions collected during minimum per unit time, but mainly because the measurements are inevitably corrupted by solar particles. This is seen in Table 2, the ACE CRIS flux plots, and in all the solar modulation correlations between ACE CRIS, IMP-8, and CLIMAX – the correlations are all excellent below about 1200 MV in all cases. This is important because the flux at solar minimum is the most critical for mission planning since it defines the largest dose.

Table 2 also shows that when the solar modulation parameter derived from the Climax Neutron count is used the model is still within about 10 % of the ACE measurements.

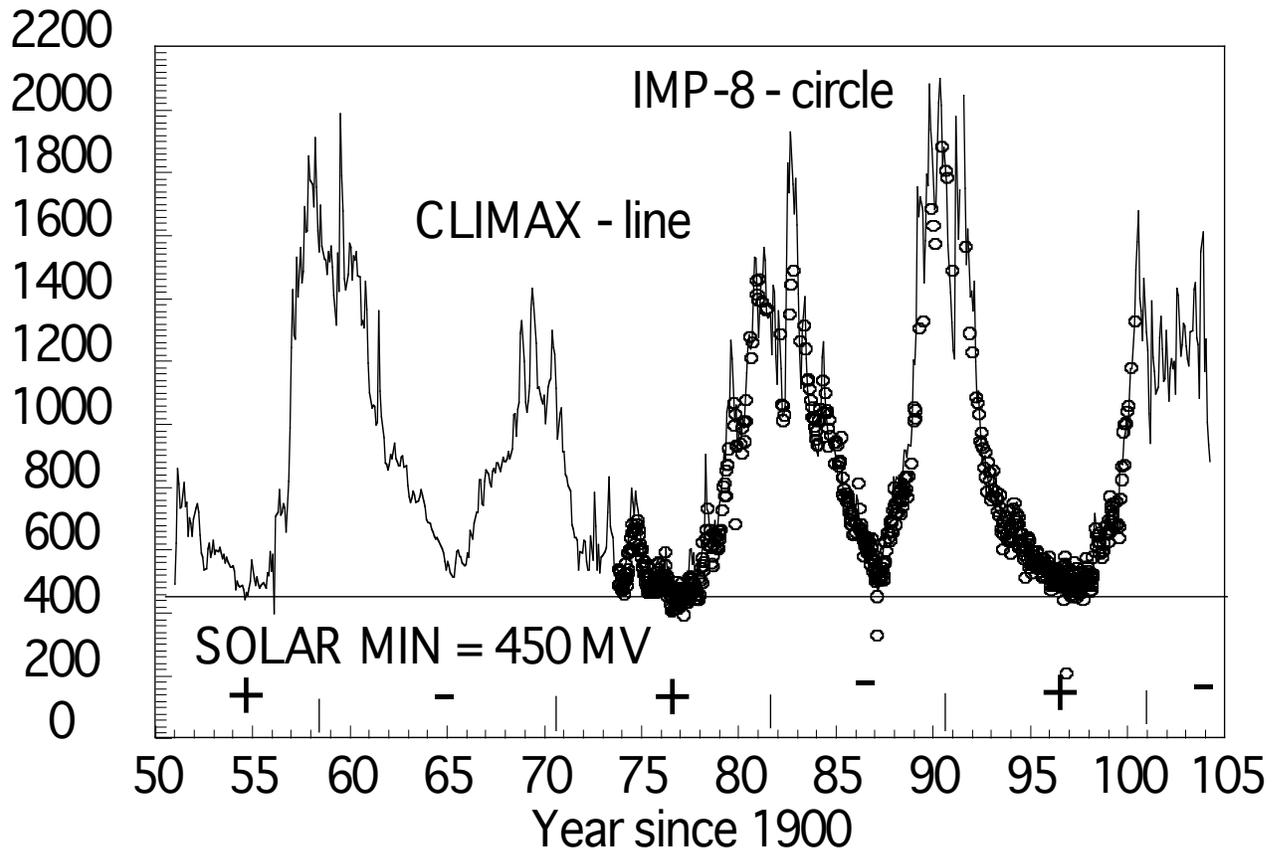


Fig. 7. Solar modulation parameter derived from the Climax neutron count (line), $\Phi_{CLI}(t)$, using the following empirical formulas: for positive cycles, $\Phi_{CLI}(t) = -1.15674 \text{ Climax} + 5434.5$ and for negative cycles, $\Phi_{CLI}(t) = -0.9276 \text{ Climax} + 4534.2$, and for high modulation (climax count less than 3850), $\Phi_{CLI}(t) = -1.8887 \text{ Climax} + 8253.75$. Also shown is the solar modulation parameter derived from IMP-8, $\Phi_{IMP-8}(t)$. The solar field switch times are: 58.39, 70.55, 81.375, 90.54, 100.915. Note that every solar minimum since 1955 has solar modulation very close to ~450 MV.

Table 2. Average RMS error in % for more abundant heavy ion elements near solar minimum (1997.6 to 1999.2) and solar maximum (1999.2 to 2000.9). % ACE is the error using the value of $\Phi_{ACE}(t)$ determined from the ACE CRIS oxygen fit. % CLI is the same except the value of $\Phi_{CLI}(t)$ determined from the CLIMAX Neutron Monitor was used.

z	Element	Error at Solar Minimum, %		Error at Solar Maximum, %	
		Φ_{ACE}	Φ_{CLI}	Φ_{ACE}	Φ_{CLI}
6	Carbon	4.1	6.9	6.1	9.7
8	Oxygen	3.4	6.0	6.2	9.6
14	Silicon	4.9	6.6	5.6	8.1
26	Iron	5.8	7.1	5.2	6.0

CONCLUSION

The updated Badhwar – O’Neill Model is shown to be accurate to about 5%, for the more abundant elements such as oxygen, carbon, and iron, which have sufficient abundance that over 1000 ions are captured in each energy bin

within a 30-day period. The statistical relationship between the number of ions captured by the instrument in a given time and the precision of the model for each element is clearly demonstrated.

This is a significant model upgrade that should provide interplanetary mission planners with highly accurate GCR environment spectra for radiation protection for astronauts and radiation hardness assurance for electronic equipment. The GCR spectra are available for any time from 1951 to present using the solar modulation parameter derived from Climax. Table 2 shows that for the more abundant elements the Climax solar modulation parameter, $\Phi_{CLI}(t)$, provides spectra accuracy better than 10% (see Table 1 for overall accuracy for all the elements).

The software model may be downloaded from the NASA JSC Parts, Packaging, and Manufacturing Branch's Web Site - <http://www4.jsc.nasa.gov/org/Ev/ev5/index.html> or by sending an e-mail to Patrick.m.oneill@nasa.gov.

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