BADHWAR – O'NEILL 2007 GALACTIC COSMIC RAY (GCR) MODEL USING ADVANCED COMPOSITION EXPLORER (ACE) MEASUREMENTS FOR SOLAR CYCLE 23

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35-WORD ABSTRACT

Advanced Composition Explorer (ACE) satellite measurements of the galactic cosmic ray flux and correlation with the Climax Neutron Monitor count over Solar Cycle 23 are used to update the Badhwar – O'Neill Galactic Cosmic Ray (GCR) model.

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INTRODUCTION

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 [1-5]. Also, the CREME 96 model (https://creme96.nrl.navy.mil/), readily available to a large group of users, still uses GCR spectra based on old balloon and satellite data. 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 GCR Model was revised in 2004 with a much improved and simplified model using ACE energy spectra measurements. The B-O'04 Model is described in detail in the COSPAR2004 paper [6].

In 2004, the ACE data started at solar minimum and ended in solar maximum.The new data extends to the end of cycle 23's solar minimum and enables us to precisely correlate GCR flux with the Climax neutron monitor rate over a complete solar cycle. This paper describes this correlation and demonstrates that quiet time GCR energy spectra for each element from 1951 to present is well defined by the B-O model with ACE GCR energy spectra and the solar modulation parameter defined by the Climax count.

The B-O Model determines the energy spectrum of each element by propagating a constant Local Intersteller Spectrum (LIS, the spectrum at the outer boundary of the heliosphere) through the heliosphere to the point of interest in the heliosphere. The level of modulation is a function of solar activity and the value of solar modulation uniquely determines the GCR energy spectra of all the elements. The ACE data itself, as it varies over the cycle, defines the solar modulation parameter for cycle 23. However, for periods when the ACE data is not available (prior to 1997 and when ACE fails), the GCR energy spectra are precisely determined by one number - the solar modulation parameter.

Fortunately, besides ACE, there are other consistent and accurate sources that can be used to determine the solar modulation parameter. Neutron monitor count, sun spot numbers, tree rings, even the content of old wine bottles have been correlated with the solar cycle and used to derive the modulation parameter.

In this paper we have detemined a new approach to determining the solar modulation parameter from the Climax Neutron Monitor by relating the neutron count at ground level to the galactic cosmic ray flux at the top-of-the-atmosphere by the known yield function for neutrons [7]. The correlation of Climax and ACE derived modulation parameters from 1997 to present ensures that the Climax derived values are valid whenever Climax data is available. Since hourly Climax data is available continously since 1951, and is expected to be available indefinately, the GCR spectra can be determined accordingly.

Therefore, the worst GCR fluxes at each of the solar minima over the past 56 years can be found. This is particularly important to mission planners who must design adequate protection for astronauts and electronic systems.

BADHWAR-O'NEILL '07 MODEL

The intensity and energy of galactic cosmic rays in the heliosphere is accurately determined by the steady-state, spherically symmetric Fokker-Planck partial differential equation accounting for diffusion, convection, and adiabatic deceleration of these particles. A single parameter describes the effect of the sun's magnetic field on particles entering the heliosphere. The solar modulation parameter, $\Phi(t)$, 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. The solar modulation parameter, $\Phi(t)$ in MV, is related to the energy and rigidity required for interstellar particles in order to

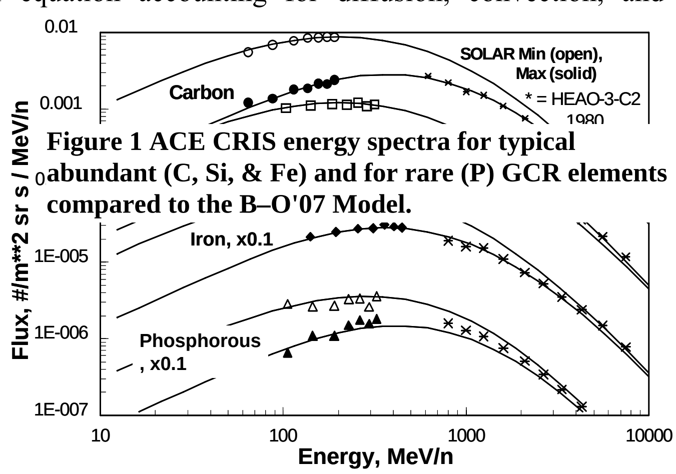

Figure 1 ACE CRIS energy spectra for typical abundant (C, Si, & Fe) and for rare (P) GCR elements compared to the B–O'07 Model.

propagate through the heliosphere to the radius in question (1 AU for Earth, Moon, or Mars).

Z	Element	γ	Avg RMS error(%)
5	Boron	3.0295	7.0
6	Carbon	2.8310	4.4 (14.1)
7	Nitrogen	2.9672	6.0
8	Oxygen	2.8000	4.9 (14.3)
9	Fluorine	2.8779	12.3
10	Neon	2.8220	5.9
11	Sodium	2.7995	7.2
12	Magnesium	2.8280	5.2
13	Aluminum	2.9054	8.5
14	Silicon	2.8265	5.3 (12.7)
15	Phosphorus	2.9844	16.3
16	Sulphur	2.8427	8.8
17	Chlorine	3.0632	14.5
18	Argon	2.9184	12.7
19	Potassium	3.1610	14.2
20	Calcium	2.9060	10.0
21	Scandium	2.9275	13.3
22	Titanium	2.7956	11.0
23	Vanadium	3.0255	14.2
24	Chromium	2.9490	10.9
25	Manganese	2.8015	12.6
26	Iron	2.7752	6.4 (12.1)
27	Cobalt	2.7489	25.9
28	Nickel	2.7146	13.9

Table 1shows the LIS energy power law exponent (γ) derived from solar cycle 23 ACE energy spectra and average RMS error of B-O'07 model for cycle 23

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/).

The Advanced Composition Explorer (ACE) is stationed at the Earth-Sun L1 libration point (about 1.5 million km from earth). The energy spectra for boron through nickel are in the range of highest modulation from roughly 50 to 500 MeV / nucleon. The ACE CRIS geometric factor is 250 cm^2 –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 old satellite instruments were < 10 cm^2-sr.

Since ACE CRIS has operated continuously since 1997, its total collection power provides a unique opportunity to refine our GCR models. Davis et al. [8] estimates the residual systematic uncertainty of the spectra measured by CRIS to be less than 5%.

With the solar modulation parameter, $\Phi_{ACE}(t)$, defined from 1997 to 2007 from the ACE Oxygen data, the value of the LIS energy power law exponent (γ) was determined for the remaining ACE elements (boron to nickel) by fitting the measured energy spectra.

Figure 1 shows typical correspondence between the ACE CRIS measurements and the Badhwar – O'Neill Model. For the more abundant elements (Carbon, Nitrogen, Oxygen, Iron, etc) the model agrees with the data within 4 - 6% RMS. However, some of the elements (Phosphorous, Fluorine, Cobalt, etc) are so rare that even with the high collection efficiency of ACE the data is so spread that it can only be fit with an RMS error of ~15%.

Table 1 shows the results of the γ fit for the new data (2007). Compared to the 2004 data fit, the update had only a minor effect on the LIS power exponent, the change was well below 1% for every element. No other parameters of the model were changed. Table 1 also shows the average RMS error of the B-O'07 model (compared to ACE) for each element for the 10 year period 1997 - 2007. For selected elements the average RMS error is also shown (in parentheses) when the solar modulation parameter derived from the Climax Neutron count (see below) is used instead of the value from ACE Oxygen.

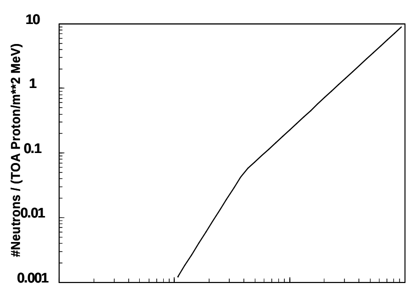

Figure 2 Neutron yield function Y(E) defines the number of neutrons produced in the earth's atmosphere for each incident TOA proton as dependent on proton energy

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

The solar modulation parameter, $\Phi_{ACE}(t)$, based on the ACE CRIS Oxygen (z=8) data provides values of Φ(t) over most of Solar Cycle 23 - from 1997 to 2007. However, values are needed over solar cycles in the past and for future times when ACE may not be available.

Fortunately, the Climax Neutron count is a reliable and accurate source for determining Φ(t). The hourly count is readily available on the internet (http://ulysses.uchicago.edu/) continuously from 1951 to present (and in the future).

The neutron monitor can be treated as if it were an instrument collecting cosmic rays just like ACE. Due to the geomagnetic cutoff, the Climax neutron count mainly depends on the high-energy (above 5 GeV) proton flux at the top of the atmosphere (TOA) and is monotonically related to it. Knowing the GCR proton flux (at 5 GeV) determines the solar modulation parameter because even at 5 GeV there is sufficient variability of the flux to derive $\Phi(t)$.

The TOA proton flux (>5 GeV) is determined from the Climax neutron count and the neutron yield function Y(E) by the integral [7]:

$$\text{Climax Count} = \int \text{TOA Proton Flux}(E)\, Y(E)\, dE$$

The yield function defines the number of neutrons produced in the earth's atmosphere for each incident TOA proton as a function of proton energy - see Figure 2.

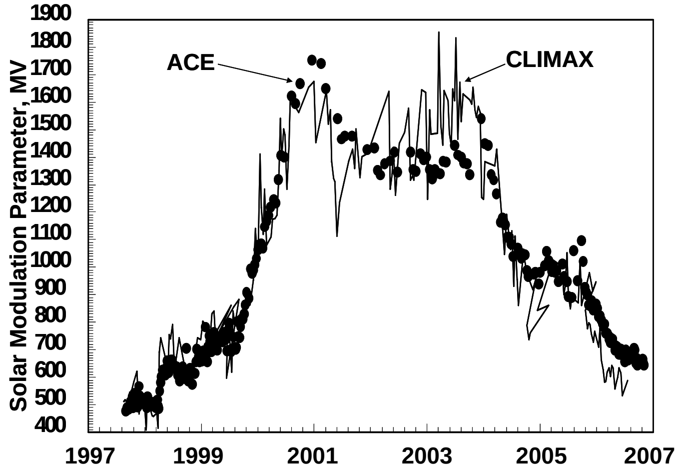

Figure 3Solar modulation parameter derived from the Climax neutron count (line) and ACE CRIS oxygen measurements are correlated

The TOA >5 GeV proton flux defines the value of $\Phi(t)$ for all the Climax measurements to date (since 1951) by simply solving for the value of $\Phi(t)$ that fits the ACE modeled proton flux at 5 GeV. Note that every Forbush Decrease must be manually removed and the hourly Climax count must be accumulated and averaged until sufficient protons are collected to provide a meaningful flux measurement before these calculations are done.

WORST CASE COSMIC RAYS - SOLAR MINIMUM

For deep space missions cosmic ray intensities at solar minimum pose the greatest threat to crew safety [9, 10]. Figure 4 shows the solar modulation parameter derived from the Climax count for the past 56 years. This period shows 6 solar minima at which the GCR flux was maximum. This figure shows that a modulation of 450 MV represents the worst case GCR flux for mission design purposes.

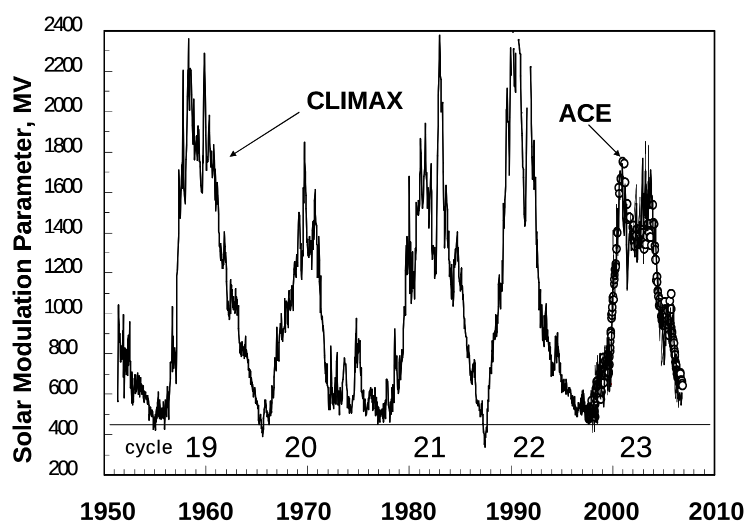

Figure 4 Solar modulation parameter derived from the Climax neutron count (line) and ACE CRIS oxygen measurements. Note that solar minimum has solar modulation of ~450 MV.

CONCLUSION

The updated Badhwar – O'Neill Model is shown to be accurate to about 5%, for the more abundant elements such as Oxygen, Carbon, Iron, etc 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 has been clearly demonstrated [6].

The BO'07 GCR Model provides 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 ~15% (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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