NASA GCR ENVIRONMENT MODEL
Badhwar - O’Neill (2014)

23 Oct., 2015
Solar Energetic Particles (SEP), Solar Modulation and Space Radiation:
New Opportunities in the AMS-02 Era

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INTRODUCTION
FOREWORD

As a foreword, I would like to state that I am presenting on behalf of S. Golge who was unable to attend this workshop; his and T. Slaba's efforts towards the improvement of the Badhwar - O'Neill model have been significant.

Also, a special thanks to P. O'Neill for his ongoing work and support in the development and improvement of the model.
INTRODUCTION

The ionizing nature of Galactic Cosmic Ray (GCR) particles poses a potential health risk for crew members in space, e.g., radiation exposure induced cancer [1].

Another significant concern arises from the interaction of GCR particles with the electronics inside and outside of a spacecraft, e.g., memory bit flips and latch-up, which are generically called Single Event Effects (SEE) [2].

To evaluate the potential risks induced by GCR, the Badhwar-O’Neill (BON) GCR flux simulation model has been developed to numerically solve the Fokker-Planck (FP) equation.
The BON model takes into account diffusion, convection, and adiabatic deceleration within the heliosphere and provides the flux of GCR particles of a given charge, Z, as a function of energy at 1AU in free-space beyond the Earth's magnetosphere.

\[
\frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 V_s U \right) - \frac{1}{3} \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 V_s \right) \right] \left[ \frac{\partial}{\partial T} \left( \alpha TU \right) \right] = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \kappa \frac{\partial U}{\partial r} \right)
\]

where \( r \) is the radial position in units of AU; 
\( T \) is the kinetic energy (MeV/n); 
\( U(r, T) \) is the GCR flux; 
\( V_s(r) \) the solar wind speed (\( \sim 400 \) km/s); 
\( \kappa(r, T) \) the particle diffusion coefficient tensor; 
and \( \alpha(T) = (T + 2E_0)/(T + E_0) \), with \( E_0 \) being the rest energy of the GCR particle.
LOCAL INTERSTELLAR PARAMETERS
At 100 AU, GCR modulation is negligible and therefore a constant GCR field, referred to as the LIS (Local Interstellar) flux spectrum ($U_0$), which represents one of the boundary conditions for BON.

**LIS Flux Spectrum**

$$U_0(Z, T) \big|_{R_b=100\text{ AU}} = j_0(Z)(T_N + E_0)\gamma(Z)\beta_N^{-1}\beta^\delta(Z)(T + E_0)^{-\gamma(Z)}$$

where $j_0$, $\delta$, and $\gamma$ are free parameters for each GCR ion; $\beta = v/c$ is the relative velocity; and $\beta_N$ is the relative velocity at $T_N = 35$ GeV/n (selected arbitrarily for fitting).
The LIS parameters are formulated by using GCR measurement data from detectors at or near 1 AU; e.g., satellite and balloon measurements. In the model, the flux of any ion beyond nickel (Z > 28) is obtained by scaling from the silicon result.

In BON14, the tuning of LIS parameters were influenced by a study that showed that GCR ions in the energy domain between 0.5 GeV/n and 4.0 GeV/n account for most of the exposure to the differential effective dose rate behind 20 g/cm\(^2\) of aluminium shielding [3].

→ This will be discussed more in J. Norbury’s talk - “Impact of AMS-II measurements on reducing GCR model uncertainties".
RESULTS
In this revision of the BON model, BON14, we have included the GCR data beyond 1970, which spans Solar Cycles 20 to 24 (to date).

In the past, the LIS parameters of the BON were uniquely influenced by measurements from the Cosmic Ray Isotope Spectrometer (CRIS) on the NASA Advanced Composition Explorer (ACE) spacecraft.

CRIS is currently measuring the flux of ions and their isotopes from boron (Z=5) to nickel (Z=28), where the lowest and highest kinetic energy measurements are ion specific. CRIS provides kinetic energy of GCR isotopes between ~ 50 - 500 MeV/n.

In BON14, greater emphasis was placed on the higher kinetic energies, a region not covered by CRIS. Nonetheless, we show that the updated model still accurately represents the lower energy regions.
Figure 1: The flux data as a function of kinetic energy for H, He, O, and Fe are shown for all the data used for calibration (this plot excludes ACE/CRIS data).
Figure 2: The differential flux for H ions as a function of energy is shown for various GCR measurements, AMS (1998), IMAX (1992), and PAMELA (2008). Those measurements are compared with BON14 for the same measurement periods. The solid black line (LIS-BON14) represents the LIS flux for H ion at R=100 AU.
Comparison of BON14 with the GCR measurement data was completed by evaluating the relative differences ($R_d$). This metric is used to analyze under- and over-predicting time periods, and to adjust fit parameters.

The average of the residual $R_d$ does not provide a complete picture of the model versus measurement agreement. Therefore, we also used the average absolute relative difference, $|R_d|$, to determine the overall difference between the model and the GCR. This metric better quantifies the overall fit agreement.

$$|R_d| = \frac{1}{N} \sum_{k=1}^{N} \left| \frac{\text{Model}_k - \text{Data}_k}{\text{Data}_k} \right|$$
Figure 3: Although the BON14 parameters were focused more on the GCR energy region between 0.5 – 4.0 GeV/n, we show that the model is in good agreement with CRIS/ACE data as well. In the figure, the 27-day average differential flux for O ions at 230.8 MeV/n from ACE/CRIS (circle) as a function of date is compared with BON14 (solid line). On the right axis their $R_d$ is shown (diamond).
Table 1: The average relative difference metrics between the entire GCR database with BON11 and BON14.

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<th>Average [%]</th>
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<tbody>
<tr>
<td></td>
<td>Rd</td>
<td></td>
<td>Rd</td>
</tr>
<tr>
<td>BON11</td>
<td>17.9</td>
<td>23.7</td>
<td></td>
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<tr>
<td>BON14</td>
<td>-0.4</td>
<td>13.0</td>
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As shown above in Table 1, the BON14 model has been improved significantly with respect to the previous BON model, BON11, both at low- and high-energy regions.
CLOSING REMARKS
CONCLUSION

The comparison of BON14 with an updated set of GCR measurements from various balloon, satellite, and space shuttle measurements is presented.


The new model LIS parameters were fitted with an updated approach based on a sensitivity analysis.

We have seen improvements over BON11 and anticipate significant model improvement in the energy region of interest with hydrogen and helium data when the new GCR measurements are available from AMS-02.
REFERENCES

