AMS1 Secondary Proton Analysis and its Contribution to the ISS Dosimetric Validation

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Three Definitions of Particles at LEO

• **Primary** GCR particles
• **Secondary downward** particles at LEO
• **Secondary upward** particles at LEO

• **Primary** GCR particles are familiar to all of you. There exist at least 10 GCR models of varying complexity and computational efficiency, and I will very briefly discuss three of them.

• **Secondary downward** particles at LEO, are generated by the collision of primary GCR and upper earth atmosphere.

• **Secondary upward** particles at LEO, are generated by the collision of primary GCR and secondary downward particles with the upper Earth atmosphere.
Motivation and Outline

• To **enhance** the physics represented in the existing environmental models at LEO

• Very brief introduction to existing LEO environmental models
• Explain the **AMS1** proton measurement
• Correlate AMS1 proton measurement with the **PAMELA** proton data
• Develop a parametric model for the downward and upward secondary proton spectra at LEO
• **Quantify** the parametric model improvements for the ISS validation work
• Brief Summary
Brief Introduction of the BO/MSU/DLR GCR Models

BO% →
\[
\frac{1}{r^2} \frac{\partial}{\partial r} \left[ r^2 V_s \Phi_i(E,t) \right] - \frac{1}{3} \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 V_s \right) \left[ \frac{\partial}{\partial E} \left( \frac{E + 2E_0}{E + E_0} \right) E \Phi_i(E,t) \right] - \frac{1}{r^2} \frac{\partial}{\partial r} \left[ r^2 \kappa(r, E, t) \frac{\partial}{\partial r} \Phi_i(E,t) \right] = 0
\]

\[\kappa(r, E, t) = \frac{\kappa_0 \beta R(E)}{V_s \phi(t)} \left[ 1 + \left( \frac{r}{r_0} \right)^2 \right]\]

MSU# →
\[\Phi_i(R, t) = \frac{C_i \beta^{\alpha_i}}{R^{\gamma_i}} \left[ \frac{R}{R + R_0(R, t)} \right]^{\Delta_i(R, t)} \]
Inversion of \( \Phi_i(R, t) \rightarrow \Phi_i(E, t) \)

DLR* →
\[\Phi_i(R, t) = \frac{C_i \beta^{\alpha_i}}{R^{\gamma_i}} \left[ \frac{R}{R + R_0(R, t)} \right]^{\Delta_i(R, t)} \]
\[\Delta(t) = c + bW(t)\]
\[W_{oulu} = -0.093NM_{oulu} + 638.7\]

All 3 models are valid at 1 AU outside the Earth geomagnetic field.

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At LEO, are there missing particles due to GCR-atmosphere interaction?
AMS1 Detector

AMS1 payload

STS 91 (last STS flight to Mir)
June 2 - 12, 1998 (10 days)
Perigee/Apogee: 350 - 390 km.
Inclination: 51.7°
Orbital period: 92 min.
FOV=64° (-32° ~ +32°) wrt. Z axis
Z axis offset accuracy=1°
Proton $E_K$ range of 0.1 - 200 GeV
SAA data are excluded
AMS1 Downward/Upward Proton Data - I

AMS1 Downward/Upward Proton Data - II

Downward

Upward

No upward proton measurements Beyond 52°

Two Questions about AMS1 Proton Measurements

Based on AMS1 downward/upward proton measurements, two questions immediately come up:

• Q1: AMS1 was a “proof of concept” simple detector, and acted as a precursor to the far more expensive and much larger AMS2 detector. So, how do you know that AMS1 was functioning properly?

• Q2: Are there any correlation between secondary downward and secondary upward AMS1 proton measurements?
Is the AMS1 Downward Proton Spectra Profile Correct?

June 2 - 12, 1998 (10 days), SAA data are excluded

**AMS1** (Alpha Magnetic Spectrometer 1)

- **Host Satellite**: Resurs DK1 (Soyuz-FG)
- **Data collection**: June 2 - 12, 1998 (10 days)
- **Perigee/Apogee**: 350 - 390 km
- **Inclination**: 51.7°
- **Period**: 92 min.
- **FOV**: 64° (wrt. Z axis) with accuracy of 1°
- **Proton $E_K$ range**: 0.1 - 200 GeV
- **SAA data are excluded**

**PAMELA** (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics)

- **Host Satellite**: Resurs DK1 (Soyuz-FG)
- **Data collection**: June 15, 2006 - present
- **Perigee/Apogee**: 360 - 604 km (~600 km. circular since 2010)
- **Inclination**: 70°
- **Period**: 94 min.
- **FOV**: 60°
- **Proton $E_K$ range**: 0.1 - 70 GeV
- **SAA/SEP data are excluded**

*Only downward ions can be collected by PAMELA*
PAMELA Secondary Downward Proton Spectra Components

Equatorial region

Short lived

Long lived

July 2006 - September 2009 (~800 days)
Downward proton, SAA/SEP data are excluded

Adriani, O., et al. (2015), Reentrant albedo proton fluxes measured by the PAMELA experiment, Journal of Geophysical Research: Space Physics, 0.1102/2015JA021019
AMS1 Downward Proton vs. PAMELA Proton Spectrum

AMS1*

PAMELA #

June 2 - 12, 1998 (10 days)
Downward proton, SAA data are excluded

July 2006 - September 2009 (~800 days)
Downward proton, SEP/SAA data are excluded


AMS1 Downward/Upward Proton Data Correlation

Downward

Upward

No upward proton measurements Beyond 52°

AMS1 Downward/Upward Proton Data Correlation - I

AMS1 Downward/Upward Proton Data Correlation - II

AMS1 Downward/Upward Proton Data Correlation - III

Criteria for Parameterization of AMS1 Downward Protons

- $0 < \lambda_m < 23$
- $23 < \lambda_m < 40$
- $40 < \lambda_m < 63$
Criteria for Parameterization of AMS1 Upward Protons

- $0 < \lambda_m < 23$
- $23 < \lambda_m < 40$
- $40 < \lambda_m < 57$
Primary GCR Proton at LEO vs. Magnetic Latitude

DLR model was used to generate the GCR spectra

Flux is converted from $\text{#/}(\text{MeV-m}^2\cdot\text{s-sr})$ to $\text{#/}(\text{MeV-cm}^2\cdot\text{day})$
Flux is converted from \(\text{#/}(\text{MeV-m}^2\text{-s-sr.})\) to \(\text{#/}(\text{MeV-cm}^2\text{-day})\)
Flux is converted from $\#/(\text{MeV-m}^2\cdot\text{s-sr})$ to $\#/(\text{MeV-cm}^2\cdot\text{day})$
US Lab REM Detector Location

- Update CAD model
- Find detector location within CAD model
- Ray-trace ISS at detector location to extract shielding thickness around detector
Calculation Results – US Lab Dose Rate

Dose Rate in Silicon, Nov. 16, 2013

- SAA Passes
- N-S high latitude region
- Equatorial region
Average Dose Rate (2 minute bins)

Dose Rate in Silicon, Nov. 16, 2013

Measured (2 min. averaged) Calculated
US Lab REM Dose Rate Data vs. Model

Coverage: Nov. 16-25, 2013
US Lab REM Validation Improvement

Coverage: Nov. 16-25, 2013

Issue to consider:

We mixed/matched 1998/2013 epochs.
Parameterization was from 1998 (AMS1)
ISS data was from 2013
Epoch Correlation between AMS1 and ISS Measurement

Summary and Future Work

• Used **AMS1** downward/upward and **PAMELA** data to show the existence of a low energy secondary particle component at LEO due to GCR-atmosphere interactions (only protons were discussed)

• From AMS1 data, provided a parametric model to account for the downward/upward production of secondary protons at LEO

• **Quantified** how the parametric model improved the ISS validation work

• Over all, we improved ISS validation by <10%

• To improve the ISS validation further, we must consider incorporating time dependency (i.e. accessing PAMELA, AMS2 data)
Back up
Criteria for Parameterization of AMS1 Data

- Accurate parameterization of the upward/downward AMS1 data, accounting for all magnetic latitudes ($\lambda_m$) and energies (yellow ovals)

- Meaningful representation of high energy roll off (blue ovals)

- A “good guess” representation of low energy roll off (green ovals). Note, while low energy roll off functional form is rather arbitrary, it can not behave like a neutron spectrum
GCR Blockage due to Earth Shadow

The graph illustrates the function $\beta(h)$, representing GCR blockage as a function of altitude $h$, measured in kilometers. The black line corresponds to $\beta(h)$, and the red line represents $\beta'(h)$. The ISS altitude is indicated by a vertical blue line at the point where $h = h_{\text{ISS}}$. As altitude increases, the blockage decreases, approaching a limiting value indicated by $4\pi$ at high altitudes.
Parameterization of Downward Proton

AMS1 data

\[
\begin{align*}
(\lambda_m &\leq 12^\circ) \quad F(E) &= E^{-a} e^{b-cE} \\
(\lambda_m &> 12^\circ) \\
(E &< 185 \text{ MeV}) \quad F(E) &= e^{[a+b(\log E)]} \\
(E &\geq 185 \text{ MeV}) \quad F(E) &= e^{[a+b(\log E)+c(\log E)/\log(\log(E))]} 
\end{align*}
\]

Low \(E\) (MeV) roll off  
\[
F(E) = 1 - e^{-(E/50)^4}
\]

High \(E\) (MeV) roll off  
\[
F(E) = e^{-(E/10000)^2}
\]
HZETRN Transport Procedure

BC₁ = LEO primary GCR + Downward

BC₂ = Upward (splash)

BC₁ → HZETRN → Dose₁

BC₂ → HZETRN → Dose₂
Model Comparison of US Lab REM Dose Rates (New vs. Old)

Coverage: Nov. 16-25, 2013
What About Trapped Protons?
PAMELA Definitions

- Events with trajectories similar to those of stably trapped protons, but originated and reabsorbed by the atmosphere during a time shorter than a few drift periods, were identified as quasi-trapped (QT)

- Precipitating protons (UT$_s$) with lifetimes shorter than a bounce period. Corresponding $\omega_{\text{bounce}}$ values are similar to those of quasi-trapped protons, while $\omega_{\text{gyro}}$ distribution is much broader outside the SAA, extending to much lower values

- Pseudotrapped protons (UT$_l$) with relatively long lifetimes. They are characterized by large gyroradii and $\omega_{\text{drift}}$, and by small $\omega_{\text{gyro}}$ and $\omega_{\text{bounce}}$ values, resulting in unstable trajectories due to resonances occurring between component frequencies. They can perform several drift cycles (up to a few hundreds) reaching large distances from the Earth’s surface, sometimes forming intermediate loops, before they are reabsorbed by the atmosphere