Recent GCR Models Compared to AMS Data

John W. Norbury\textsuperscript{1}, Kathryn Whitman\textsuperscript{2}, Kerry Lee\textsuperscript{2}, Tony C. Slaba\textsuperscript{1}, Francis F. Badavi\textsuperscript{3}

\textsuperscript{1} NASA Langley Research Center, Hampton, Virginia, USA
\textsuperscript{2} NASA Johnson Space Center, Houston, Texas, USA
\textsuperscript{3} Old Dominion University, Norfolk, Virginia, USA

April 23 - 26, 2018
Abbreviations

- ACE - CRIS = Advanced Composition Explorer - Cosmic Ray Isotope Spectrometer
- AMS = Alpha Magnetic Spectrometer
- DLR = Deutsches Zentrum für Luft (German Aerospace Center)
- GCR = Galactic Cosmic Ray
- ISO = International Standardization Organization
- SINP = Skobeltsyn Institute of Nuclear Physics
- SPENVIS = SPace ENVironment Information System
**Intro. AMS & dark matter - Antimatter \((e^+, p^-)\)**

**Universe**
- Ordinary Matter 5%
- Dark Matter (DM) 20%
  - Most viable particle = Neutralino
    - Lightest Supersymmetric Particle (LSP) = Weakly Interacting Massive Particle (WIMP)
- Dark Energy 75%

**\(e^+, p^-\) prime targets for indirect detection of Galactic DM**

**Possible sources of \(e^+, p^-\)**
- Primary Production:
  - Annihilation of DM particles
  - Evaporation of Primordial black holes
  - Kaluza-Klein particles (=WIMP)
  - Pulsar, Supernova remnant, Microquasar
- Secondary production:
  - \(pp\) collisions (GCR with protons in Interstellar medium)
**Intro. AMS & Dark Matter - Antimatter ($e^+, p^-$)**

**PAMELA (satellite)**
- Payload for AntiMatter Exploration & Light nuclei Astrophysics
- $p^-$ consistent with secondary production
- Excess of $e^+$ (1 - 100 GeV) (DM?)

**ATIC (balloon Antarctica)**
- Advanced Thin Ionization Chamber
- Excess of $e^{+−}$ (300 - 700 GeV)
  - $e^{+−}$ = “electrons” (can’t distinguish charge)

---

**Antiproton to proton flux**

Adriani et al., Phys. Rev. Lett. 102, 051101, 2009
AMS confirms positron excess

- Differences at low energy - due to solar modulation during the different time periods that the data sets were taken
- Grey band: $pp \rightarrow \pi \rightarrow e^+$ in galaxy

The positron fraction in high-energy cosmic rays. The new measurement from the AMS extends over a wider energy range and has much lower uncertainty than the earlier measurements from the PAMELA and Fermi-LAT satellites (or older balloon experiments). The AMS measurement confirms an excess in the high-energy positron fraction, above what is expected from positrons produced in cosmic-ray interactions. The grey band indicates the expected range in the positron fraction.

PRIMARY (H, He, C, N, O ...) VS. SECONDARY (Li, Be, B) GCR

- Big Bang fusion
- Cosmic ray fission
- Dying low-mass stars
- Merging neutron stars
- Exploding massive stars
- Exploding white dwarfs


JOHN NORBURY (NASA LANGLEY)
GCR MODELS & AMS DATA
APRIL 23 - 26, 2018

Wikipedia: Cmglee
Data: Jennifer Johnson (OSU)

PRIMARY (H, He, C, N, O ...) VS. SECONDARY (Li, Be, B) GCR

C produced & accelerated in astrophysical sources

B entirely produced by collision of heavier nuclei (C, O, etc.) with interstellar medium

B/C ratio measures amount of interstellar material traversed

Aguilar et al., Phys. Rev. Lett. 117, 231102, 2016; 120, 021101, 2018

Positron excess discovered by AMS


- Consistent with Dark Matter particle (Neutralino) with mass 1 TeV
- Dark Matter or Pulsars?
- Very high energy measurements underway - behaviour of fall-off after maximum will provide definitive signature
**INTRODUCTION - AMS & SPACE RADIATION**

- Sensitivity studies for GCR environmental modeling:
  - A variety of sensitivity studies have been performed to quantify relative importance of specific ions and energies in the GCR spectrum to exposure behind shielding and tissue Slaba et al., Space Weather 12, 217, 2014
  - Highly efficient methods have been developed to propagate GCR model uncertainty into exposure quantities behind shielding Slaba et al., Space Weather 12, 217, 2014
  - These efforts led to automated procedures that were subsequently used to refine GCR model parameters and significantly reduce uncertainties O’Neill et al., NASA TP 2015-218569
  - These quantitative assessments were used to inform and define requirements for obtaining new and highly significant measurements from the Alpha Magnetic Spectrometer (AMS-2) detector on the International Space Station (ISS). This updated GCR model has now been integrated with NASA cancer risk model.

An important realization from these studies has been that **90% of the effective dose is contributed from GCR energies above 250 MeV/n**, which is the upper energy limit of the Advanced Composition Explorer / Cosmic Ray Isotope Spectrometer (ACE/CRIS) satellite, which has contributed to most of the GCR data

- Higher energy data are needed, which is why the AMS-2 measurements are so important
I N T R O D U C T I O N - A M S & S P A C E R A D I A T I O N

Introduction

GCR ion in free space before propagating into any shielding material. The contribution from each ion and boundary energy to effective dose depends directly on the shielding material, shielding thickness, and solar conditions. Therefore, the sensitivity analysis is performed for different shielding materials, shielding thickness, and solar conditions.

Throughout this section, it is important to remember that the ions and energies being discussed refer to the energy of each ion before impinging on any shielding material. The discussion should not be confused with the local particles and energies depositing energy at the tissue site. The intent of this analysis and discussion is to determine how exposure quantities depend on the GCR field before interacting with shielding materials or human tissue.

The quantity that describes effective dose as a function of boundary ion energy may be written as

$$h_Z(E_B) \equiv \frac{\partial H_Z(E_B)}{\partial E_B}$$

where $E_B$ is the boundary energy and $H_Z$ and $h_Z$ are the cumulative and differential effective dose rates as a function of boundary kinetic energy for GCR ion $Z$. The cumulative effective dose rate, $H_Z(E_B)$, is the effective dose delivered by boundary energies greater than $E_B$ from GCR ion $Z$. The differential effective dose rate is simply the derivative of $H_Z$ with respect to $E_B$.

Monte Carlo transport codes are, in principle, well suited to simulate the quantity in equation (1), since contributions to specific exposure quantities can be directly tallied as a function of the radiation type and energy impinging on the shielding geometry. However, in practice, performing the full sensitivity analysis for each GCR ion and boundary energy and a range of shielding thicknesses and materials is computationally expensive. An alternative approach utilizing HZETRN-π [Wilson et al., 1991; Slaba et al., 2010b, 2010c; Norman et al., 2013] is implemented in this work. The numerical procedure and computational tools used to express effective dose as a function of boundary energy for each GCR ion is described in Appendix A.

For all calculations in the sensitivity study, effective dose is computed using the International Commission on Radiological Protection (ICRP) 60 quality factor [International Commission on Radiological Protection (ICRP), 1990] and ICRP 103 tissue weights [ICRP, 2007] with the FAX (Female Adult Voxel) human phantom [Kramer et al., 2004] as described by Slaba et al. [2010a]. Radiation transport has been performed using the HZETRN-π/EM code. The BON2010 [Neill, 2010] model was used to evaluate the GCR spectrum for solar minimum and solar maximum conditions, and October 1976 and June 2001 were used as representative dates for solar minimum and maximum, respectively. These dates were chosen to bound the range of solar conditions that might occur. One would not expect the relative importance of specific ions and energy
**Rigidity**

\[ r_G = \text{GYRO-RADIUS}, \quad Q = Ze = \text{CHARGE} \]

\[ R \equiv \frac{|p|c}{Q} \equiv r_G B \]

- Particles of same rigidity have same path in magnetic field
- Same gyro-radius \( r_G \) (radius of circular motion if circle \( \perp \) to B)

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>R (GV)</th>
<th>KE (MeV/n)</th>
<th>KE (GeV/n)</th>
<th>R (GV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^1\text{H})</td>
<td>1</td>
<td>433</td>
<td>1</td>
<td>1.7</td>
</tr>
<tr>
<td>(^4\text{He})</td>
<td>1</td>
<td>125</td>
<td>1</td>
<td>3.4</td>
</tr>
<tr>
<td>(^{16}\text{O})</td>
<td>1</td>
<td>125</td>
<td>1</td>
<td>3.4</td>
</tr>
<tr>
<td>(^{56}\text{Fe})</td>
<td>1</td>
<td>109</td>
<td>1</td>
<td>3.6</td>
</tr>
</tbody>
</table>
HYDROGEN (H) → primary GCR
May 19, 2011 – November 26, 2013

HELUM (He) → primary GCR
May 19, 2011 – November 26, 2013

BORON / CARBON (B/C) ratio
May 19, 2011 – May 26, 2016

HELUM (He), CARBON (C), OXYGEN (O) → primary GCR
May 19, 2011 – May 26, 2016

LITHIUM (Li), BERYLLIUM (Be), BORON (B) → secondary GCR
Li/C, Be/C, B/C, Li/O, Be/O, B/O, Li/B, Be/B ratios
May 19, 2011 – May 26, 2016
Aguilar et al., Phys. Rev. Lett. 120, 021101, 2018
Scaled flux (right) emphasizes high energy shape

Famous break near 300 GV

Spectrum much harder than previous measurements

Previous measurements lie higher after break - i.e. softer
AMS & OTHER DATA: HYDROGEN FLUX VS. RIGIDITY

AMS data harder than previous high energy measurements
AMS DATA: HELIUM (PRIMARY) FLUX VS. RIGIDITY

Scaled flux (right) emphasizes high energy shape

Another famous break at same rigidity near 300 GV

Both H and He have similar break at same rigidity
Scaled flux (right) emphasizes high energy shape

Another famous break at same rigidity near 300 GV

Both H and He have similar break at same rigidity
AMS & other data: Helium flux vs. rigidity

AMS data harder than previous high energy measurements

AMS DATA: CARBON (PRIMARY) FLUX VS. RIGIDITY

Scaled flux (right) emphasizes high energy shape

Similar break near 200 GV
AMS DATA: OXYGEN (PRIMARY) FLUX VS. RIGIDITY

Scaled flux (right) emphasizes high energy shape

Similar break near 200 GV
Scaled flux (right) emphasizes high energy shape
Secondary GCR spectra harder than primary spectra
AMS DATA: BERYLLIUM (SECONDARY) FLUX VS. RIGIDITY

Scaled flux (right) emphasizes high energy shape
Secondary GCR spectra harder than primary spectra
Scaled flux (right) emphasizes high energy shape

Secondary GCR spectra harder than primary spectra
AMS & other data for B/C ratio

Theoretical model (dashed line) explaining AMS $e^+$ & $p^-$ results by secondary production ruled out by B/C data

AMS measurements of primary cosmic rays, H, He, C, O show spectral hardening above 200 GV.

Above 60 GV, the He, C, and O spectra found to have identical rigidity dependence.

If spectral hardening related to injected spectra at source, then similar hardening expected for both primaries & secondaries.

But, if hardening related to propagation in Galaxy then stronger hardening expected for secondaries compared to primaries.

“'No theoretical model predicted the observed spectral behavior of either the primary or secondary cosmic rays seen with AMS’???

Aguilar et al., Phys. Rev. Lett. 120, 021101, 2018
Four models will be compared to AMS data:

- **Badhwar - O’Neill (BON14) model**

- **DLR model**

- **SINP model**
  Kuznetsov, Popova, Panasyuk, J. Geophys. Res. Space Phys. 115, 1463, 2017

- **ISO15390 model - taken from SPENVIS**
  Nymmik et al., Adv. Space Res. 17, 19, 1996
RESULTS: HYDROGEN FLUX VS. KINETIC ENERGY

Model comparisons to data
RESULTS: HYDROGEN FLUX VS. KINETIC ENERGY

Model comparisons to data - linear plot
Results: Hydrogen Flux (Scaled) vs. Kinetic Energy

Model comparisons to scaled data
RESULTS: HELIUM FLUX VS. KINETIC ENERGY

Model comparisons to data
RESULTS: HELIUM FLUX VS. KINETIC ENERGY

Model comparisons to data - linear plot
RESULTS: HELIUM FLUX (SCALED) VS. KINETIC ENERGY

Helium (2011May19–2016May26)

Model comparisons to scaled data
RESULTS: CARBON FLUX VS. KINETIC ENERGY

Model comparisons to data
RESULTS: CARBON FLUX VS. KINETIC ENERGY

Model comparisons to data - linear plot
RESULTS: CARBON FLUX (SCALED) VS. KINETIC ENERGY

Model comparisons to scaled data

Carbon (2011May19–2016May26)

Flux x KE$^{2.7}$ [m$^{-2}$ sr$^{-1}$ s$^{-1}$ (GeV/n)$^{1.7}$]

Kinetic Energy [GeV/n]

DATA
BON14
DLR
SINP
ISO

Model comparisons to scaled data
RESULTS: OXYGEN FLUX VS. KINETIC ENERGY

Model comparisons to data
RESULTS: OXYGEN FLUX VS. KINETIC ENERGY

Model comparisons to data - linear plot
RESULTS: OXYGEN FLUX (SCALED) VS. KINETIC ENERGY

Model comparisons to scaled data
RESULTS: B/C RATIO VS. KINETIC ENERGY

Boron/Carbon (2011May19–2016May26)

Model comparisons to data - linear plot

DATA
BON14
DLR
SINP
ISO
Model comparisons to data
RESULT: LITHIUM FLUX VS. KINETIC ENERGY

Model comparisons to data - linear plot
**RESULTS: LITHIUM FLUX (SCALED) VS. KINETIC ENERGY**

Model comparisons to scaled data

Models show spectral hardening for secondaries vs. primaries
RESULTS: BERYLLIUM FLUX VS. KINETIC ENERGY

Model comparisons to data
RESULTS: BERYLLIUM FLUX VS. KINETIC ENERGY

Model comparisons to data - linear plot
RESULTS: BERYLLIUM FLUX (SCALED) VS. KINETIC ENERGY

Model comparisons to scaled data
Models show spectral hardening for secondaries vs. primaries
RESULTS: BORON FLUX VS. KINETIC ENERGY

![Graph showing model comparisons to data for Boron flux vs. kinetic energy.](image)

Model comparisons to data
RESULTS: BORON FLUX VS. KINETIC ENERGY

Model comparisons to data - linear plot
**RESULTS: BORON FLUX (SCALED) VS. KINETIC ENERGY**

- **Boron (2011May19–2016May26)**

Model comparisons to scaled data

Models show spectral hardening for secondaries vs. primaries
RESULTS: SUMMARY PLOTS

Next 3 pages show all plots on single slides, for inter-comparison
Hydrogen (2011May19–2013Nov26)

Helium (2011May19–2016May26)

Carbon (2011May19–2016May26)

Oxygen (2011May19–2016May26)

Lithium (2011May19–2016May26)

Beryllium (2011May19–2016May26)

Boron (2011May19–2016May26)
AMS data of sufficiently high quality to distinguish between different models for both primary & secondary spectra

Low energy behavior $< 20$ GeV (space radiation region)
- ISO model shows largest deviations (except for Li)
- BON14, DLR, SINP similar for primary ions (He, C, O)
- SINP under-predicts secondary ions (Li, Be, B)
  (Due to He scaling? Better to scale secondaries to Li?)
- SINP cannot predict GCR ratios as function of energy
  (Because all heavy ion fluxes are simply He scaled by a constant factor)

High energy TeV behavior (not important for space radiation)
- General comparisons of models to data not good

Month by month data would be very useful
ACKNOWLEDGEMENTS

Thanks to

Claudio Corti – University of Hawaii
Veronica Bindi – University of Hawaii
Daniel Matthia – German Aerospace Center (DLR)
Nikolay Kuznetsov – Skobeltsyn Institute of Nuclear Physics (SINP)

Work supported by Advanced Exploration Systems (AES) Division under Human Exploration & Operations Mission Directorate of NASA
THE END

john.w.norbury@nasa.gov