Solar Energetic Particles, Solar Modulation and Space Radiation
New Opportunities in the AMS-2 Era
Meeting # 2
Washington D.C., USA

COMPARING SPACE RADIATION GCR MODELS WITH AMS-2 DATA

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ABBREVIATIONS

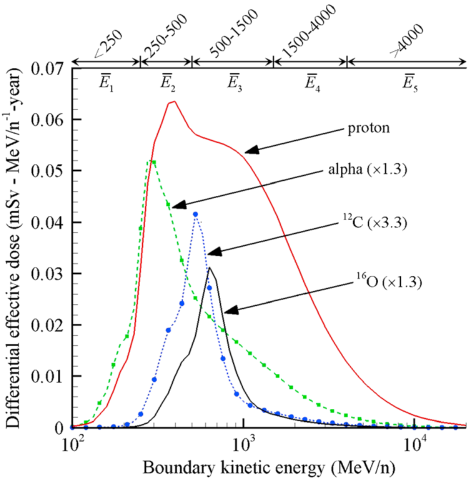
- ACE - CRIS = Advanced Composition Explorer - Cosmic Ray Isotope Spectrometer
- AMS = Alpha Magnetic Spectrometer
- DLR = Deutsches Zentrum für Luft (German Aerospace Center)
- GCR = Galactic Cosmic Ray
- ISO = International Standardization Organization
- SPENVIS = SPace ENVironment Information System

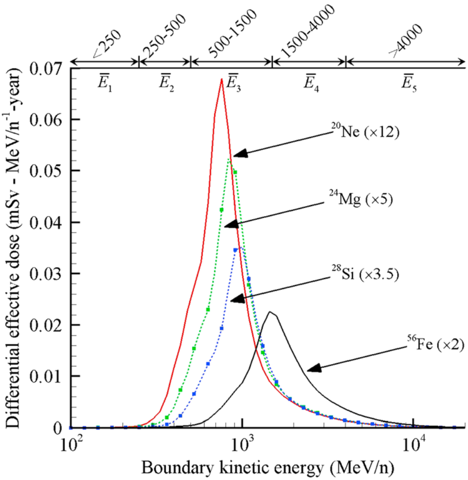
Outline

INTRODUCTION

- 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

INTRODUCTION





Effective dose contributions as a function of energy

Slaba & Blattnig, Space Weather 12, 217, 2014

extracted from – Aguilar et al., Phys. Rev. Lett. 114, 171103, 2015

TABLE I: The proton flux Φ as a function of rigidity at the top of AMS in units of $[\mathrm{m}^2 \cdot \mathrm{sr} \cdot \mathrm{s} \cdot \mathrm{GV}]^{-1}$ including errors due to statistics (stat.); contributions to the systematic error from the trigger (trig.); acceptance, background contamination, geomagnetic cutoff, and event selection (acc.); the rigidity resolution function and unfolding (unf.); and the absolute rigidity scale (scale); and the total systematic error (syst.).

Rigidity [GV]	Φ	$\sigma_{\text{stat.}}$	$\sigma_{\text{trig.}}$	$\sigma_{\text{acc.}}$	$\sigma_{\text{unf.}}$	σ_{scale}	$\sigma_{\text{syst.}}$
1.00 – 1.16	(6.269	0.008	0.012	0.249	0.087	0.015	$0.268) \times 10^2$
1.16 – 1.33	(6.625	0.004	0.011	0.206	0.086	0.013	$0.226) \times 10^2$
1.33 – 1.51	(6.432	0.004	0.007	0.158	0.077	0.008	$0.177) \times 10^2$
1.51 – 1.71	(6.059	0.003	0.006	0.134	0.068	0.004	$0.151) \times 10^2$
1.71 – 1.92	(5.544	0.002	0.005	0.110	0.059	0.002	$0.126) \times 10^2$
1.92 – 2.15	(4.993	0.002	0.004	0.090	0.051	0.001	$0.104) \times 10^2$
2.15 – 2.40	(4.420	0.002	0.004	0.073	0.043	0.003	$0.085) \times 10^2$
2.40 – 2.67	(3.878	0.001	0.003	0.059	0.037	0.004	$0.069) \times 10^2$

⋮

extracted from – Aguilar et al., Phys. Rev. Lett. 115, 211101, 2015

TABLE I: The helium flux Φ as a function of rigidity at the top of AMS in units of $[\mathrm{m}^2 \cdot \mathrm{sr} \cdot \mathrm{s} \cdot \mathrm{GV}]^{-1}$ including errors due to statistics (stat.); contributions to the systematic error from the trigger (trig.); geomagnetic cutoff, acceptance, and background contamination (acc.); the rigidity resolution function and unfolding (unf.); and the absolute rigidity scale (scale); and the total systematic error (syst.).

Rigidity [GV]	Φ	$\sigma_{\text{stat.}}$	$\sigma_{\text{trig.}}$	$\sigma_{\text{acc.}}$	$\sigma_{\text{unf.}}$	σ_{scale}	$\sigma_{\text{syst.}}$	
1.92 – 2.15	(6.031	0.007	0.002	0.106	0.054	0.012	0.120	)$\times 10^1$
2.15 – 2.40	(5.657	0.006	0.001	0.087	0.046	0.008	0.098	)$\times 10^1$
2.40 – 2.67	(5.174	0.005	0.001	0.073	0.036	0.004	0.082	)$\times 10^1$
2.67 – 2.97	(4.694	0.004	0.001	0.063	0.031	0.003	0.070	)$\times 10^1$
2.97 – 3.29	(4.176	0.004	0.001	0.055	0.026	0.004	0.061	)$\times 10^1$
3.29 – 3.64	(3.650	0.003	0.001	0.048	0.022	0.005	0.053	)$\times 10^1$
3.64 – 4.02	(3.145	0.003	0.001	0.041	0.018	0.005	0.045	)$\times 10^1$
4.02 – 4.43	(2.671	0.002	0.001	0.035	0.014	0.005	0.038	)$\times 10^1$

⋮

extracted from – Aguilar et al., Phys. Rev. Lett. 117, 231102, 2016

TABLE SM I: The boron to carbon flux ratio (B/C) as a function of rigidity including errors due to statistics (stat.), contributions to the systematic error from the backgrounds subtraction (back.), the trigger and the acceptance calculation (acc.), the unfolding procedure and the rigidity resolution function (unf.), the absolute rigidity scale (scale), and the total systematic error (syst.).

Rigidity [GV]	(B/C)	$\sigma_{\text{stat.}}$	$\sigma_{\text{back.}}$	$\sigma_{\text{acc.}}$	$\sigma_{\text{unf.}}$	σ_{scale}	$\sigma_{\text{syst.}}$
1.92 – 2.15	0.2994	0.0018	0.0012	0.0128	0.0014	0.0002	0.0129
2.15 – 2.40	0.3098	0.0017	0.0012	0.0123	0.0013	0.0001	0.0124
2.40 – 2.67	0.3143	0.0015	0.0011	0.0119	0.0012	0.0001	0.0120
2.67 – 2.97	0.3173	0.0014	0.0011	0.0115	0.0012	0.0001	0.0116
2.97 – 3.29	0.3212	0.0013	0.0011	0.0111	0.0012	0.0001	0.0112
3.29 – 3.64	0.3230	0.0013	0.0011	0.0107	0.0011	0.0000	0.0108
3.64 – 4.02	0.3251	0.0013	0.0011	0.0103	0.0010	0.0000	0.0104
4.02 – 4.43	0.3243	0.0012	0.0011	0.0098	0.0010	0.0000	0.0099

⋮

extracted from – Aguilar et al., Phys. Rev. Lett. 117, 231102, 2016

TABLE SM II: The boron to carbon flux ratio (B/C) as a function of kinetic energy including errors due to statistics (stat.), contributions to the systematic error from the backgrounds subtraction (back.), the trigger and the acceptance calculation (acc.), the unfolding procedure and the rigidity resolution function (unf.), the absolute rigidity scale (scale), the error associated to rigidity to kinetic energy conversion due to uncertainties in the boron isotopic composition (conv.), and the total systematic error (syst.).

E_K [GeV/n]	(B/C)	$\sigma_{\text{stat.}}$	$\sigma_{\text{back.}}$	$\sigma_{\text{acc.}}$	$\sigma_{\text{unf.}}$	σ_{scale}	$\sigma_{\text{conv.}}$	$\sigma_{\text{syst.}}$
0.406 – 0.491	0.3210	0.0018	0.0013	0.0149	0.0015	0.0001	0.0031	0.0154
0.491 – 0.588	0.3251	0.0017	0.0012	0.0142	0.0013	0.0000	0.0033	0.0147
0.588 – 0.696	0.3214	0.0015	0.0012	0.0134	0.0012	0.0000	0.0035	0.0140
0.696 – 0.821	0.3213	0.0014	0.0011	0.0128	0.0012	0.0000	0.0036	0.0134
0.821 – 0.959	0.3188	0.0013	0.0011	0.0122	0.0011	0.0001	0.0037	0.0128
0.959 – 1.11	0.3174	0.0012	0.0011	0.0115	0.0010	0.0001	0.0038	0.0123
1.11 – 1.28	0.3142	0.0012	0.0011	0.0109	0.0009	0.0001	0.0039	0.0117
1.28 – 1.47	0.3082	0.0011	0.0011	0.0102	0.0009	0.0001	0.0040	0.0110
1.47 – 1.68	0.3060	0.0010	0.0011	0.0096	0.0008	0.0001	0.0041	0.0105

⋮

RIGIDITY r_G = GYRO-RADIUS, $Q = Ze$ = CHARGE

$$R \equiv \frac{|\mathbf{p}|c}{Q} \equiv r_G B$$

- Particles of same rigidity have same path in magnetic field
- Same gyro-radius r_G (radius of circular motion if circle $\perp$ to B)
- 1 GeV/n particle has R = 1 GV [GV $\equiv$ giga-volt]

Conversion of AMS data

$E \equiv$ total energy, $T \equiv$ kinetic energy, $\mathbf{p} \equiv$ 3-momentum,
$m \equiv$ mass, $c \equiv$ speed of light

$$
\begin{aligned}
E &\equiv T + mc^2 \\
E^2 &= (|\mathbf{p}|c)^2 + (mc^2)^2 = (T + mc^2)^2 \\
&= (RQ)^2 + (mc^2)^2
\end{aligned}
$$

$$
T = \sqrt{(RQ)^2 + (mc^2)^2} - mc^2
$$

$$
R = \frac{1}{Q}\sqrt{T(T + 2mc^2)}
$$

AMS data is differential rigidity flux:

$$\frac{dF}{dR} \ (\mathrm{m}^2 \ \mathrm{sr} \ \mathrm{s} \ \mathrm{GV})^{-1}$$

Want to convert to differential kinetic energy flux:

$$\frac{dF}{dT} \ (\mathrm{m}^2 \ \mathrm{sr} \ \mathrm{s} \ \mathrm{GeV})^{-1}$$

$$\frac{dF}{dT} = \frac{dF}{dR}\frac{dR}{dT}$$

CONVERSION OF AMS DATA

$$\frac{dF}{dT} = \frac{dF}{dR}\frac{dR}{dT}$$

$$\frac{dR}{dT} = \frac{T + mc^2}{Q\sqrt{T(T + 2mc^2)}} = \frac{1 + mc^2/T}{Q\sqrt{1 + 2mc^2/T}}$$

$$\frac{dR}{dT} \approx \frac{1}{Q} \quad \text{for} \quad T >> mc^2$$

$$\text{For protons :} \quad \frac{dR}{dT} \approx 1 \quad \Rightarrow \frac{dF}{dT} \approx \frac{dF}{dR}$$

Summary: Conversion of AMS data

Conversion of Rigidity to Kinetic Energy (x-axis)

$$T = \sqrt{(RQ)^2 + (mc^2)^2} - mc^2$$

Conversion of Differential Flux (y-axis)

$$\frac{dF}{dT} = \frac{T + mc^2}{Q\sqrt{T(T + 2mc^2)}} \frac{dF}{dR}$$

Summary: Conversion of AMS data

m = total mass of particle, A = mass number
T = total kinetic energy (KE) of particle, units GeV
$\tilde{T}$ = KE of particle, units GeV/n, $\quad T = A\tilde{T}$

Conversion of Rigidity to $\tilde{T}$ (x-axis)

$$\tilde{T} = \left[\sqrt{(RQ)^2 + (mc^2)^2} - mc^2 \right] / A$$

Conversion of Differential Flux (y-axis)

$$\frac{dF}{d\tilde{T}} = A \frac{A\tilde{T} + mc^2}{Q\sqrt{A\tilde{T}(A\tilde{T} + 2mc^2)}} \frac{dF}{dR}$$

Conversion of AMS data: the easy AMS way!

$$\frac{dF}{dT} = \frac{dF}{dR}\frac{dR}{dT}$$

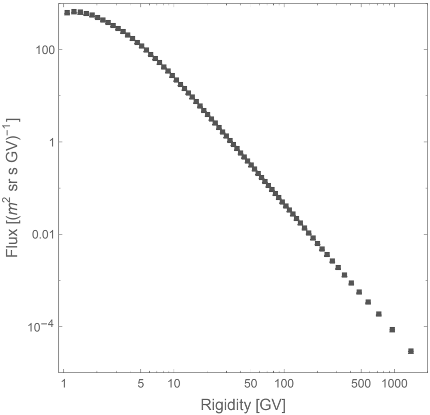
$$\approx \frac{dF}{dR}\frac{\Delta R}{\Delta T} = \frac{dF}{dR}\frac{R_{\text{high}} - R_{\text{low}}}{T_{\text{high}} - T_{\text{low}}}$$

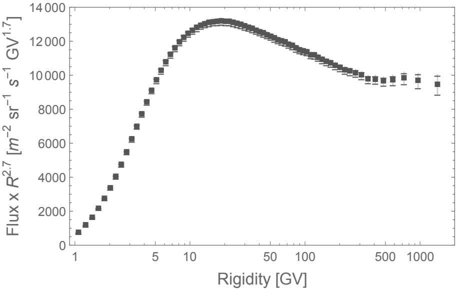
RESULTS

Four models will be compared to AMS data:

- Badhwar - O'Neill (BON14) model
  O'Neill, Golge, Slaba, NASA Tech. Paper 218569, 2015
- DLR model
  Matthia et al., Adv. Space Res. 51, 329, 2013
- ISO15390 model - taken from SPENVIS
  Nymmik et al., Adv. Space Res. 17, 19, 1996
- CREME96 model - taken from SPENVIS
  Tylka et al., IEE Trans. Nucl. Sci. 44, 2150, 1997

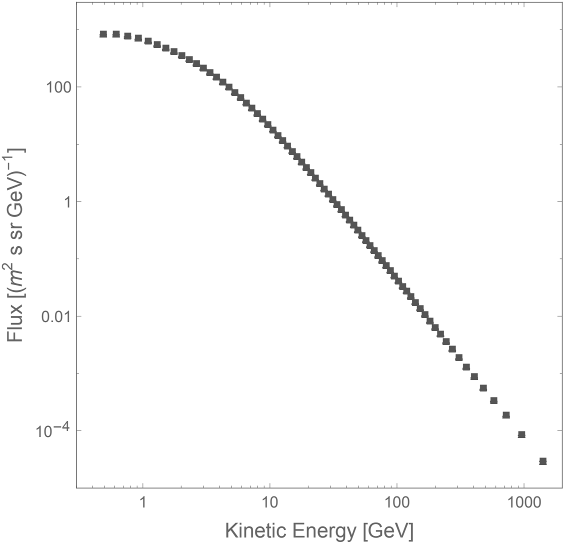
RESULTS: HYDROGEN FLUX VERSUS RIGIDITY





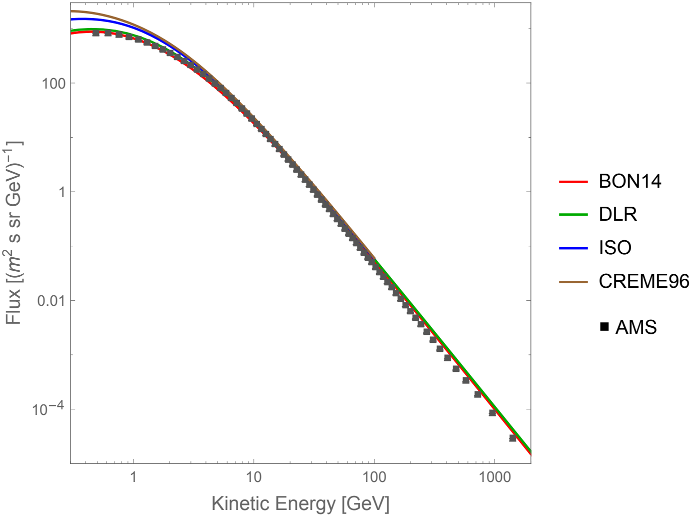
Scaled flux (right) emphasizes high energy shape

RESULTS: HYDROGEN FLUX VERSUS KINETIC ENERGY



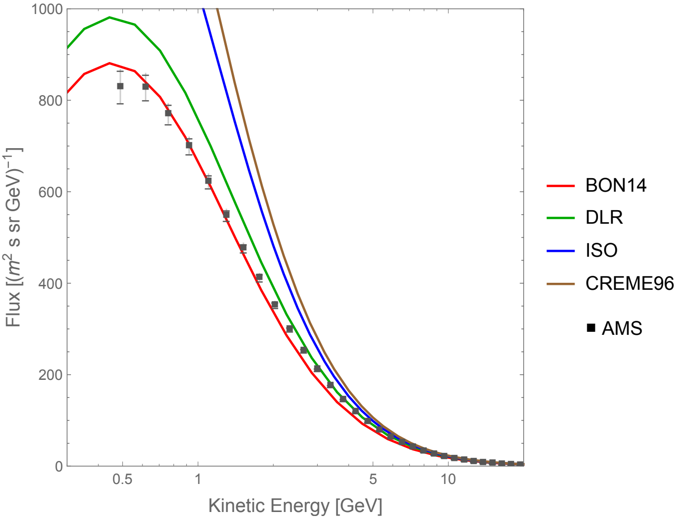
Conversion from rigidity data

Results: Hydrogen flux versus kinetic energy



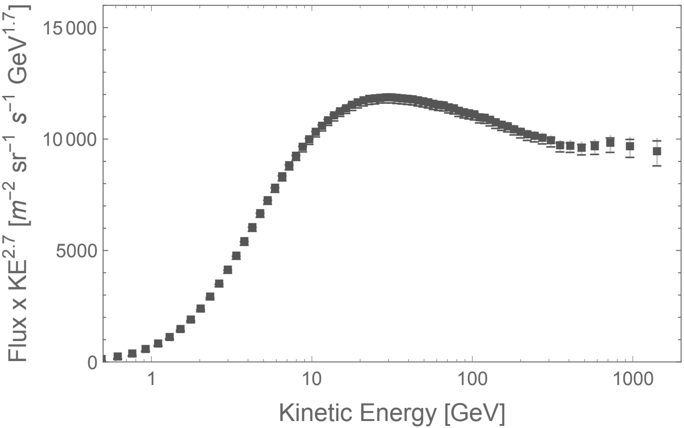
Model comparisons to data

RESULTS: HYDROGEN FLUX VERSUS KINETIC ENERGY



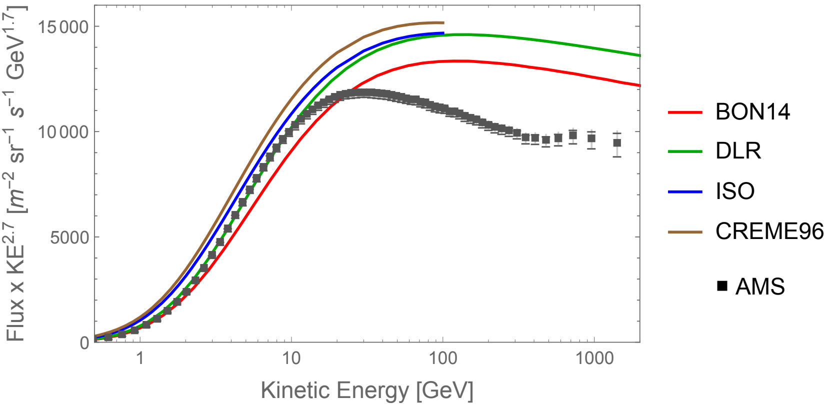
Model comparisons to data - linear plot

RESULTS: HYDROGEN FLUX (SCALED) VERSUS KINETIC ENERGY

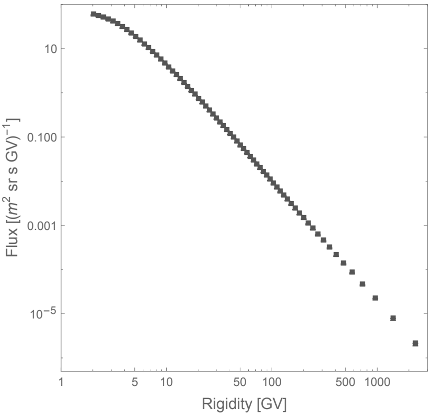


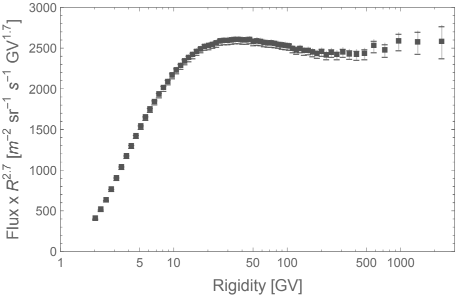
Scaled flux converted from rigidity data

Results: Hydrogen flux (scaled) versus kinetic energy



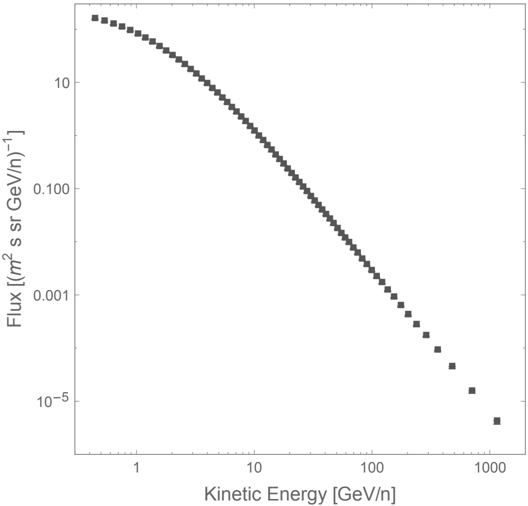
Model comparisons to scaled data





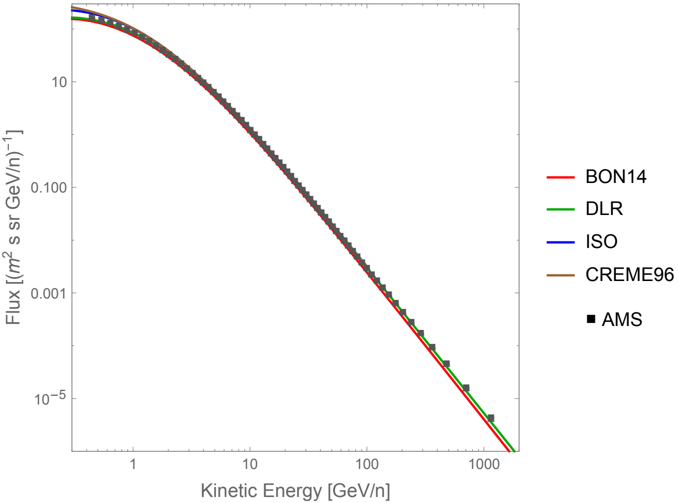
Scaled flux (right) emphasizes high energy shape

Results: Helium flux versus kinetic energy



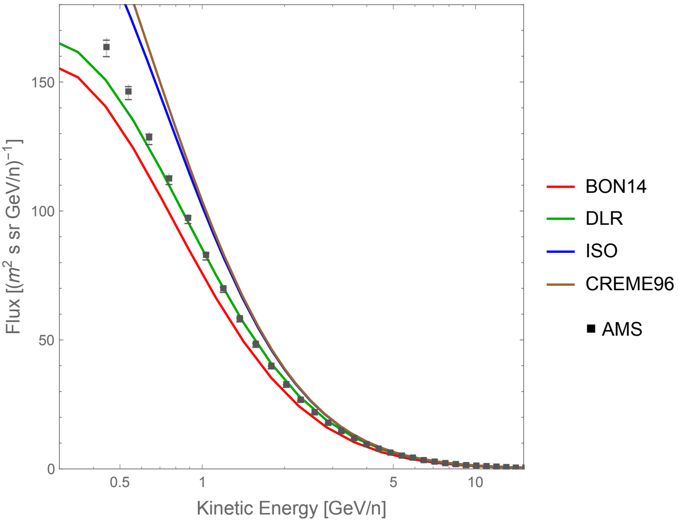
Conversion from rigidity data

Results: Helium flux versus kinetic energy

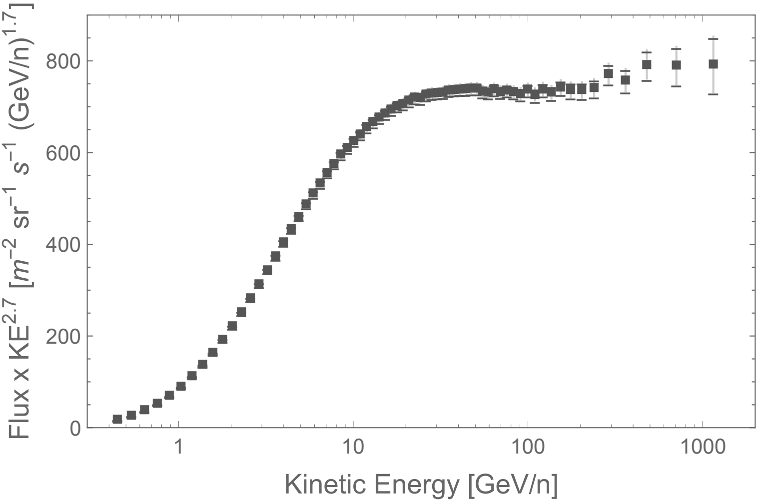


Model comparisons to data

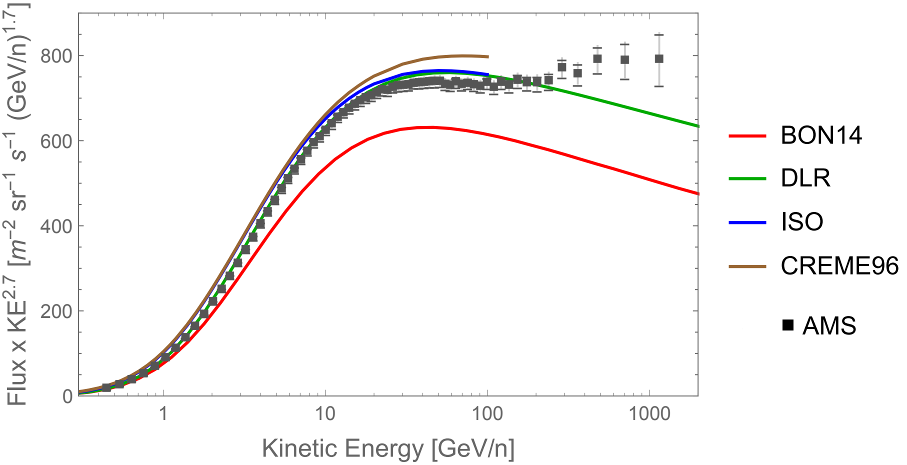
RESULTS: HELIUM FLUX VERSUS KINETIC ENERGY



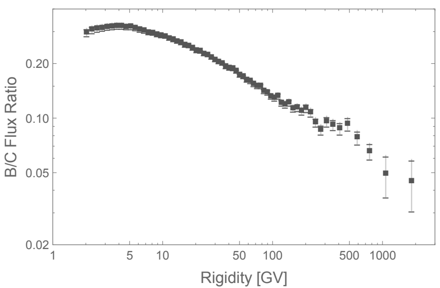
Model comparisons to data - linear plot

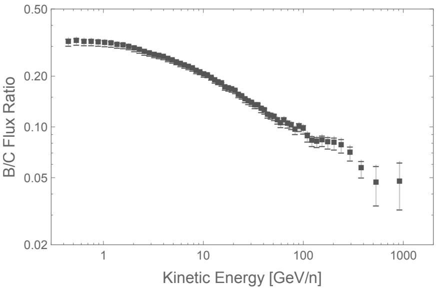


Scaled flux converted from rigidity data



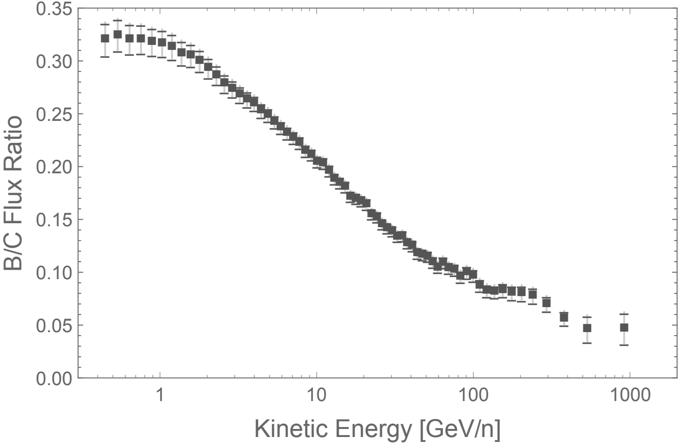
Model comparisons to scaled data


B/C Flux Ratio
0.20
0.10
0.05
0.02
1
5
10
50
100
500
1000
Rigidity [GV]


B/C Flux Ratio
0.50
0.20
0.10
0.05
0.02
1
10
100
1000
Kinetic Energy [GeV/n]

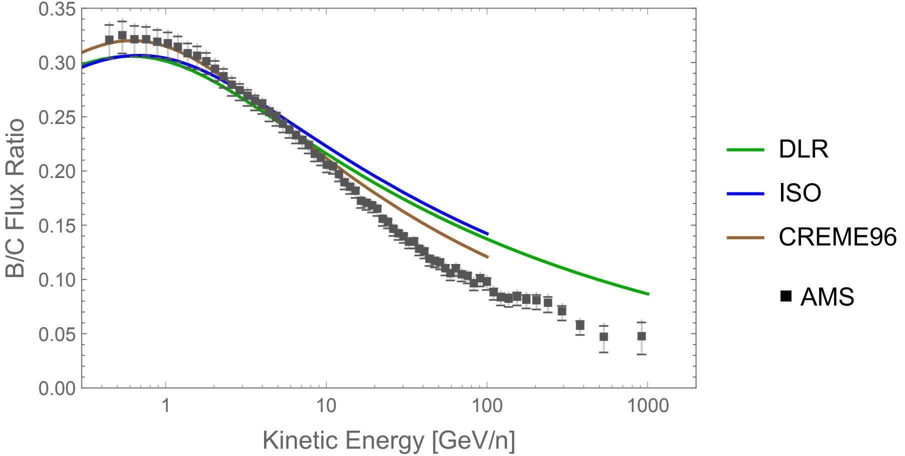
AMS data

Results: B/C ratio versus kinetic energy



AMS data - linear plot

Results: B/C ratio versus kinetic energy



Model comparisons to data - linear plot

SUMMARY - COMPARISON OF MODELS WITH AMS DATA

- Hydrogen data
    - BON14 excellent agreement
    - DLR moderate agreement
    - ISO & CREME96 poor agreement
    - All models fail with scaled data at very high energy
      - but not important for space radiation
- Helium data
    - DLR excellent agreement
    - BON14, ISO & CREME96 moderate agreement
    - All models fail with scaled data at very high energy
      - but not important for space radiation
- Boron / Carbon ratio
    - DLR, ISO & CREME96 good agreement
    - All models fail at very high energy
      - but not important for space radiation
    - BON14 model not yet updated

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THE END

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