Solar Energetic Particles, Solar Modulation and Space Radiation
New Opportunities in the AMS-2 Era
Meeting # 3
Washington D.C., USA

RECENT GCR MODELS COMPARED TO AMS 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
- SINP = Skobeltsyn Institute of Nuclear Physics
- SPENVIS = SPace ENVironment Information System

OUTLINE

1. INTRODUCTION
2. AMS PUBLICATIONS
3. AMS DATA
4. RESULTS
5. SUMMARY & CONCLUSIONS

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)

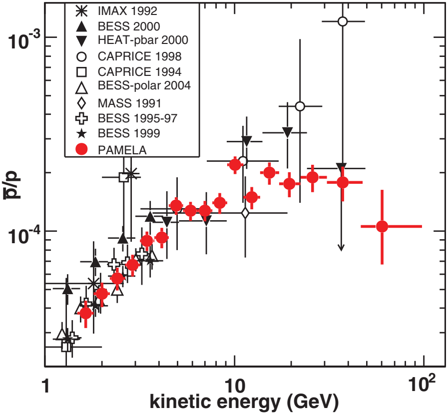
- Payload for AntiMatter Exploration & Light nuclei Astrophysics
- p^- consistent with secondary production
- Excess of e^+ (1 - 100 GeV) (DM?)

ATIC (balloon Antarctica)

(Wefel, Adams)

- Advanced Thin Ionization Chamber
- Excess of e^{+-} (300 - 700 GeV)

  e^{+-}="electrons"
  (can't distinguish charge)



Antiproton to proton flux

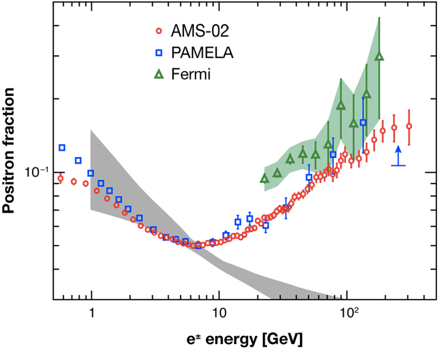
Adriani et al., Phys. Rev. Lett. 102, 051101, 2009

INTRO. AMS & DARK MATTER - ANTIMATTER (e^+, p^-)

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: $pp \to \pi \to e^+$ in galaxy

http://ams.nasa.gov

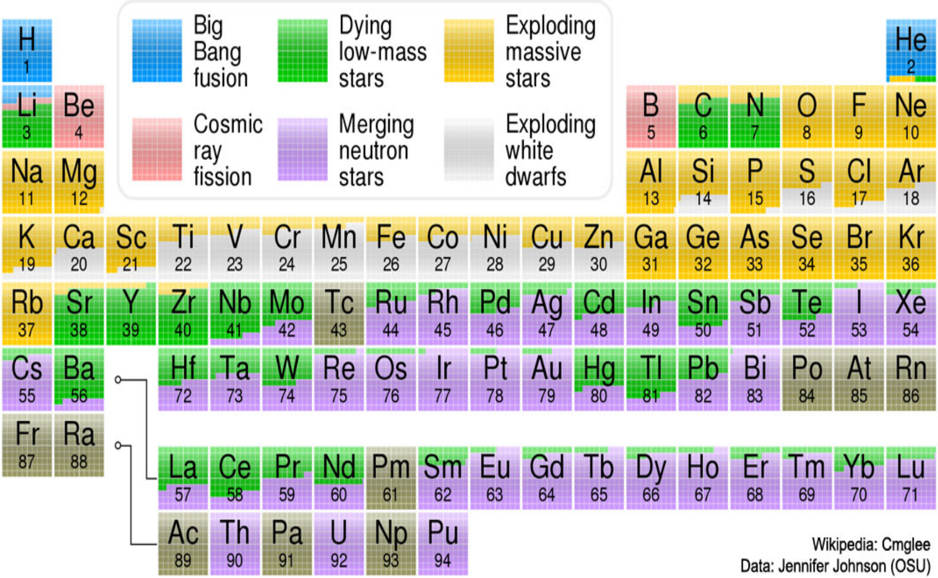


The positron fraction in high-energy cosmic rays. The new measurement from the AMS extends over a wider energy range and has much lower uncertainty than the earlier measurements from the PAMELA and Fermi-LAT satellites (or older balloon experiments). The AMS measurement confirms an excess in the high-energy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

The grey band indicates the expected range in the positron fraction.

Aguilar et al., Phys. Rev. Lett. 110, 141102, 2013

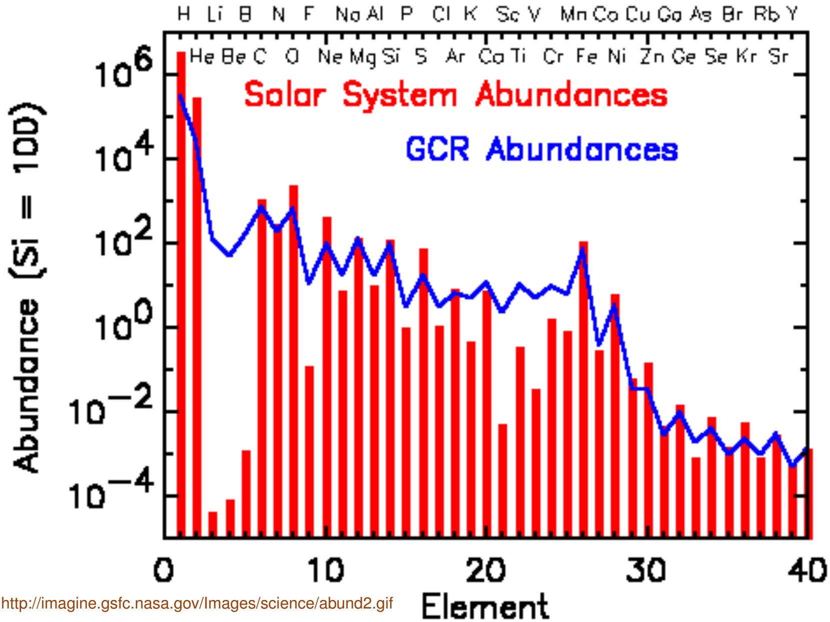
PRIMARY (H, HE, C, N, O ...) VS. SECONDARY (LI, BE, B) GCR



Wikipedia: Cmglee
Data: Jennifer Johnson (OSU)

https://apod.nasa.gov/apod/ap171024.html

PRIMARY (H, HE, C, N, O ...) VS. SECONDARY (LI, BE, B) GCR



http://imagine.gsfc.nasa.gov/Images/science/abund2.gif

INTRO. AMS & DARK MATTER - BORON/CARBON

- 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

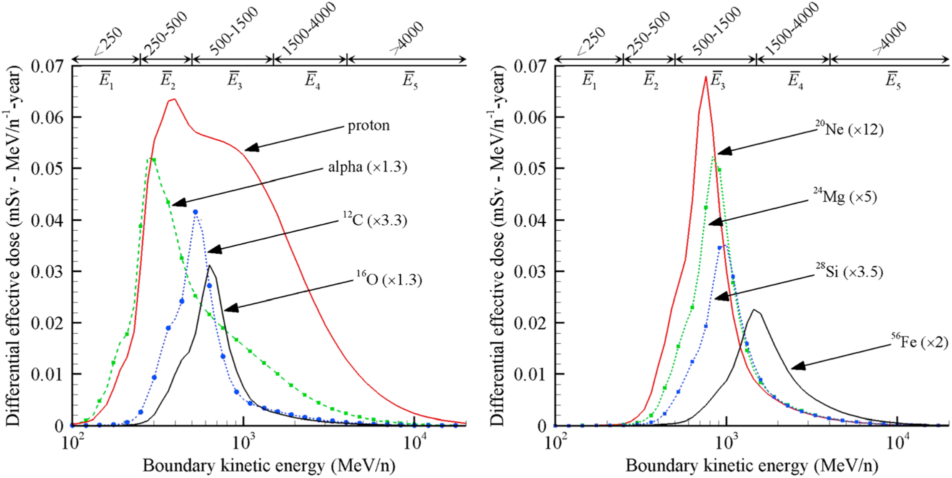
  Aguilar et al., Phys. Rev. Lett. 110, 141102, 2013

  - 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

INTRODUCTION - AMS & SPACE RADIATION



Effective dose contributions as a function of energy

Slaba & Blattnig, Space Weather 12, 217, 2014

INTRODUCTION - AMS & SPACE RADIATION

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

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

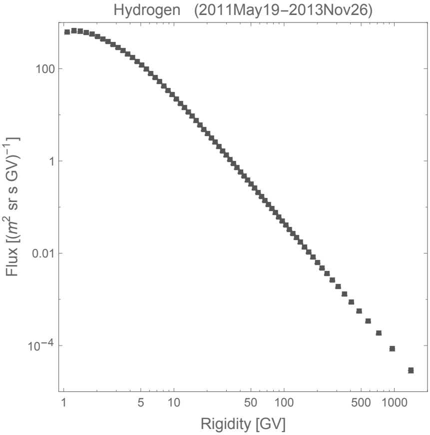
- Particles of same rigidity have same path in magnetic field
- Same gyro-radius r_G (radius of circular motion if circle $\perp$ to B)

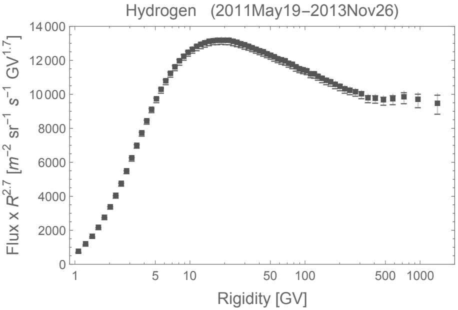
Nucleus	R (GV)	KE (MeV/n)		KE (GeV/n)	R (GV)
^{1}H	1	433		1	1.7
^{4}He	1	125		1	3.4
^{16}O	1	125		1	3.4
^{56}Fe	1	109		1	3.6

AMS PUBLICATIONS

- HYDROGEN (H) → primary GCR
  May 19, 2011 – November 26, 2013
  Aguilar et al., Phys. Rev. Lett. 114, 171103, 2015
- HELIUM (He) → primary GCR
  May 19, 2011 – November 26, 2013
  Aguilar et al., Phys. Rev. Lett. 115, 211101, 2015
- BORON / CARBON (B/C) ratio
  May 19, 2011 – May 26, 2016
- HELIUM (He), CARBON (C), OXYGEN (O) → primary GCR
  May 19, 2011 – May 26, 2016
  Aguilar et al., Phys. Rev. Lett. 119, 251101, 2017
- 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

AMS DATA: HYDROGEN (PRIMARY) FLUX VS. RIGIDITY





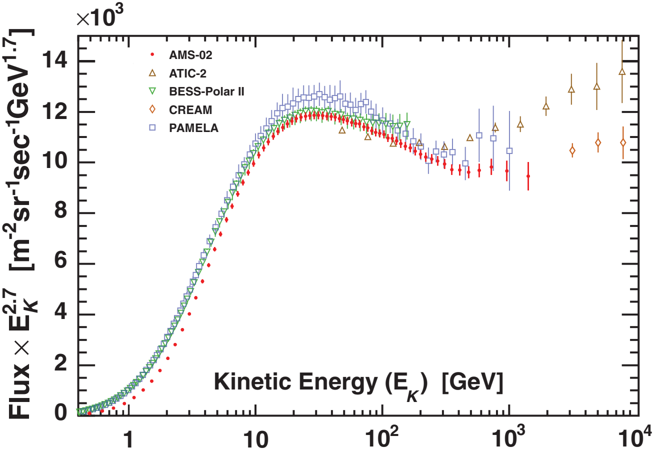
Scaled flux (right) emphasizes high energy shape

Famous break near 300 GV

Spectrum much harder than previous measurements

Previous measurements lie higher after break - i.e. softer

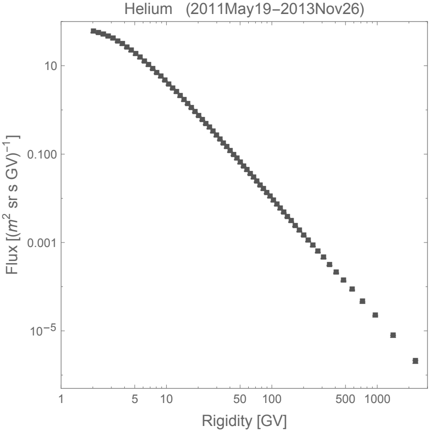
AMS & OTHER DATA: HYDROGEN FLUX VS. RIGIDITY

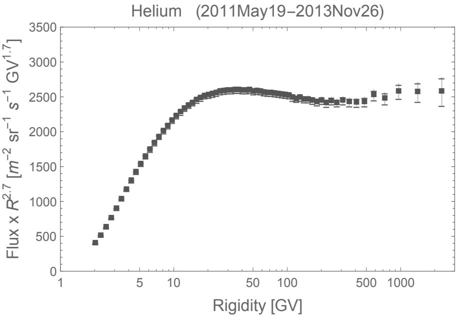


Aguilar et al., Phys. Rev. Lett. 114, 171103, 2015

AMS data harder than previous high energy measurements

AMS DATA: HELIUM (PRIMARY) FLUX VS. RIGIDITY



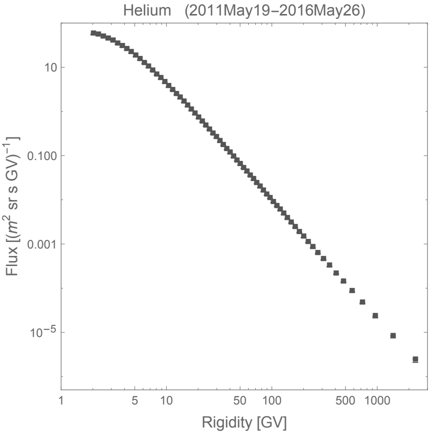


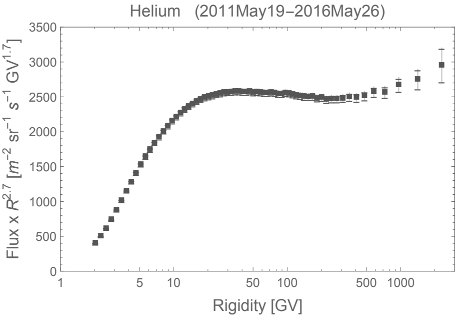
Scaled flux (right) emphasizes high energy shape

Another famous break at same rigidity near 300 GV

Both H and He have similar break at same rigidity

AMS DATA: HELIUM (PRIMARY) FLUX VS. RIGIDITY



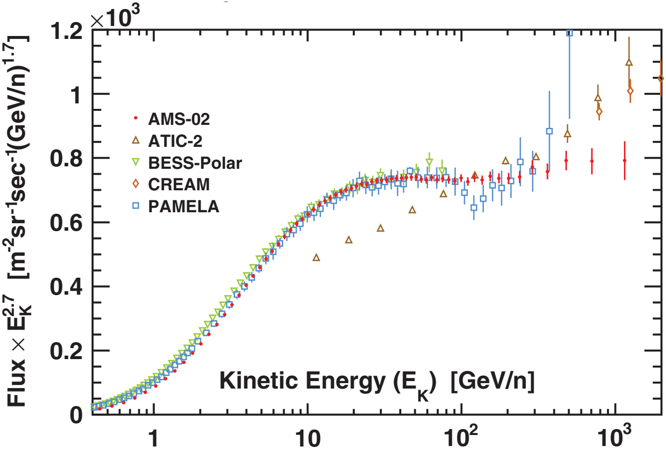


Scaled flux (right) emphasizes high energy shape

Another famous break at same rigidity near 300 GV

Both H and He have similar break at same rigidity

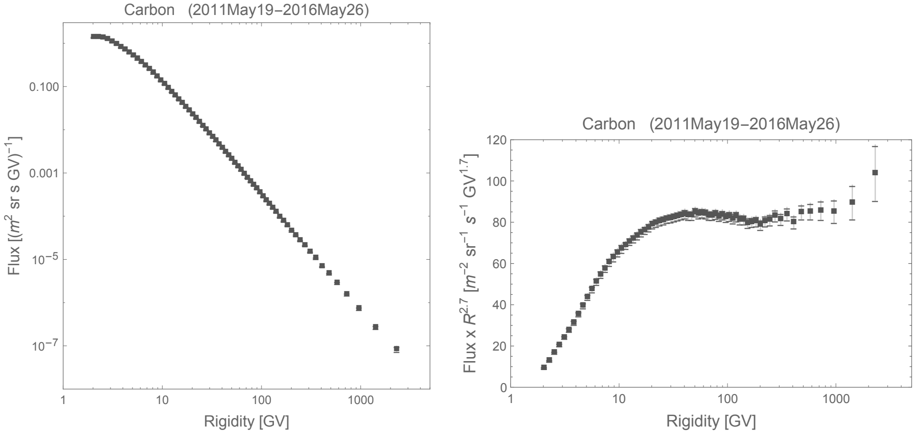
AMS & OTHER DATA: HELIUM FLUX VS. RIGIDITY



Aguilar et al., Phys. Rev. Lett. 115, 211101, 2015

AMS data harder than previous high energy measurements

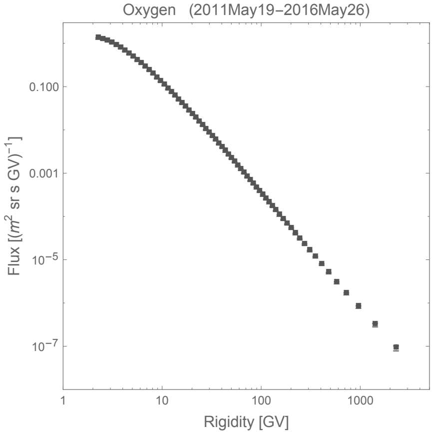
AMS DATA: CARBON (PRIMARY) FLUX VS. RIGIDITY

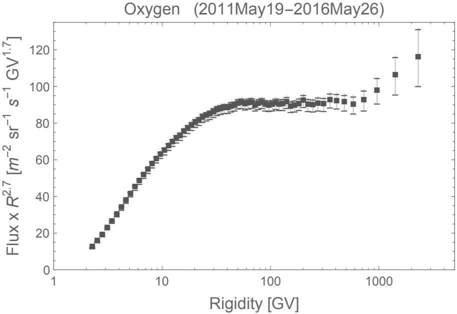


Scaled flux (right) emphasizes high energy shape

Similar break near 200 GV

AMS DATA: OXYGEN (PRIMARY) FLUX VS. RIGIDITY

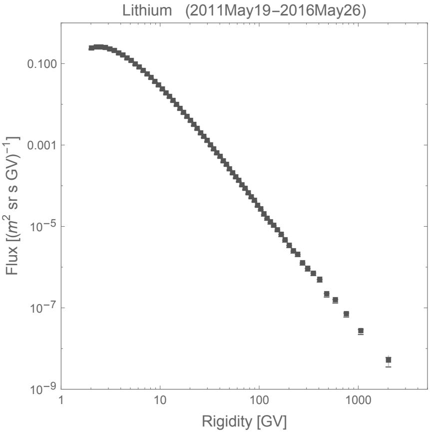


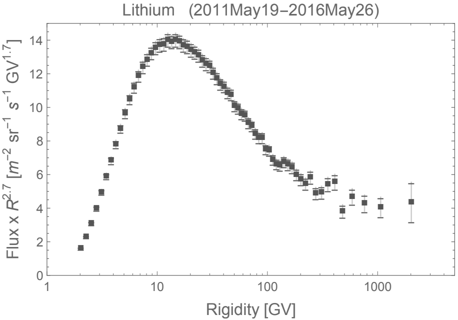


Scaled flux (right) emphasizes high energy shape

Similar break near 200 GV

AMS DATA: LITHIUM (SECONDARY) FLUX VS. RIGIDITY

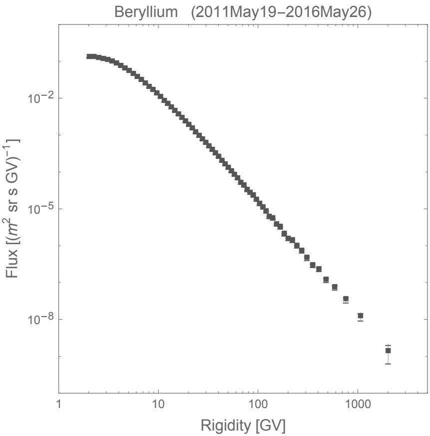


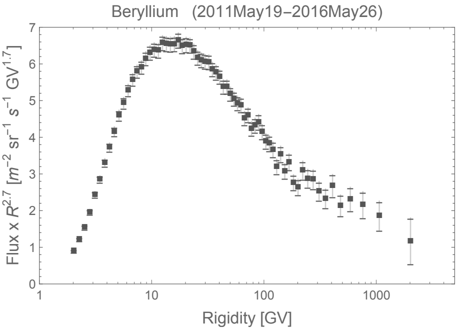


Scaled flux (right) emphasizes high energy shape

Secondary GCR spectra harder than primary spectra

AMS DATA: BERYLLIUM (SECONDARY) FLUX VS. RIGIDITY

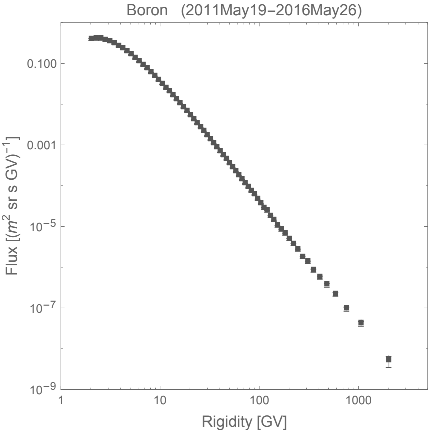


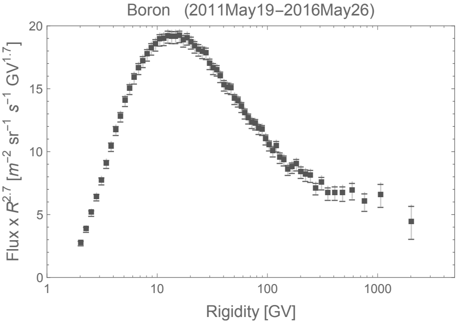


Scaled flux (right) emphasizes high energy shape

Secondary GCR spectra harder than primary spectra

AMS DATA: BORON (SECONDARY) FLUX VS. RIGIDITY

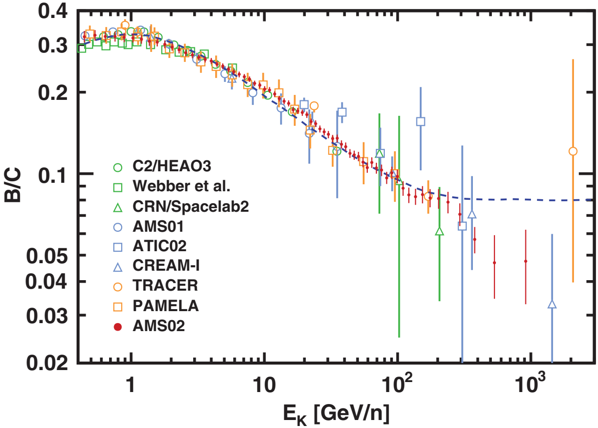




Scaled flux (right) emphasizes high energy shape

Secondary GCR spectra harder than primary spectra

AMS & OTHER DATA: B/C RATIO



AMS & other data for B/C ration

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

Aguilar et al., Phys. Rev. Lett. 119, 251101, 2017

AMS DATA SUMMARY

- 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

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

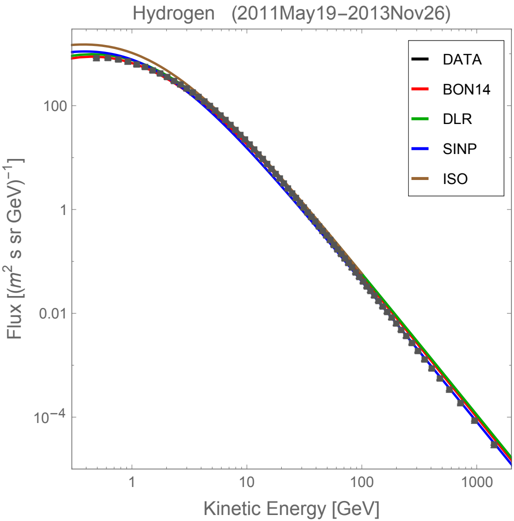
- SINP model

  Kuznetsov, Popova, Panasyuk, J. Geophys. Res. Space Phys. 115, 1463, 2017

- ISO15390 model - taken from SPENVIS

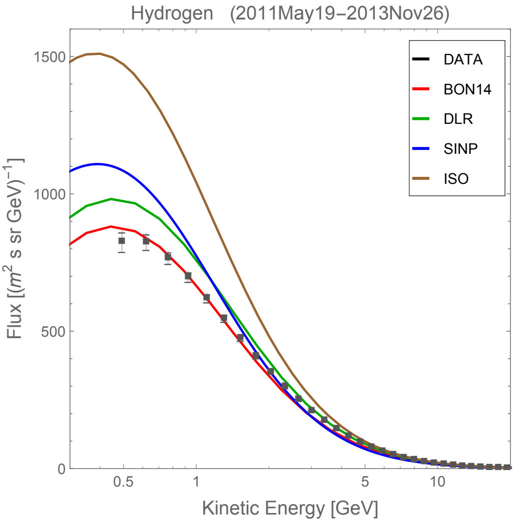
  Nymmik et al., Adv. Space Res. 17, 19, 1996

RESULTS: HYDROGEN FLUX VS. KINETIC ENERGY



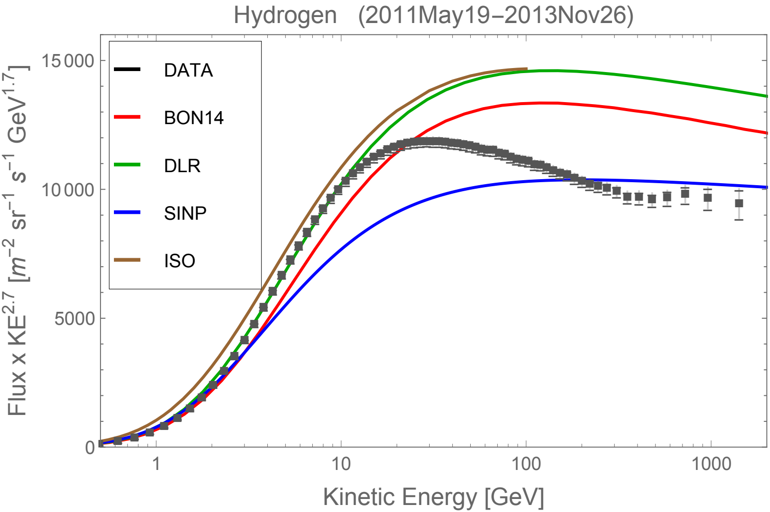
Model comparisons to data

RESULTS: HYDROGEN FLUX VS. KINETIC ENERGY



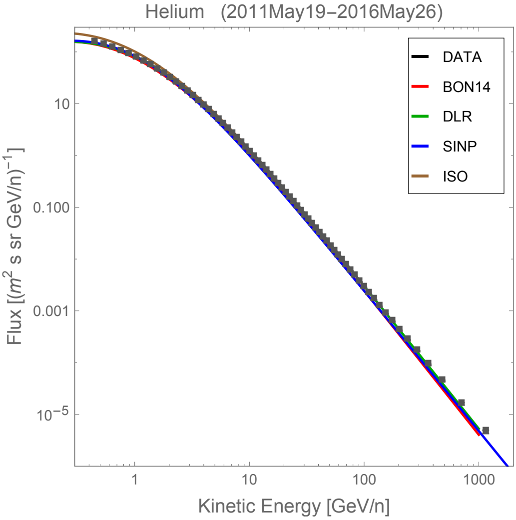
Model comparisons to data - linear plot

RESULTS: HYDROGEN FLUX (SCALED) VS. KINETIC ENERGY



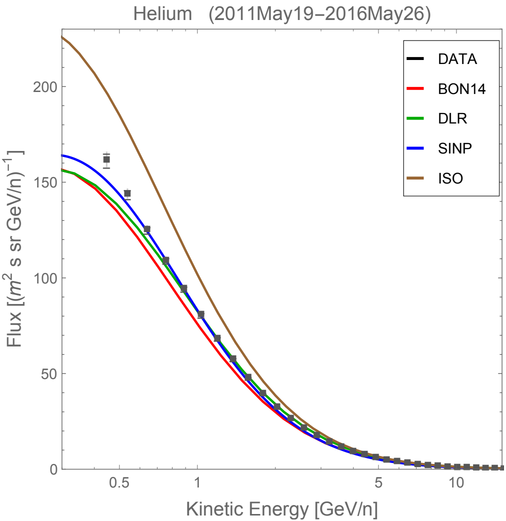
Model comparisons to scaled data

RESULTS: HELIUM FLUX VS. KINETIC ENERGY



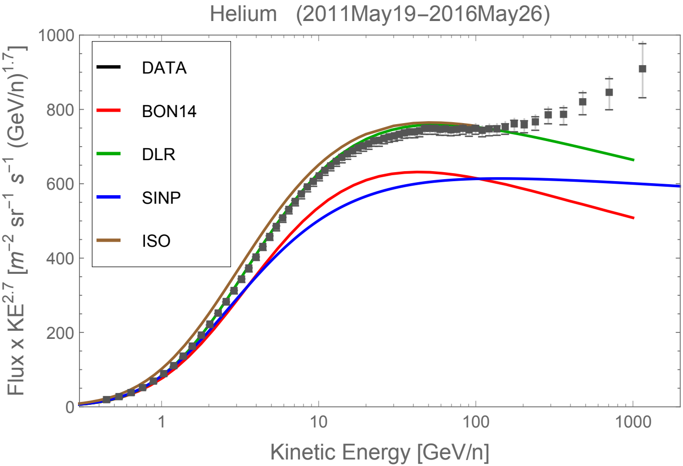
Model comparisons to data

RESULTS: HELIUM FLUX VS. KINETIC ENERGY



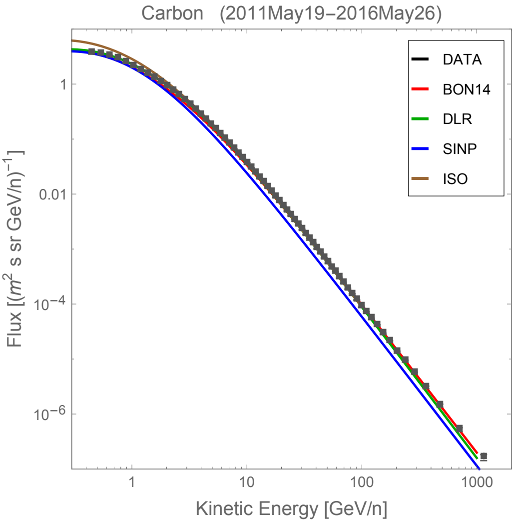
Model comparisons to data - linear plot

RESULTS: HELIUM FLUX (SCALED) VS. KINETIC ENERGY



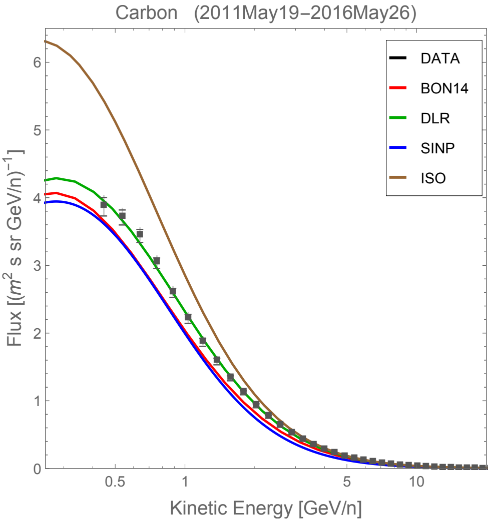
Model comparisons to scaled data

RESULTS: CARBON FLUX VS. KINETIC ENERGY



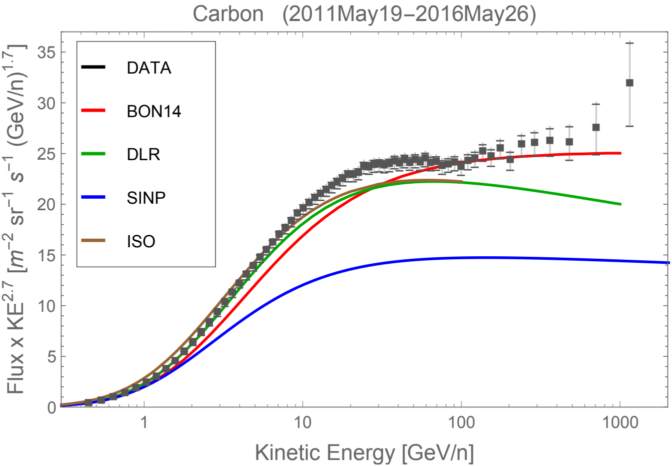
Model comparisons to data

RESULTS: CARBON FLUX VS. KINETIC ENERGY



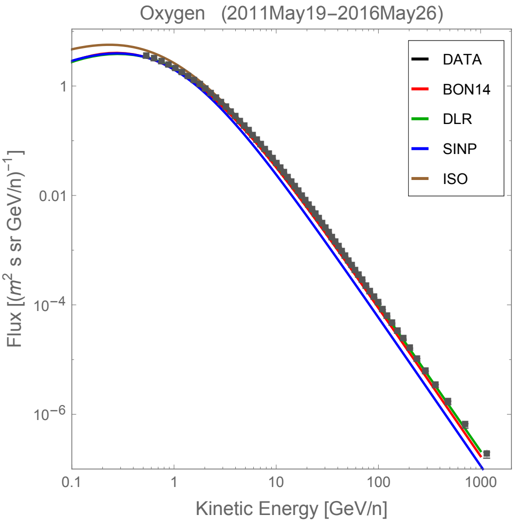
Model comparisons to data - linear plot

RESULTS: CARBON FLUX (SCALED) VS. KINETIC ENERGY



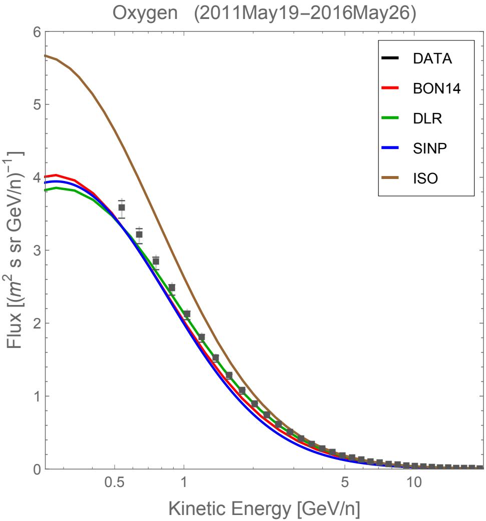
Model comparisons to scaled data

RESULTS: OXYGEN FLUX VS. KINETIC ENERGY



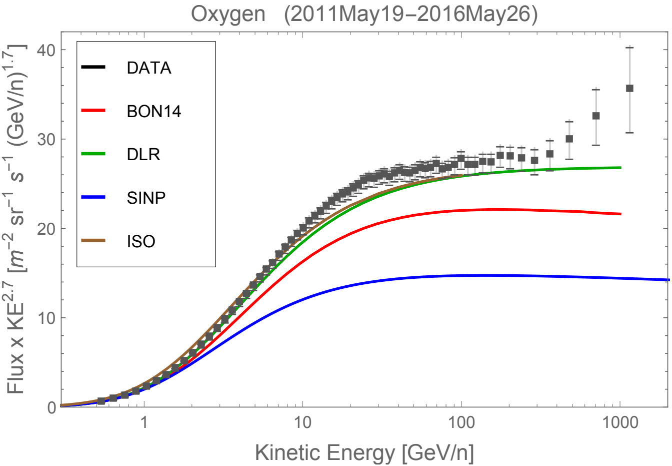
Model comparisons to data

RESULTS: OXYGEN FLUX VS. KINETIC ENERGY



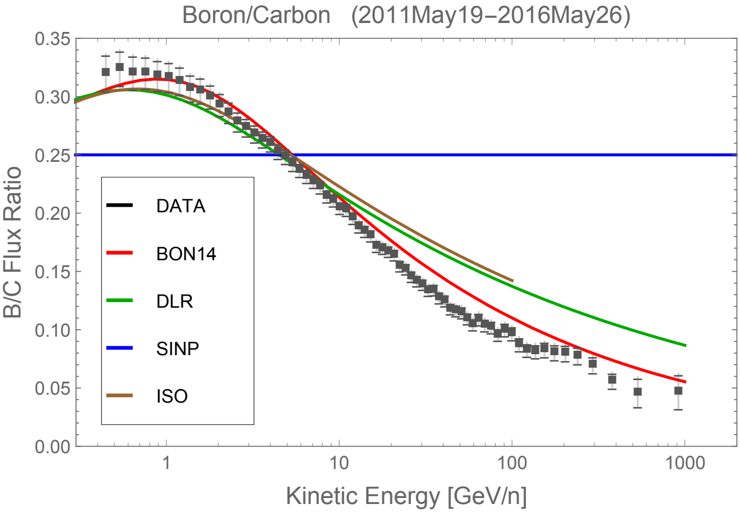
Model comparisons to data - linear plot

RESULTS: OXYGEN FLUX (SCALED) VS. KINETIC ENERGY



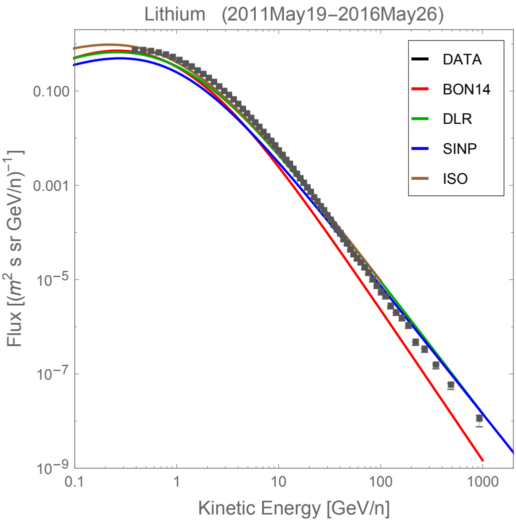
Model comparisons to scaled data

RESULTS: B/C RATIO VS. KINETIC ENERGY



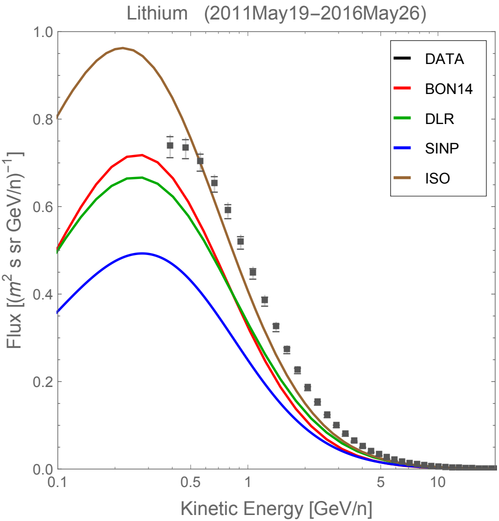
Model comparisons to data - linear plot

RESULTS: LITHIUM FLUX VS. KINETIC ENERGY



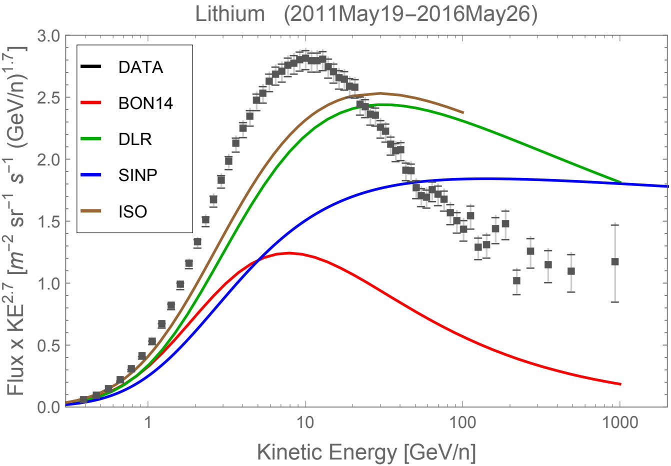
Model comparisons to data

RESULTS: LITHIUM FLUX VS. KINETIC ENERGY



Model comparisons to data - linear plot

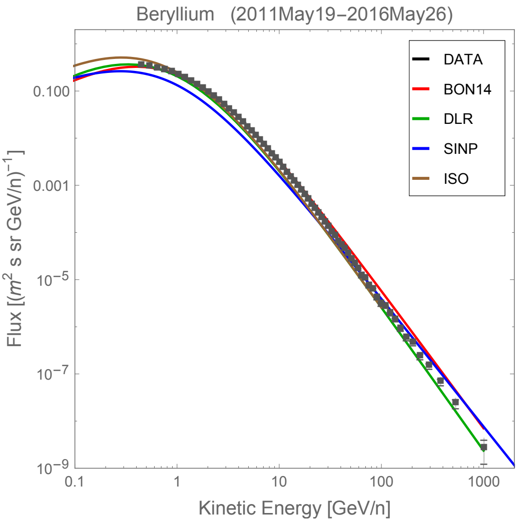
RESULTS: LITHIUM FLUX (SCALED) VS. KINETIC ENERGY



Model comparisons to scaled data

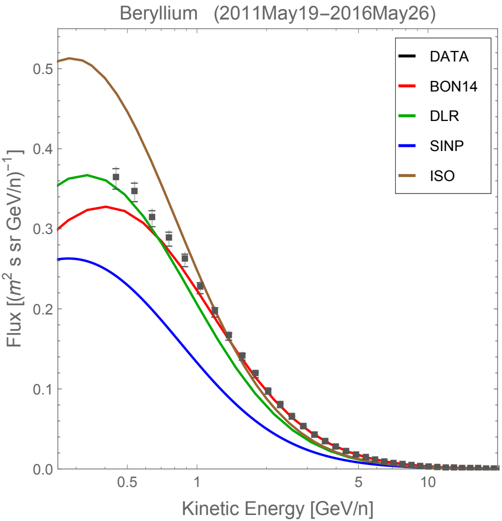
Models show spectral hardening for secondaries vs. primaries

RESULTS: BERYLLIUM FLUX VS. KINETIC ENERGY



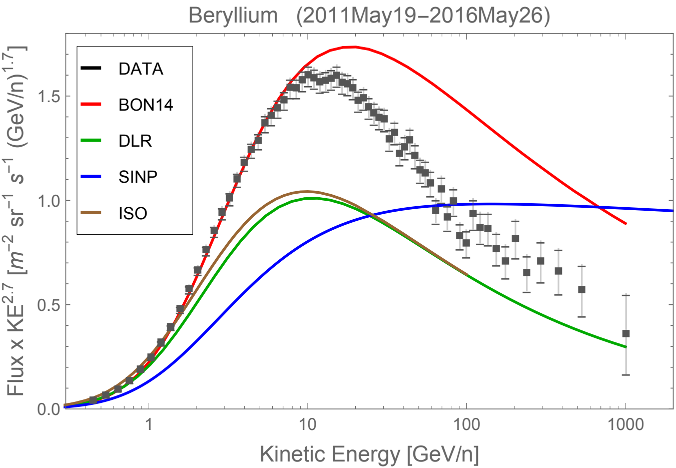
Model comparisons to data

RESULTS: BERYLLIUM FLUX VS. KINETIC ENERGY



Model comparisons to data - linear plot

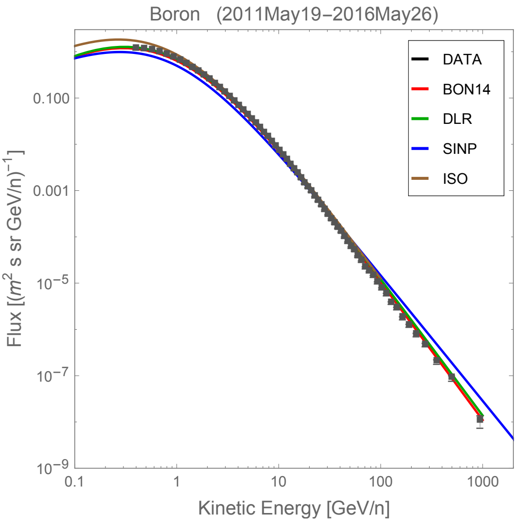
RESULTS: BERYLLIUM FLUX (SCALED) VS. KINETIC ENERGY



Model comparisons to scaled data

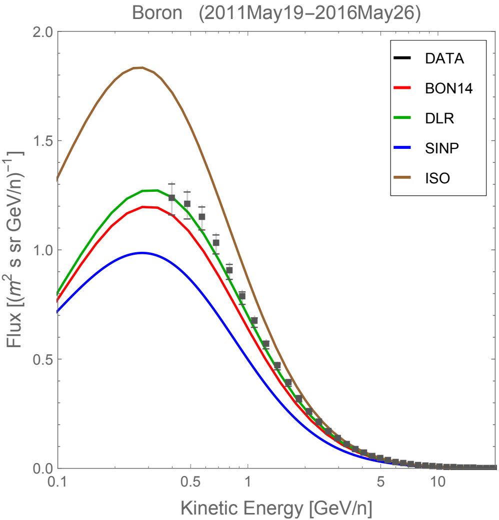
Models show spectral hardening for secondaries vs. primaries

RESULTS: BORON FLUX VS. KINETIC ENERGY



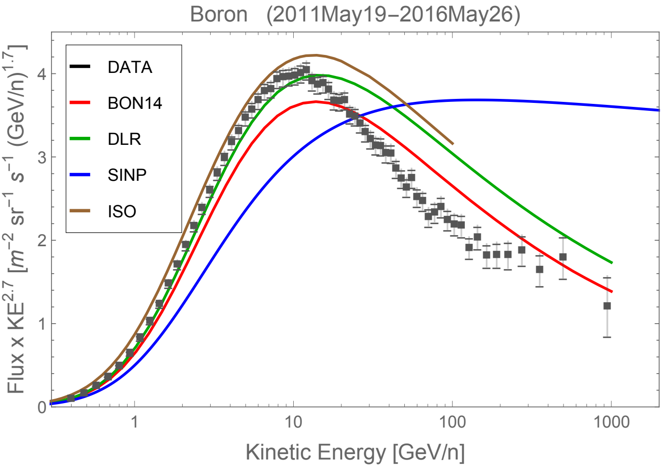
Model comparisons to data

RESULTS: BORON FLUX VS. KINETIC ENERGY



Model comparisons to data - linear plot

RESULTS: BORON FLUX (SCALED) VS. KINETIC ENERGY

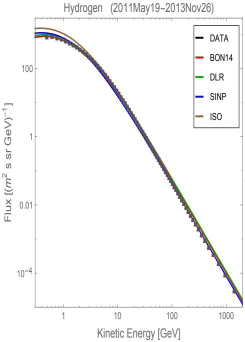


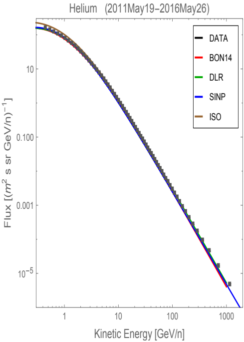
Model comparisons to scaled data

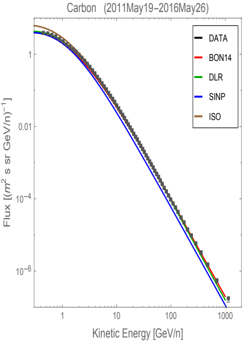
Models show spectral hardening for secondaries vs. primaries

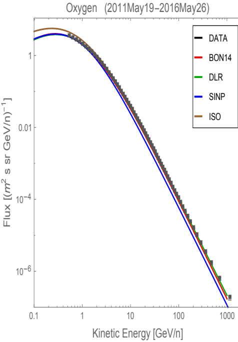
RESULTS: SUMMARY PLOTS

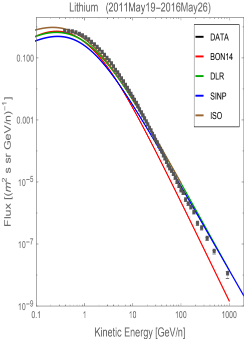
Next 3 pages show all plots on single slides, for inter-comparison

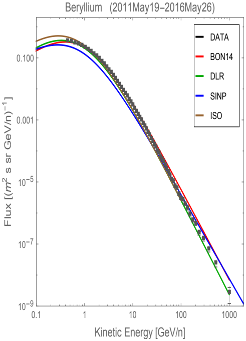

Hydrogen (2011May19–2013Nov26)
DATA
BON14
DLR
SINP
ISO
Flux [(m² s sr GeV)⁻¹]
100
1
0.01
10⁻⁴
1
10
100
1000
Kinetic Energy [GeV]

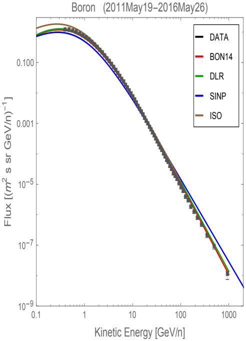

Helium (2011May19–2016May26)
DATA
BON14
DLR
SINP
ISO
Flux [(m² s sr GeV/n)⁻¹]
10
0.100
0.001
10⁻⁵
1
10
100
1000
Kinetic Energy [GeV/n]

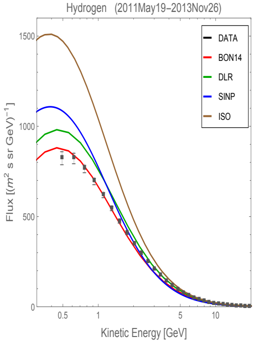

Carbon (2011May19–2016May26)
DATA
BON14
DLR
SINP
ISO
Flux [(m² s sr GeV/n)⁻¹]
1
0.01
10⁻⁴
10⁻⁶
1
10
100
1000
Kinetic Energy [GeV/n]

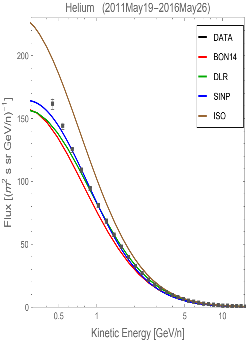

Oxygen (2011May19–2016May26)
DATA
BON14
DLR
SINP
ISO
Flux [(m² s sr GeV/n)⁻¹]
1
0.01
10⁻⁴
10⁻⁶
0.1
1
10
100
1000
Kinetic Energy [GeV/n]

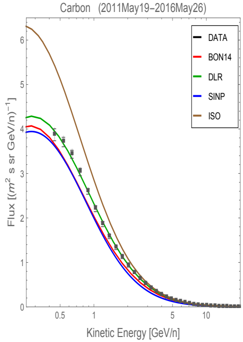

Lithium (2011May19–2016May26)
DATA
BON14
DLR
SINP
ISO
Flux [(m² s sr GeV/n)⁻¹]
0.100
0.001
10⁻⁵
10⁻⁷
10⁻⁹
0.1
1
10
100
1000
Kinetic Energy [GeV/n]

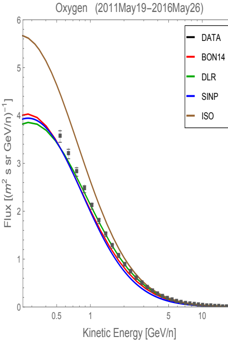

Beryllium (2011May19–2016May26)
DATA
BON14
DLR
SINP
ISO
Flux [(m² s sr GeV/n)⁻¹]
0.100
0.001
10⁻⁵
10⁻⁷
10⁻⁹
0.1
1
10
100
1000
Kinetic Energy [GeV/n]

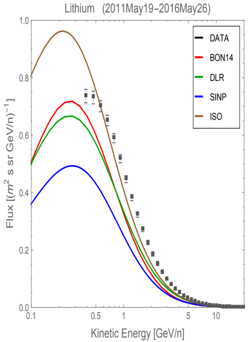

Boron (2011May19–2016May26)
DATA
BON14
DLR
SINP
ISO
Flux [(m² s sr GeV/n)⁻¹]
0.100
0.001
10⁻⁵
10⁻⁷
10⁻⁹
0.1
1
10
100
1000
Kinetic Energy [GeV/n]

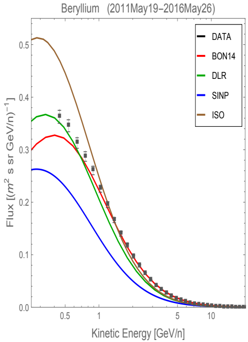

Hydrogen (2011May19–2013Nov26)

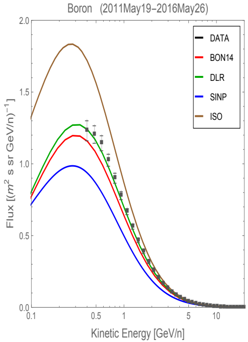

Helium (2011May19–2016May26)


Carbon (2011May19–2016May26)

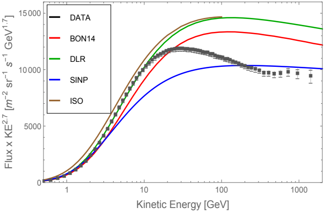

Oxygen (2011May19–2016May26)


Lithium (2011May19–2016May26)

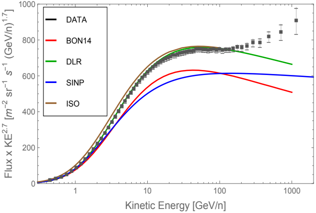

Beryllium (2011May19–2016May26)


Boron (2011May19–2016May26)

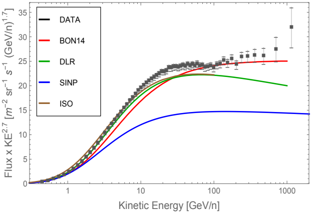
Hydrogen (2011May19–2013Nov26)



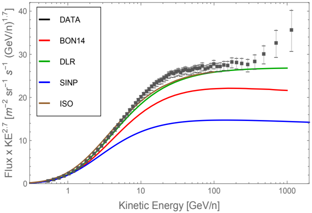
Helium (2011May19–2016May26)



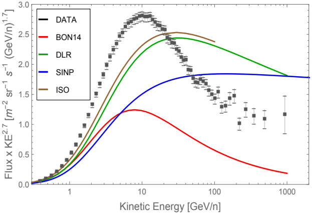
Carbon (2011May19–2016May26)



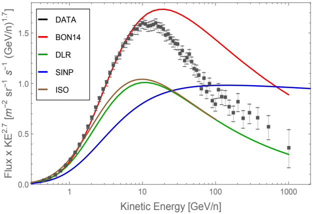
Oxygen (2011May19–2016May26)



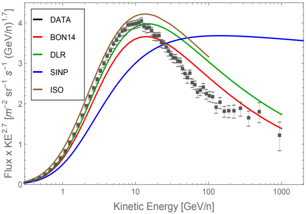
Lithium (2011May19–2016May26)



Beryllium (2011May19–2016May26)



Boron (2011May19–2016May26)



SUMMARY & CONCLUSIONS

- 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

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THE END

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