



ISS Partners - Exploration Radiation Health and Protection Meeting
*Radiation Environment and Risk Analysis at and near the Lunar surface:
Cis-lunar Vehicle Requirements*

Moscow State University Skobeltsyn Institute of Nuclear Physics, Russian Federal Space Agency
ESA Permanent Mission in the Russian Federation, Sretensky Blvd., Moscow, Russia
Technical Interchange Meeting (TIM) #6

MODEL COMPARISONS TO NEW ALPHA MAGNETIC SPECTROMETER (AMS) DATA

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ABBREVIATIONS

- AMS = Alpha Magnetic Spectrometer
- BON = Badhwar - O'Neill (model)
- DLR = Deutsches Zentrum für Luft (German Aerospace Center)
- ESA = European Space Agency
- GCR = Galactic Cosmic Ray
- ISMT = International Standards Maturation Team
- ISO = International Standardization Organization
- PAMELA = Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics
- SINP = Skobeltsyn Institute for Nuclear Physics
- SPENVIS = SPace ENVironment Information System
- TIM = Technical Interchange Meeting

- 1 INTRODUCTION & TIM#4 ACTIONS
- 2 AMS PUBLICATIONS
- 3 AMS DATA
- 4 GCR MODEL COMPARISONS TO AMS DATA
- 5 SUMMARY & FUTURE ACTIONS

INTRODUCTION & TIM#4 ACTIONS

Actionees:

- NASA Langley Research Center: John Norbury
- European Space Agency: Daniel Matthiä
- Skobeltsyn Institute of Nuclear Physics / Moscow State University:
Nikolay Kuznetsov, Mikhail Podzolko

Actions:

- 1 The Russian team will provide the SINP-2016 GCR environment model to the ISMT Radiation Experts Team
(Kuznetsov, Podzolko)
- 2 NASA team will implement SINP-2016 into OLTARIS (Norbury)
- 3 Publish analysis of AMS-II data presented at TIM#4
(Norbury, Matthiä, Kuznetsov, Podzolko)
- 4 Analyze new AMS-II data when the data become available
(Norbury, Matthiä, Kuznetsov, Podzolko)

ACTION #1: RUSSIAN TEAM WILL PROVIDE SINP-2016 GCR ENVIRONMENT MODEL TO ISMT RADIATION EXPERTS TEAM (KUZNETSOV, PODZOLKO)

- NASA JSC team (Kerry Lee, Katie Whitman) implemented SINP-2016 GCR model from published results
- Very useful help from Prof. Kuznetsov

ACTION #2: NASA TEAM WILL IMPLEMENT SINP-2016 INTO OLTARIS (NORBURY)

- SINP-2016 GCR environment model now available on OLTARIS
- Thanks to Chris Sandridge, Tony Slaba, Kerry Lee, Katie Whitman

ACTION #3: PUBLISH ANALYSIS OF AMS-II DATA PRESENTED AT TIM#4 (NORBURY, MATTHIÄ, KUZNETSOV, PODZOLKO)

Life Sciences in Space Research 18 (2018) 64–71



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Life Sciences in Space Research

journal homepage: www.elsevier.com/locate/issr



Comparison of space radiation GCR models to recent AMS data

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ARTICLE INFO

Keywords:

Space radiation
Galactic cosmic rays
Alpha magnetic spectrometer

ABSTRACT

This paper is the third in a series of comparisons of American (NASA) and Russian (ROSCOSMOS) space radiation calculations. The present work focuses on calculation of fluxes of galactic cosmic rays (GCR), which are a constant source of radiation that constitutes one of the major hazards during deep space exploration missions for both astronauts/cosmonauts and hardware. In this work, commonly used GCR models are compared with recently published measurements of cosmic ray Hydrogen, Helium, and the Boron-to-Carbon ratio from the Alpha Magnetic Spectrometer (AMS). All of the models were developed and calibrated prior to the publication of the AMS data; therefore this an opportunity to validate the models against an independent data set.



Contents lists available at ScienceDirect

Life Sciences in Space Research

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Comparing HZETRN, SHIELD, FLUKA and GEANT transport codes

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ARTICLE INFO

Keywords:

Space radiation
Radiation transport
HZETRN
SHIELD

ABSTRACT

For the first time, the American (NASA) and Russian (ROSCOSMOS) space radiation transport codes, HZETRN and SHIELD respectively, are directly compared to each other. Calculations are presented for Galactic Cosmic Ray (GCR) minimum Hydrogen, Oxygen and Iron projectiles incident on a uniform Aluminum cylinder of varying thickness. Comparisons are made for the flux spectra of neutrons, light ions ($Z \leq 2$), heavy ions ($Z > 2$) and pions emitted from the back of the Aluminum cylinder. In order to provide more benchmark comparisons, some calculations with the GEANT and FLUKA transport codes are also shown.

1. Introduction

International cooperation in the exploration of space is expected to continue with human missions to Mars. Protection of astronauts from the harmful effects of space radiation is a major factor that needs to be

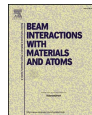
is a direct comparison of the American and Russian codes HZETRN and SHIELD respectively, with each other. The present paper represents the first such direct comparison of these two important space radiation transport codes.

While the main focus of this paper is to compare the NASA



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journal homepage: www.elsevier.com/locate/nimb

SHIELD and HZETRN comparisons of pion production cross sections

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A B S T R A C T

A program of comparing American (NASA) and Russian (ROSCOSMOS) space radiation transport codes has recently begun, and the first paper directly comparing the NASA and ROSCOSMOS space radiation transport codes, HZETRN and SHIELD respectively has recently appeared. The present work represents the second time that NASA and ROSCOSMOS calculations have been directly compared, and the focus here is on models of pion production cross sections used in the two transport codes mentioned above. It was found that these models are in overall moderate agreement with each other and with experimental data. Disagreements that were found are discussed.

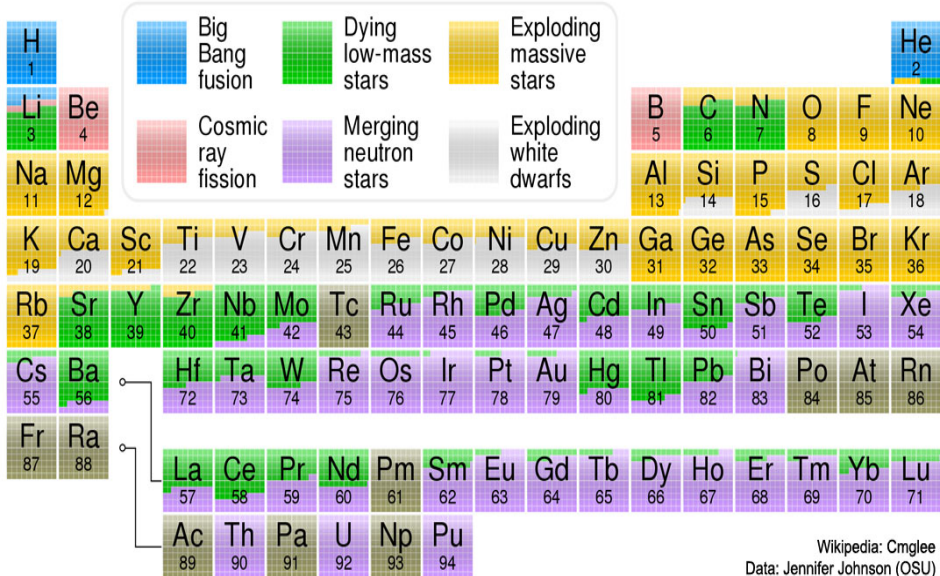
Future exploration-class human space missions will continue to rely heavily on international cooperation, and a program has recently begun with the aim of comparing space radiation calculations between the American (NASA) and Russian (ROSCOSMOS) space agencies. This activity has involved several workshops in Moscow, with radiation experts sharing calculations and results from a wide variety of space

transporting the full GCR energy spectrum for the H, O and Fe projectile components being separately transported through various thicknesses of Al shielding (1, 10, 100 g/cm²). That study also included comparisons with the FLUKA code [10]. It was found that HZETRN, SHIELD and FLUKA were in excellent agreement for thick (100 g/cm²) shielding for H, O, and Fe projectiles and also in excellent agreement for high

ACTION #4: ANALYZE NEW AMS-II DATA WHEN DATA BECOME AVAILABLE (NORBURY, MATTHIÄ, KUZNETSOV, PODZOLKO)

- New results shown today

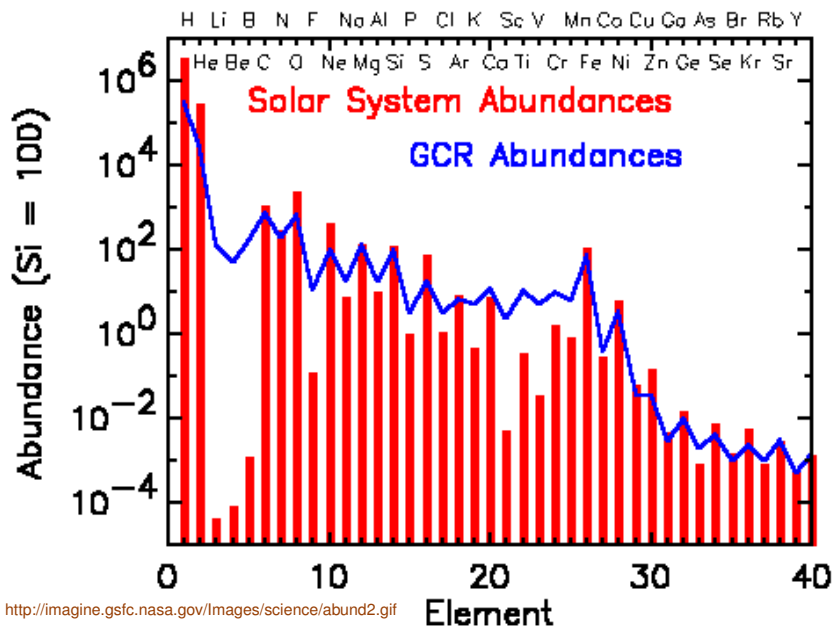
PRIMARY (H, He, C, N, O ...) VS. SECONDARY (Li, Be, B) GCR



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

Wikipedia: Cmglee
Data: Jennifer Johnson (OSU)

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



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

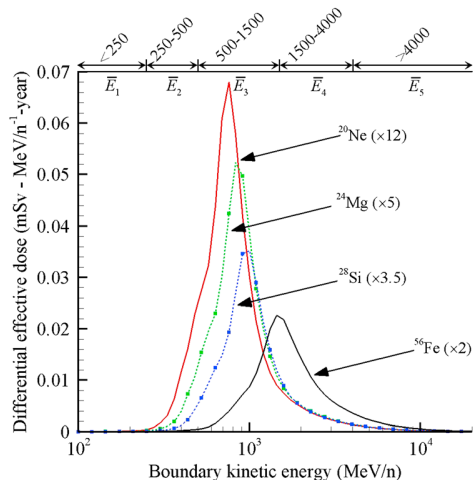
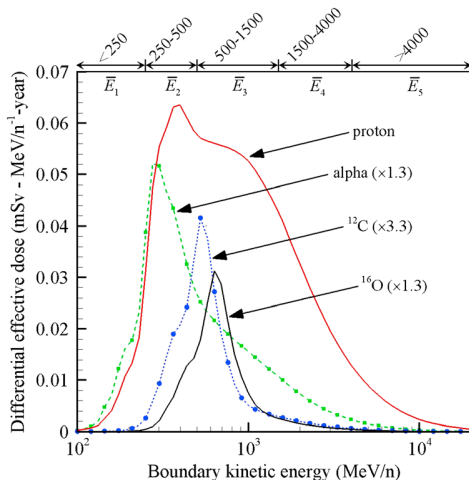
- Positron excess discovered by AMS

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

- Consistent with Dark Matter (DM) particle (Neutralino) of mass 1 TeV
- Dark Matter or Pulsars?
- Theories which explain e^+ excess with conventional sources make B/C predictions, because both e^+ and B/C traverse same paths
 - if can't model B/C correctly then e^+ excess likely DM!
- Very high energy measurements underway
 - high energy more direct path: easier model
 - behavior of fall-off after maximum will provide definitive signature

- Sensitivity studies for GCR environmental modeling:
Slaba et al., Space Weather 12, 217, 2014
- 90% effective dose contributed from GCR energies > 250 MeV/n
= Upper energy limit of the Advanced Composition Explorer /
Cosmic Ray Isotope Spectrometer (ACE/CRIS) satellite, which
has contributed to most GCR data
- Higher energy data are needed, which is why the AMS-II
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)
^1H	1	433		1	1.7
^4He	1	125		1	3.4
^{16}O	1	125		1	3.4
^{56}Fe	1	109		1	3.6

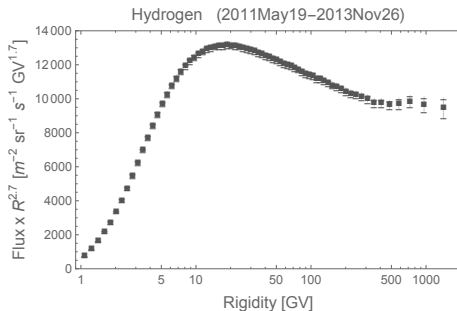
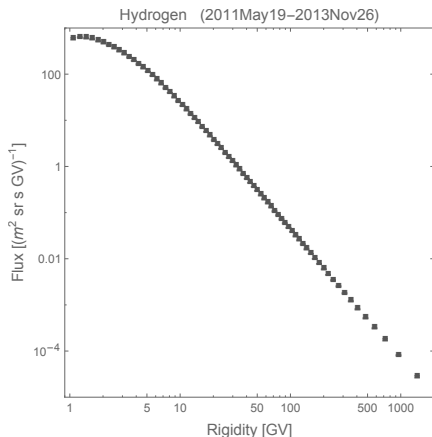
- **HYDROGEN (H)** → Primary GCR
May 19, 2011 – November 26, 2013 → Total
Aguilar et al., Phys. Rev. Lett. 114, 171103, 2015
- **HELIUM (He)** → Primary GCR
May 19, 2011 – November 26, 2013 → Total
Aguilar et al., Phys. Rev. Lett. 115, 211101, 2015
- **BORON / CARBON (B/C) ratio** → Secondary / Primary GCR
May 19, 2011 – May 26, 2016 → Total
Aguilar et al., Phys. Rev. Lett. 117, 231102, 2016

AMS PUBLICATIONS - TIM#6 ANALYSIS - TODAY

- **HELIUM (He), CARBON (C), OXYGEN (O)** → Primary GCR
May 19, 2011 – May 26, 2016 → Total
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 ratios → Secondary / Primary
Li/B, Be/B ratios → Secondary / Secondary
May 19, 2011 – May 26, 2016 → Total
Aguilar et al., Phys. Rev. Lett. 120, 021101, 2018

- **HYDROGEN (H), HELIUM (He)** → Primary GCR
May 15, 2011 – May 9, 2017 → 79 Bartels rotations
Aguilar et al., Phys. Rev. Lett. 121, 051101, 2018
- **NITROGEN (N)** → Primary & Secondary GCR
N/O ratio → (Primary & Secondary) / Primary
N/B ratio → (Primary & Secondary) / Secondary
May 19, 2011 – May 26, 2016 → Total
Aguilar et al., Phys. Rev. Lett. 121, 051103, 2018

AMS DATA: HYDROGEN (PRIMARY) FLUX VS. RIGIDITY



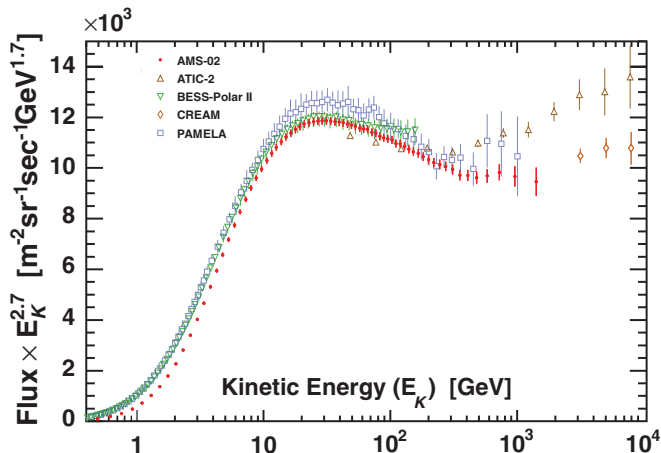
Scaled flux (right) emphasizes high energy shape

Famous break near 300 GV

Spectrum much harder than previous measurements

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

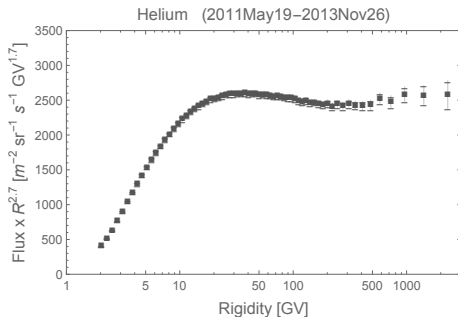
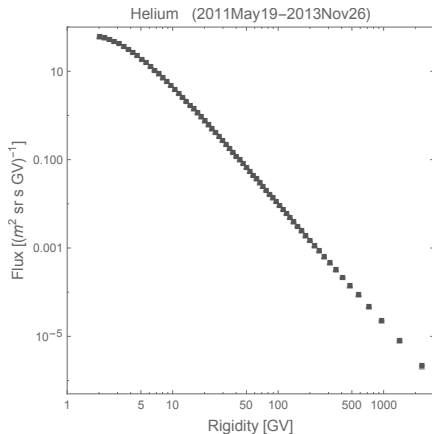
AMS & OTHER DATA: HYDROGEN FLUX VS. RIGIDITY



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

AMS data harder than previous high energy measurements

AMS DATA: HELIUM (PRIMARY) FLUX VS. RIGIDITY

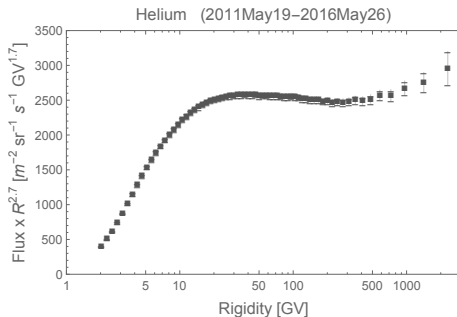
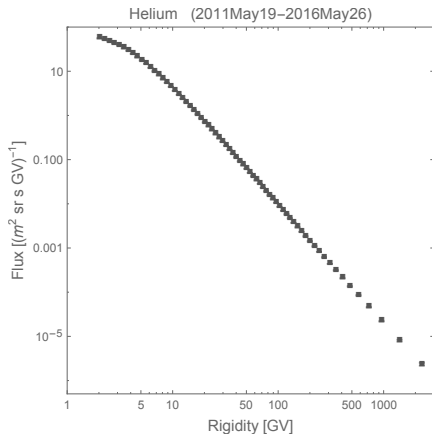


Scaled flux (right) emphasizes high energy shape

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

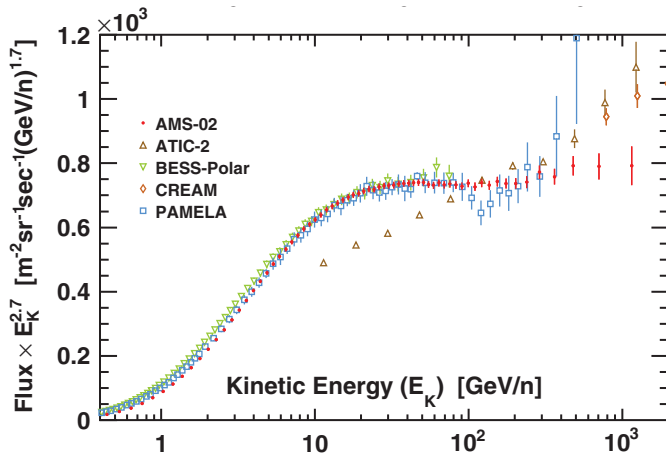


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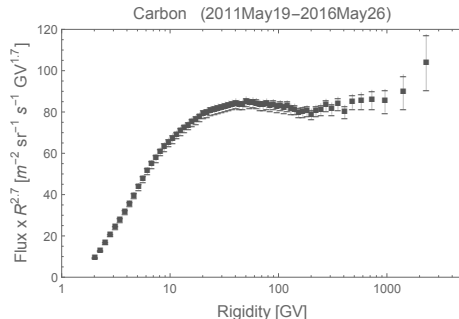
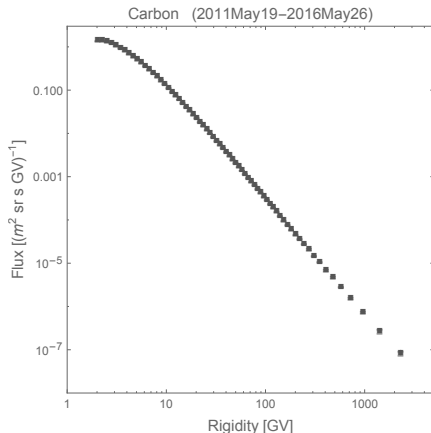
AMS & OTHER DATA: HELIUM FLUX VS. RIGIDITY



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

AMS data harder than previous high energy measurements

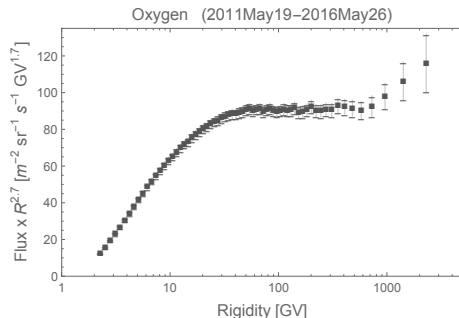
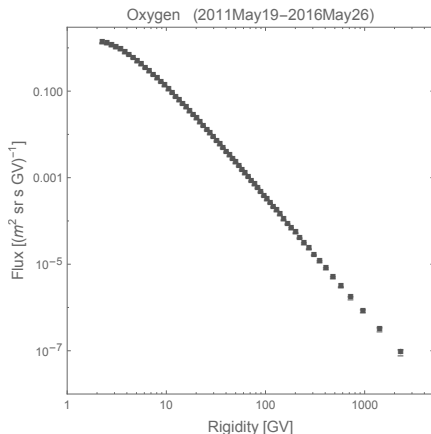
AMS DATA: CARBON (PRIMARY) FLUX VS. RIGIDITY



Scaled flux (right) emphasizes high energy shape

Similar break near 200 GV

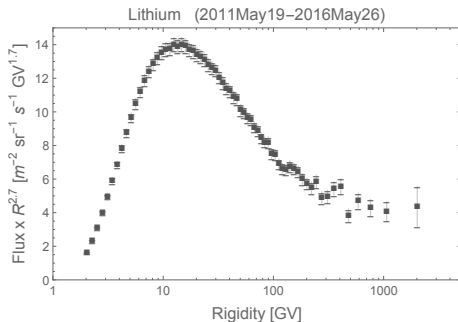
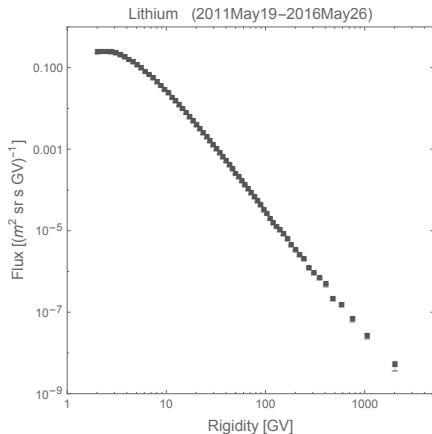
AMS DATA: OXYGEN (PRIMARY) FLUX VS. RIGIDITY



Scaled flux (right) emphasizes high energy shape

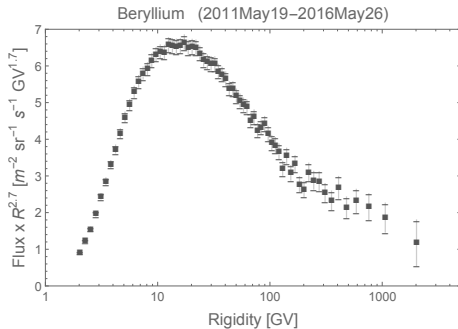
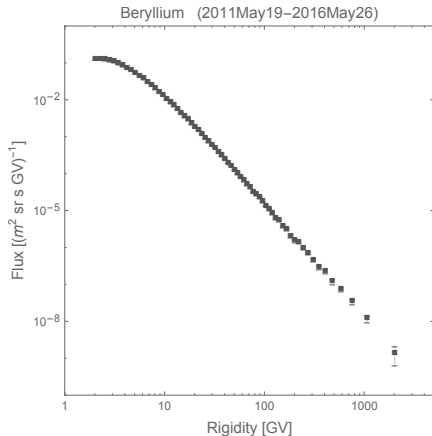
Similar break near 200 GV

AMS DATA: LITHIUM (SECONDARY) FLUX VS. RIGIDITY



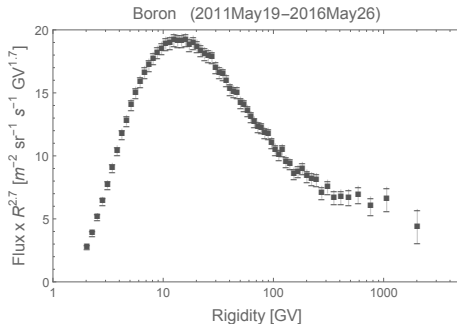
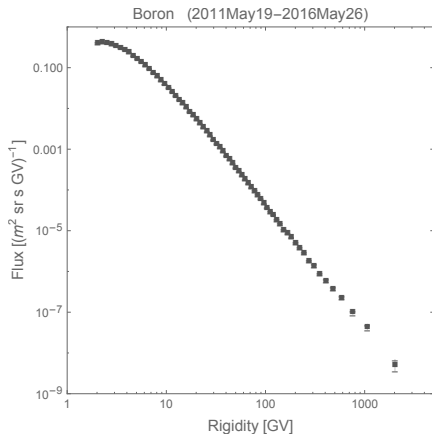
Scaled flux (right) emphasizes high energy shape
Secondary GCR spectra harder than primary spectra

AMS DATA: BERYLLIUM (SECONDARY) FLUX VS. RIGIDITY



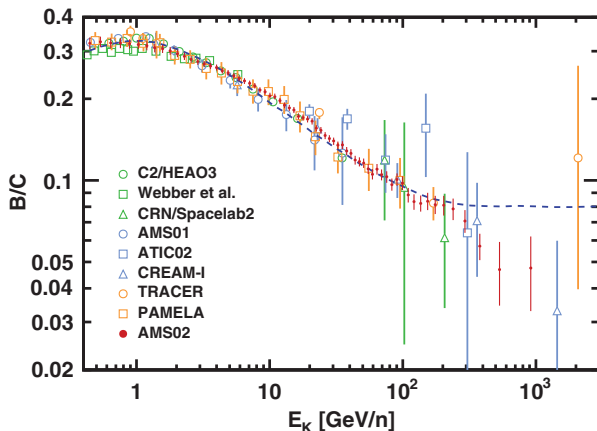
Scaled flux (right) emphasizes high energy shape
Secondary GCR spectra harder than primary spectra

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 ratio

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, 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**

O'Neill, Golge, Slaba, NASA Tech. Paper 218569, 2015

- **DLR model**

Matthia et al., Adv. Space Res. 51, 329, 2013

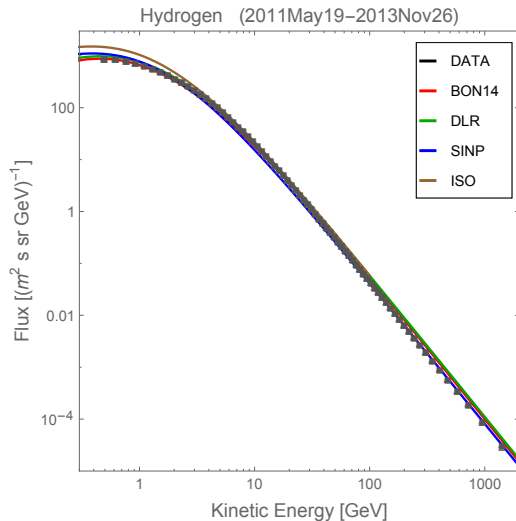
- **SINP model**

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

- **ISO15390 model - taken from SPENVIS**

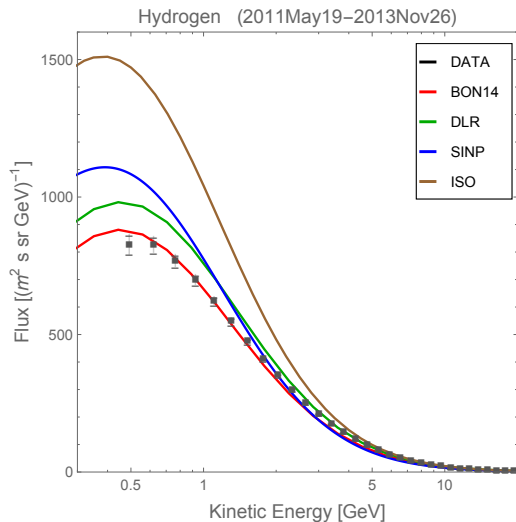
Nymmik et al., Adv. Space Res. 17, 19, 1996

RESULTS: HYDROGEN FLUX VS. KINETIC ENERGY



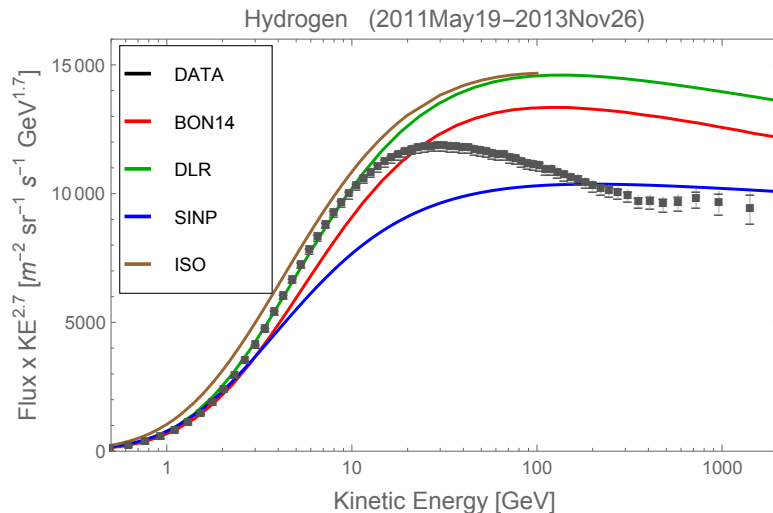
Model comparisons to data

RESULTS: HYDROGEN FLUX VS. KINETIC ENERGY



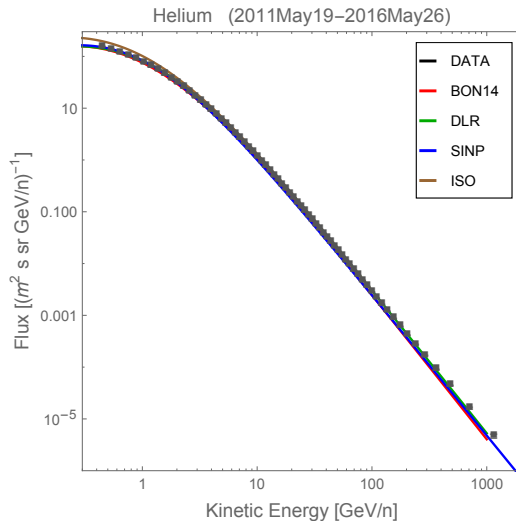
Model comparisons to data - linear plot

RESULTS: HYDROGEN FLUX (SCALED) VS. KINETIC ENERGY



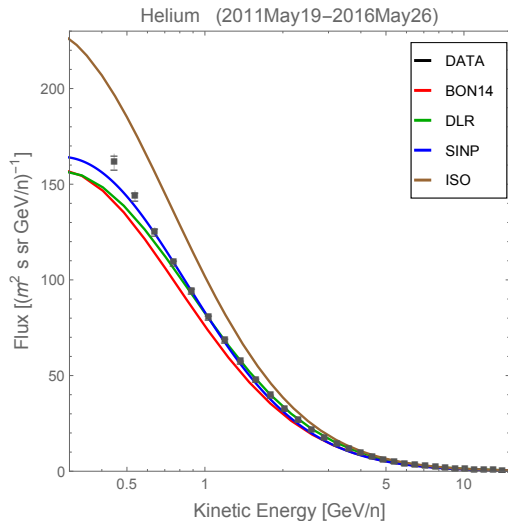
Model comparisons to scaled data

RESULTS: HELIUM FLUX VS. KINETIC ENERGY



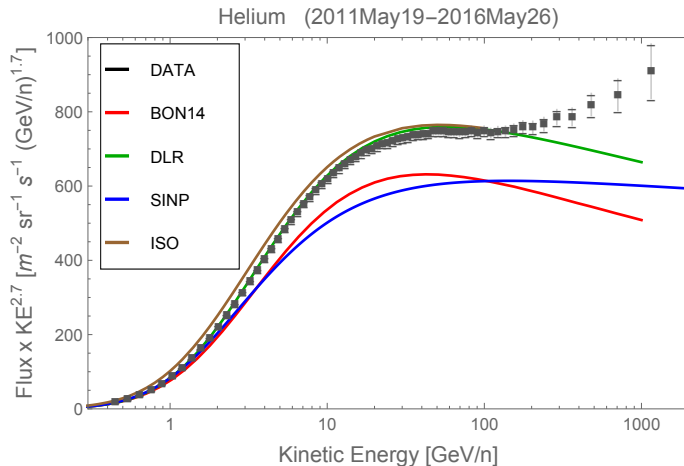
Model comparisons to data

RESULTS: HELIUM FLUX VS. KINETIC ENERGY



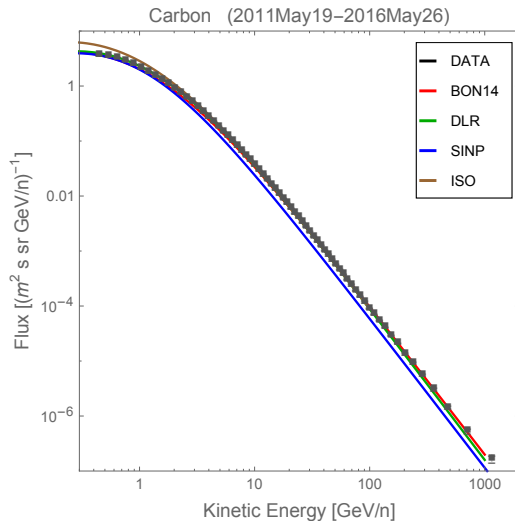
Model comparisons to data - linear plot

RESULTS: HELIUM FLUX (SCALED) VS. KINETIC ENERGY



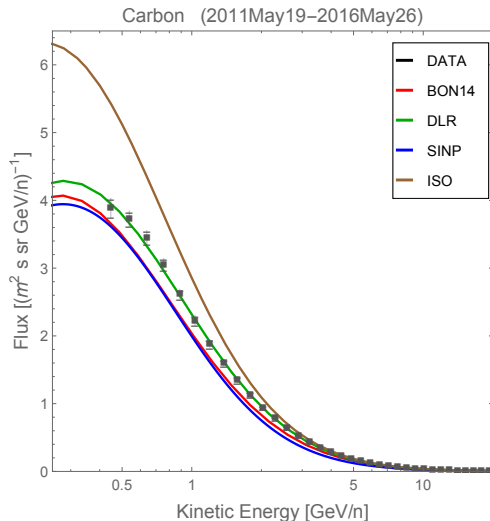
Model comparisons to scaled data

RESULTS: CARBON FLUX VS. KINETIC ENERGY



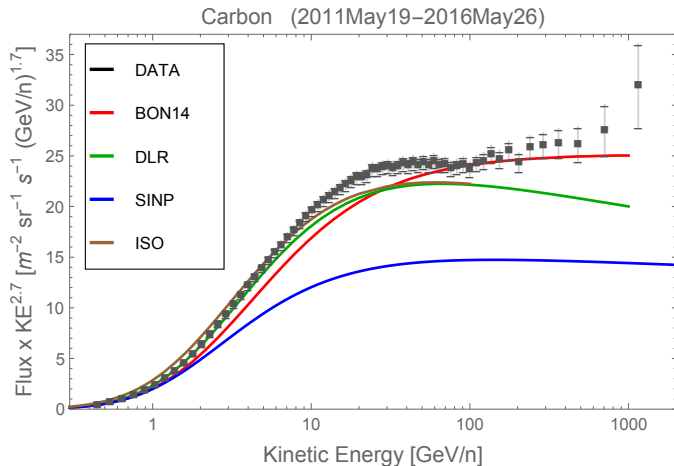
Model comparisons to data

RESULTS: CARBON FLUX VS. KINETIC ENERGY



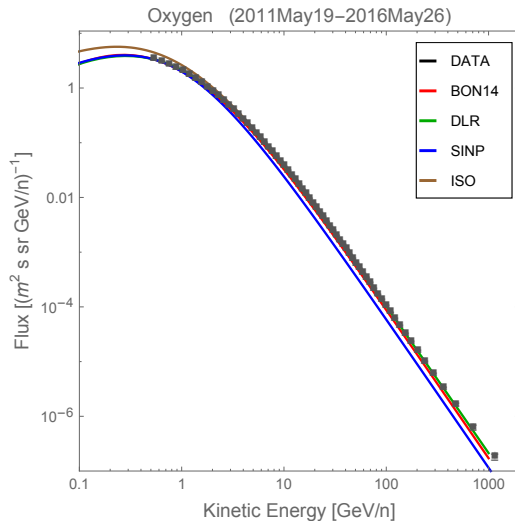
Model comparisons to data - linear plot

RESULTS: CARBON FLUX (SCALED) VS. KINETIC ENERGY



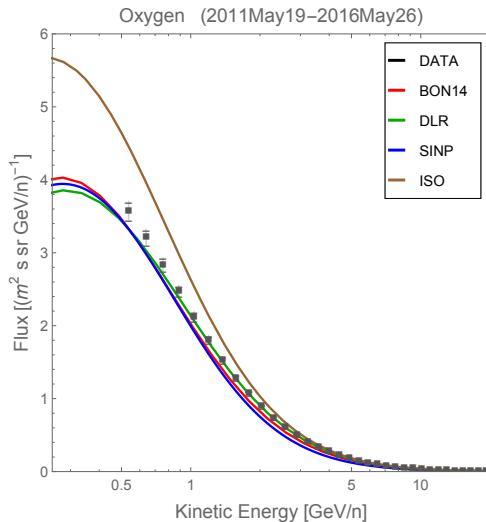
Model comparisons to scaled data

RESULTS: OXYGEN FLUX VS. KINETIC ENERGY



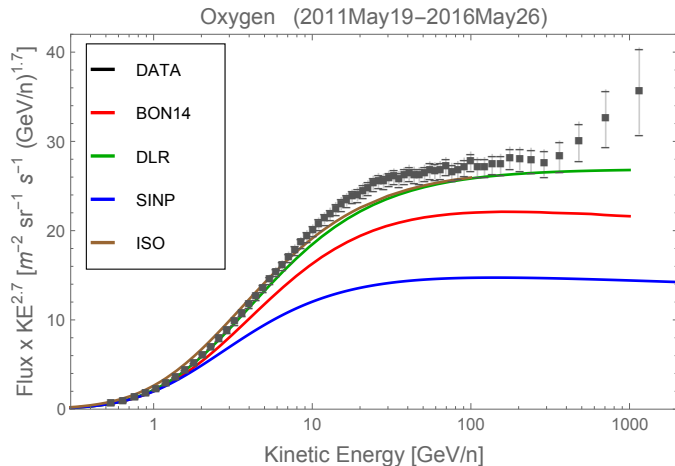
Model comparisons to data

RESULTS: OXYGEN FLUX VS. KINETIC ENERGY



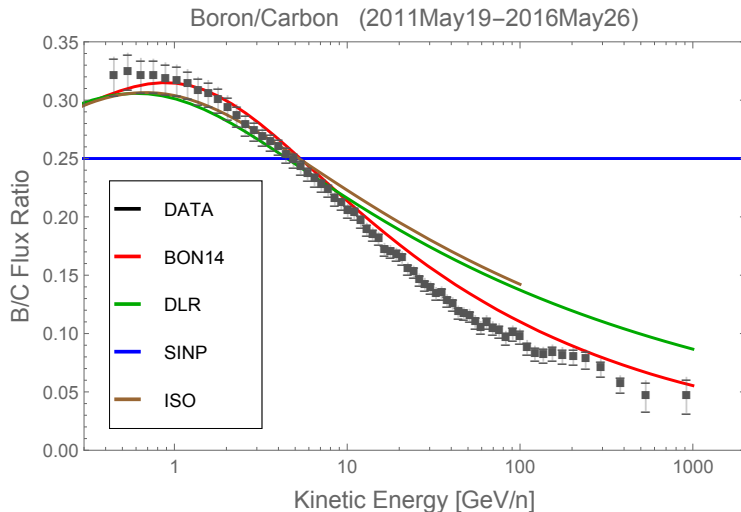
Model comparisons to data - linear plot

RESULTS: OXYGEN FLUX (SCALED) VS. KINETIC ENERGY



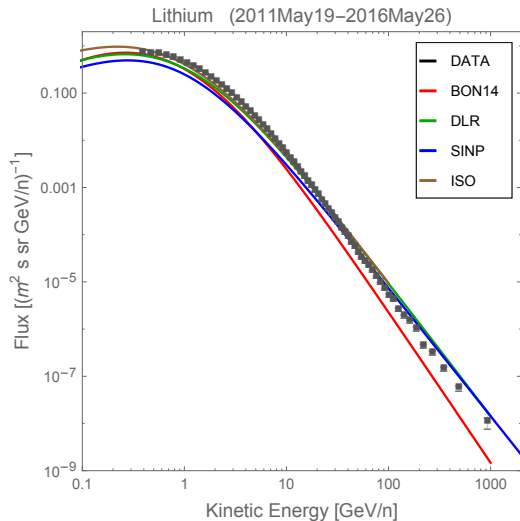
Model comparisons to scaled data

RESULTS: B/C RATIO VS. KINETIC ENERGY



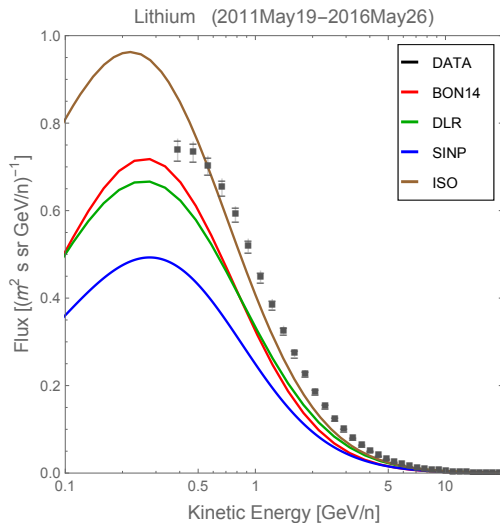
Model comparisons to data - linear plot

RESULTS: LITHIUM FLUX VS. KINETIC ENERGY



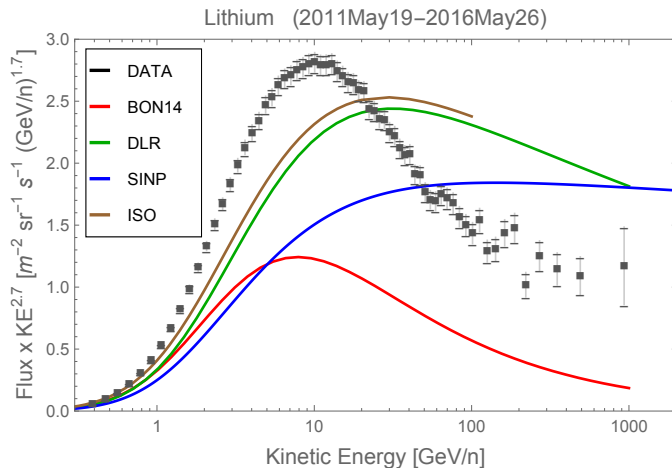
Model comparisons to data

RESULTS: LITHIUM FLUX VS. KINETIC ENERGY



Model comparisons to data - linear plot

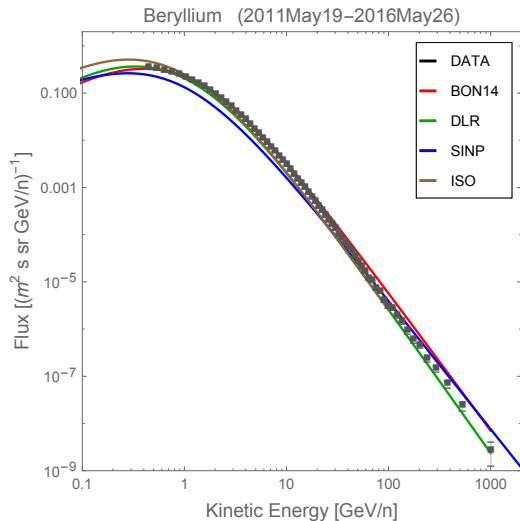
RESULTS: LITHIUM FLUX (SCALED) VS. KINETIC ENERGY



Model comparisons to scaled data

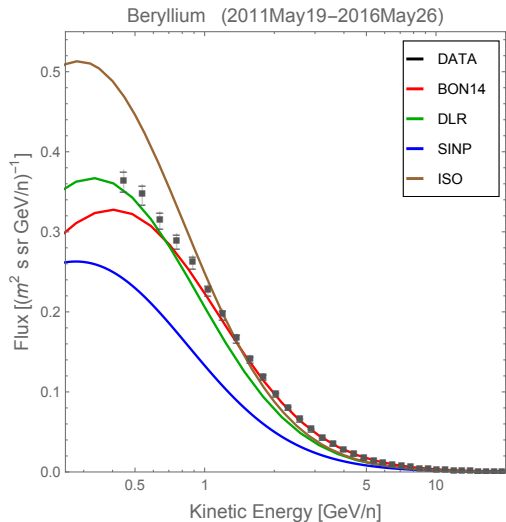
Models show spectral hardening for secondaries vs. primaries

RESULTS: BERYLLIUM FLUX VS. KINETIC ENERGY



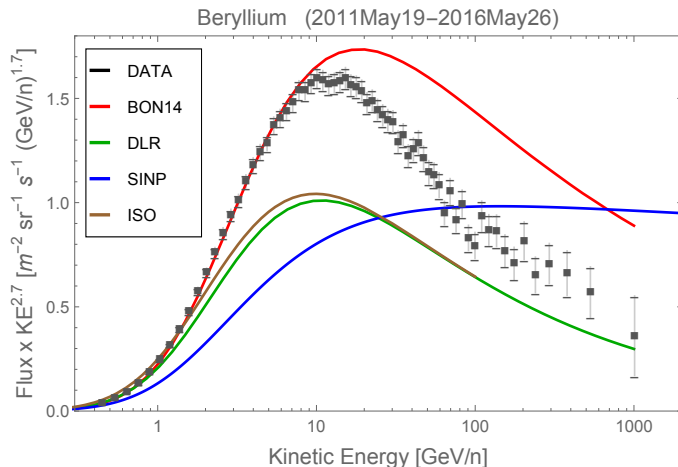
Model comparisons to data

RESULTS: BERYLLIUM FLUX VS. KINETIC ENERGY



Model comparisons to data - linear plot

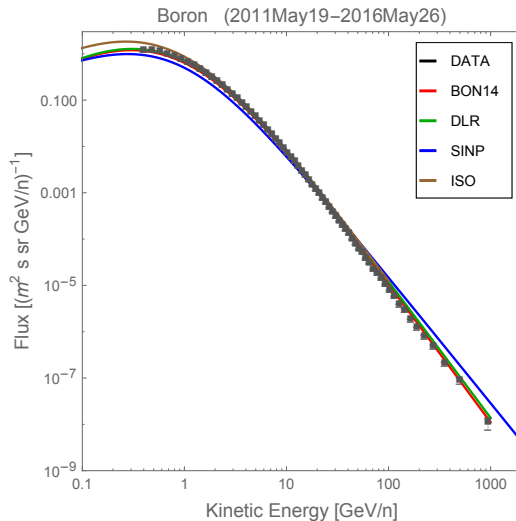
RESULTS: BERYLLIUM FLUX (SCALED) VS. KINETIC ENERGY



Model comparisons to scaled data

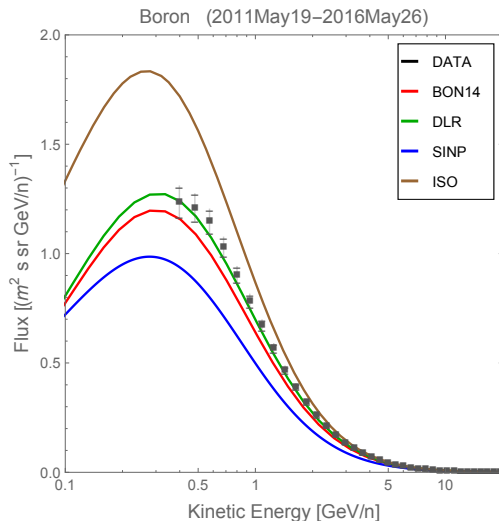
Models show spectral hardening for secondaries vs. primaries

RESULTS: BORON FLUX VS. KINETIC ENERGY



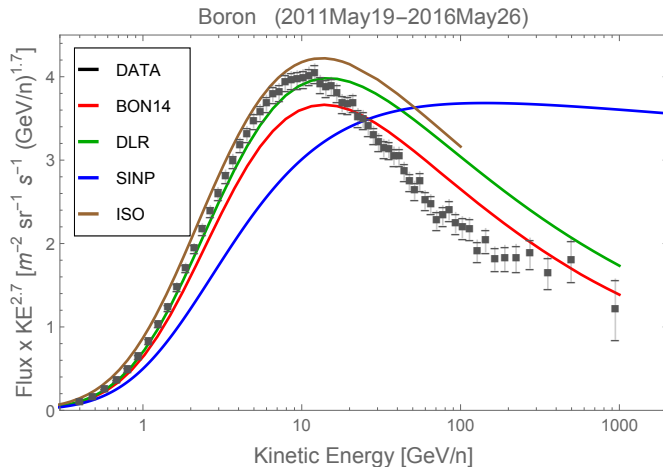
Model comparisons to data

RESULTS: BORON FLUX VS. KINETIC ENERGY



Model comparisons to data - linear plot

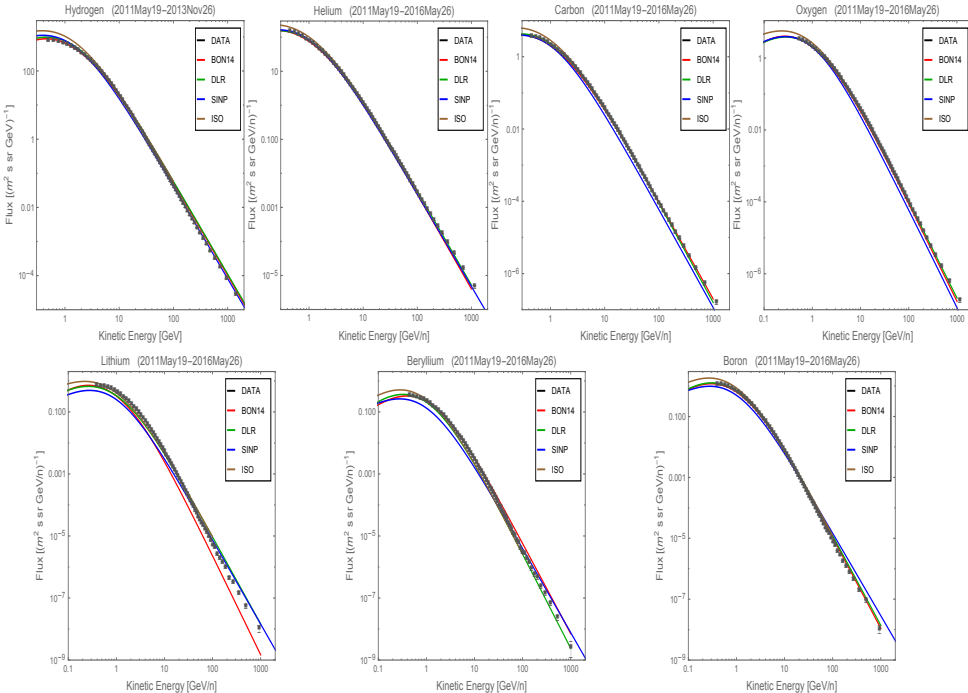
RESULTS: BORON FLUX (SCALED) VS. KINETIC ENERGY

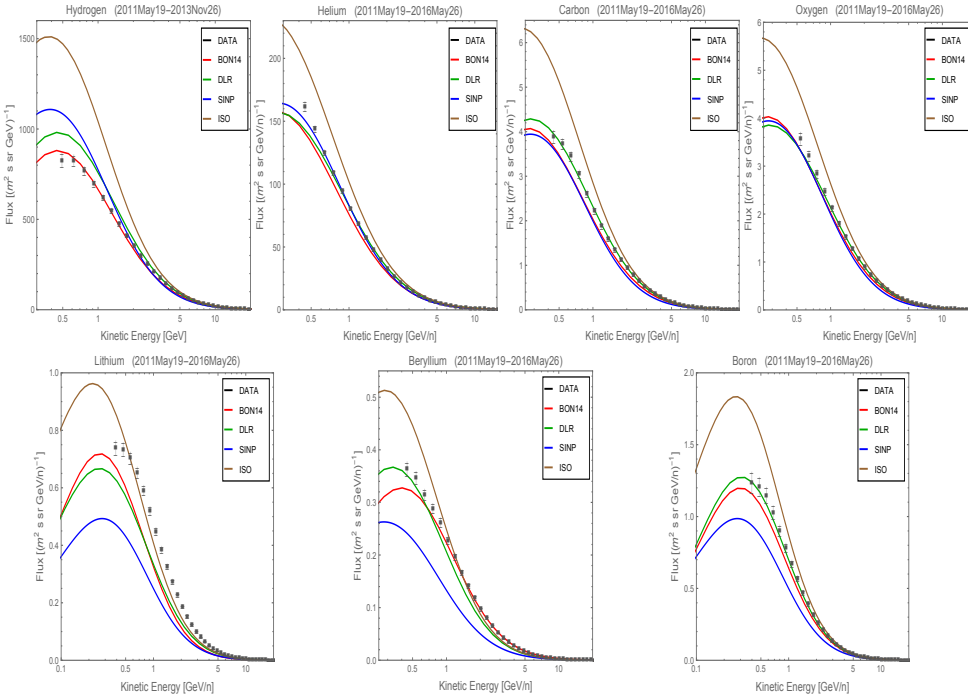


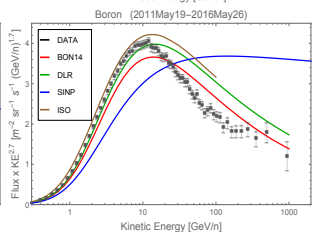
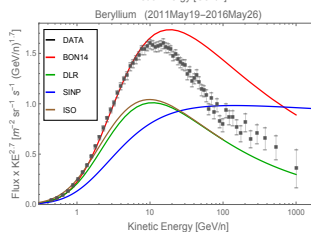
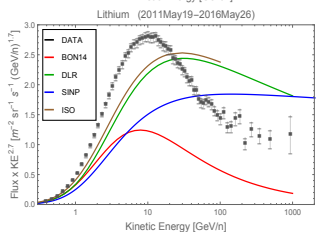
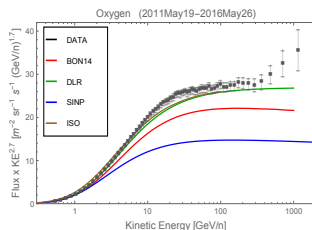
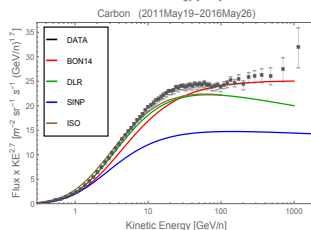
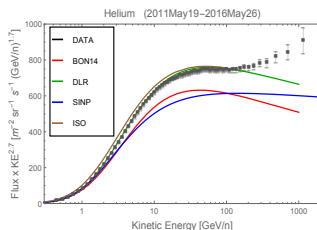
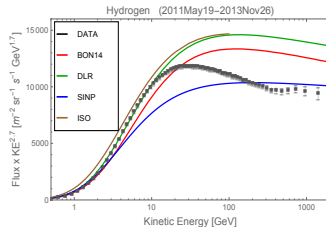
Model comparisons to scaled data

Models show spectral hardening for secondaries vs. primaries

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







SUMMARY

- 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
 - New PAMELA data now published
 - New AMS monthly data now published

SUMMARY OF ACTIONS

- ① The Russian team will provide the SINP-2016 GCR environment model to the ISMT Radiation Experts Team (Kuznetsov, Podzolko)
NASA JSC team implemented SINP-2016 GCR model from published results. Very useful help from Prof. Kuznetsov.
- ② NASA team will implement SINP-2016 into OLTARIS (Norbury)
SINP-2016 GCR environment model now available on OLTARIS
Thanks to Chris Sandridge, Tony Slaba, Kerry Lee, Katie Whitman
- ③ Publish analysis of AMS-II data presented at TIM#4
(Norbury, Matthiä, Kuznetsov, Podzolko)
Norbury, Whitman, Lee, Slaba, Badavi,
Life Sciences in Space Research 18, 64, 2018
- ④ Analyze new AMS-II data when the data become available
(Norbury, Matthiä, Kuznetsov, Podzolko)
New results shown today

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THE END

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