Results from AMS-02 on the International Space Station

June 9th, 2015
WIN2015, Heidelberg

Iris Gebauer for the AMS collaboration
AMS-02: THE ALPHA MAGNETIC SPECTROMETER 02

• **Volume** 64 m$^3$, height 4 m

• **Weight** 8500 kg

• **Power** 2500 W

• **Data downlink** 9 Mbps (minimum)

• **Magnetic field** 0.15 T (400 x Earth, PAMELA: 0.4 T, but H=44.5 cm)

• **Launch** May 16th, 2011 (Endeavour)

• **Data taking** as of May 19th, 2011

• **Construction** 1999-2010 (>3 PhD generations)

• **Mission duration**: until the end of ISS operation (currently 2024)
Cosmic ray spectra up to TeV energies
Indirect Dark Matter search: $e^+, \bar{p}, \gamma, \ldots$
Direct search for primordial antimatter: He, C, \ldots.
Solar physics effects over 11 years solar cycle
Gamma ray physics (skymaps, photon spectra)

TODAY:
Proton flux measurement
Positron fraction and electron and positron fluxes
Antiproton/proton ratio
Nuclei
GALACTIC COSMIC RAYS: FROM SOURCE TO US

\[ \pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm \]

SNR, p, e^-, Sun
AMS-02 RESULTS
The isotropic proton flux $\Phi_i$ for the $i^{th}$ rigidity bin $(R_i, R_i + \Delta R_i)$ is

$$\Phi_i = \frac{N_i}{A_i \epsilon_i T_i \Delta R_i}$$

$N_i$ is the number of events, 300 million proton events have been selected;
$A_i$ is the effective acceptance;
$\epsilon_i$ is the trigger efficiency;
$T_i$ is the measurement time (which depends in geomagnetic cutoff, orbit and operations).

To match the statistics, extensive systematic error studies were made.
AMS-02 PROTON FLUX

Flux $\times E_k^{2.7}$ [m$^{-2}$sr$^{-1}$sec$^{-1}$GeV$^{-1}$]

Kinetic Energy ($E_k$) [GeV]

AMS-02
ATIC-2
BESS-Polar II
CREAM
PAMELA
AMS-02 PROTON FLUX FIT TO TWO POWER LAWS:

$R^\gamma, R^\gamma + \Delta\gamma$ with a characteristic transition rigidity $R_0$ and smoothness $s$. 

\[ \Phi = C \left( \frac{R}{45 \text{ GV}} \right)^\gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta\gamma/s} \right]^s \]

Feature in source spectrum? Propagation effect?

Solid curve fit of Eq. $\Phi$ to the data.
(Fit to data above 45 GV: $\chi^2$/d.f. = 25/26)
Dashed curve uses the same fit values but with $\Delta\gamma$ set to zero.

$R_0 = 336 \pm 44^{(\text{fit})} \pm 66^{(\text{sys})} \pm 1^{(\text{sol})} \text{ GV}$

$\gamma = -2.845 \pm 0.02^{(\text{fit})} \pm 0.003^{(\text{sys})} \pm 0.004^{(\text{sol})}$

$\Delta\gamma = 0.133 \pm 0.032^{(\text{sys})} \pm 0.030^{(\text{sol})} \pm 0.005^{(\text{sol})}$
PHYSICS OF 11 MILLION $e^+$, $e^-$ EVENTS

Measuring electrons and positrons

**TRD**
(transition radiation)
to identify $e^\pm$

**ECAL** measures $E$
Tracker measures $p$
$e^\pm$: $E=p$
proton: $E<p$

**ECAL**
(shower shape)
to separate $e^\pm$ from protons
AMS-02 POSITRON FRACTION MEASUREMENT

Based on 10.9 million $e^+$ and $e^-$ events

- Flattening above 200 GeV confirmed
- Relative error on last point ~20%
- No hint at structure

Phys. Rev. Lett. 113, 121101 (Sept. 2014)
IS THERE A MAXIMUM IN THE POSITRON FRACTION?

There is an energy beyond which it ceases to increase

- Above 200 GeV the fraction no longer exhibits an increase with energy

- “Minimal model”:
  \[ \Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_c E^{-\gamma_c} e^{-\Xi_c} \]
  \[ \Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_c E^{-\gamma_c} e^{-\Xi_c} \]

common source

Zero crossing 275 +/- 32 GeV

11 million \(e^+, e^-\) events
COMBINED (\(e^+ + e^-\)) FLUX: EVENT SELECTION

Independent of charge sign measurement → no charge confusion

High selection efficiency: 70 % @ TeV
Small systematics on acceptance: 2% @ TeV
AMS-02 $e^+ + e^-$ FLUX

Energy Range: 0.5 GeV to 1 TeV

no feature in the sum flux

Phys. Rev. Lett. 113, 221102 (Nov 2014)
AMS-02 $e^+e^- \text{ FLUX}$

$$\gamma = \frac{d \log (\Phi)}{d \log (E)}$$

- Spectral index drops from -2.2 at 3 GeV to -3.2 above 10 GeV
- Remains constant above 30 GeV
\[ \Phi(e^+ + e^-) = C \ E^\gamma \]

\[ \gamma = -3.170 \pm 0.008 \text{ (stat + syst.)} \pm 0.008 \text{ (energy scale)} \]

\[ E > 30 \text{ GeV} \]

The flux is consistent with a single power law above 30 GeV.
WHAT DO WE LEARN FROM THE NEW DATA?

Models based on 15 mio. DRAGON runs.

$C_{CR} + p_{Gas} \rightarrow B + ...$

B/C fixed → cosmic ray interaction rate fixed → positrons fixed

boron/carbon

- ACE
- HEAO
- CREAM

Ratio vs. E (GeV/n)

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June 9th, 2015, WIN2015 Heidelberg
WHAT DO WE LEARN FROM THE NEW DATA?

Estimating the additional source contribution from data

\[ \text{e}^+ + \text{e}^- \text{ flux} \]

- **Primary e^-**: tuned for electron data
- **Signal**: calculated from \( \text{e}^+ + \text{e}^- \) data
- **Secondary e^+**: transport model prediction (15 Mio models)

break required
ANTIPROTON/PROTON RATIO

\[ \frac{\bar{p}}{p} \text{ ratio} \]

\[ 10^{-4} \]

\[ 10^{-5} \]

\[ \text{IRigidity} \ (\text{GV}) \]

AMS-02
ANTIPROTON/PROTON RATIO

CAVEAT: additional uncertainties from cross sections not included

Secondary production (optimized for PAMELA)
ANTIPROTON/PROTON RATIO

CAVEAT: additional uncertainties from cross sections not included

Secondary production (optimized for PAMELA)
AMS-02 NUCLEI MEASUREMENTS

AMS proton flux

Lithium flux

AMS Helium Flux

B/C Ratio

- Exposure time of 40 months
- 7M Carbons, 2M Borons

Flux $\times R^{2.7}$ [m$^{-2}$sr$^{-1}$s$^{-1}$GV$^{-1}$]

Rigidity [GV]

Flux $\times R^{2.7}$ [GV$^{1.7}$ m$^{-2}$ sr$^{-1}$ s$^{-1}$]

Rigidity [GV]
SUMMARY

AMS-02 is operating stable on the ISS since May 2011.

The latest AMS measurements of the positron fraction, the antiproton/proton ratio, the behavior of the fluxes of electrons, positrons, protons, helium, and other nuclei provide precise and unexpected information.

The accuracy and characteristics of the data, require a comprehensive model to ascertain if their origin is from dark matter, astrophysical sources, acceleration mechanisms or a combination.
OPERATING AMS-02 ON THE ISS

TRD
24 Heaters
8 Pressure Sensors
482 Temperature Sensors

Silicon Tracker
4 Pressure Sensors
32 Heaters
142 Temperature Sensors

ECAL
80 Temperature Sensors

TOF & ACC
64 Temperature Sensors

Magnet
68 Temperature Sensors

RICH
96 Temperature Sensors

1118 temperature sensors
5 radiators
298 thermostatically controlled heaters
POCC: PAYLOAD OPERATIONS CONTROL CENTER

POCC
Payload Operations Control Center

Monitoring + Commanding

Communication with NASA

4 positions monitoring
11 Subdetectors (24/7)

LEAD position monitoring the entire system

CERN, Geneve
CSIST, Taiwan
DATA ACQUISITION

AMS

TDRS Satellites

Astronaut at ISS AMS Laptop

Ku-Band
High Rate (down): Events <10Mbit/s

S-Band
Low Rate (up & down):
Commanding: 1 Kbit/s
Monitoring: 30 Kbit/s

Flight Operations

Ground Operations

AMS-02 ↔ GROUND

POCC, SOC at CERN

AMS computers at MSFC, AL

White Sands, Ground Terminal, NM
VERIFICATION OF POSITRON FRACTION

Using two independent samples:
Positron fraction analysis with TRD only

Good agreement between TRD only and full sample.
ELECTRON AND POSITRON FLUXES

spectral index = \frac{d \log (\Phi)}{d \log (E)}

$\Phi(e^+ + e^-) = C \cdot E^\gamma$

$\gamma = -3.170 \pm 0.008 \text{ (stat + syst.)} \pm 0.008 \text{ (energy scale)}$

$E > 30 \text{ GeV}$
SYSTEMATIC ERRORS ON THE PROTON FLUX

- $\sigma_{\text{trig}}$: trigger efficiency
- $\sigma_{\text{acc}}$: I) the acceptance and event selection
  II) background contamination
  III) geomagnetic cutoff
- $\sigma_{\text{unf}}$: I) unfolding
  II) rigidity resolution function
- $\sigma_{\text{scale}}$: the absolute rigidity scale

<table>
<thead>
<tr>
<th>Rigidity [GV]</th>
<th>$\Phi$</th>
<th>$\sigma_{\text{stat.}}$</th>
<th>$\sigma_{\text{trig.}}$</th>
<th>$\sigma_{\text{acc.}}$</th>
<th>$\sigma_{\text{unf.}}$</th>
<th>$\sigma_{\text{scale}}$</th>
<th>$\sigma_{\text{syst.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 – 108</td>
<td>(4.085)</td>
<td>0.007</td>
<td>0.006</td>
<td>0.040</td>
<td>0.035</td>
<td>0.022</td>
<td>0.058 $\times 10^{-2}$</td>
</tr>
<tr>
<td>108 – 116</td>
<td>(3.294)</td>
<td>0.007</td>
<td>0.005</td>
<td>0.033</td>
<td>0.028</td>
<td>0.018</td>
<td>0.047 $\times 10^{-2}$</td>
</tr>
<tr>
<td>116 – 125</td>
<td>(2.698)</td>
<td>0.006</td>
<td>0.004</td>
<td>0.027</td>
<td>0.023</td>
<td>0.016</td>
<td>0.039 $\times 10^{-2}$</td>
</tr>
<tr>
<td>125 – 135</td>
<td>(2.174)</td>
<td>0.005</td>
<td>0.004</td>
<td>0.022</td>
<td>0.019</td>
<td>0.013</td>
<td>0.032 $\times 10^{-2}$</td>
</tr>
<tr>
<td>135 – 147</td>
<td>(1.727)</td>
<td>0.004</td>
<td>0.003</td>
<td>0.018</td>
<td>0.016</td>
<td>0.011</td>
<td>0.026 $\times 10^{-2}$</td>
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<tr>
<td>147 – 160</td>
<td>(1.358)</td>
<td>0.003</td>
<td>0.003</td>
<td>0.014</td>
<td>0.013</td>
<td>0.009</td>
<td>0.021 $\times 10^{-2}$</td>
</tr>
<tr>
<td>160 – 175</td>
<td>(1.065)</td>
<td>0.003</td>
<td>0.002</td>
<td>0.011</td>
<td>0.010</td>
<td>0.007</td>
<td>0.017 $\times 10^{-2}$</td>
</tr>
<tr>
<td>175 – 192</td>
<td>(8.212)</td>
<td>0.023</td>
<td>0.017</td>
<td>0.087</td>
<td>0.079</td>
<td>0.059</td>
<td>0.133 $\times 10^{-3}$</td>
</tr>
<tr>
<td>192 – 211</td>
<td>(6.299)</td>
<td>0.019</td>
<td>0.014</td>
<td>0.068</td>
<td>0.062</td>
<td>0.047</td>
<td>0.104 $\times 10^{-3}$</td>
</tr>
<tr>
<td>211 – 233</td>
<td>(4.793)</td>
<td>0.015</td>
<td>0.011</td>
<td>0.053</td>
<td>0.049</td>
<td>0.039</td>
<td>0.083 $\times 10^{-3}$</td>
</tr>
<tr>
<td>233 – 259</td>
<td>(3.605)</td>
<td>0.012</td>
<td>0.009</td>
<td>0.040</td>
<td>0.039</td>
<td>0.031</td>
<td>0.065 $\times 10^{-3}$</td>
</tr>
<tr>
<td>259 – 291</td>
<td>(2.647)</td>
<td>0.009</td>
<td>0.007</td>
<td>0.030</td>
<td>0.029</td>
<td>0.024</td>
<td>0.049 $\times 10^{-3}$</td>
</tr>
<tr>
<td>291 – 330</td>
<td>(1.884)</td>
<td>0.007</td>
<td>0.006</td>
<td>0.022</td>
<td>0.022</td>
<td>0.019</td>
<td>0.037 $\times 10^{-3}$</td>
</tr>
</tbody>
</table>
AMS-02 PROTON FLUX SPECTRAL INDEX VARIATION:
Model independent measurement of spectral index

\[ \gamma = \frac{d \log (\Phi)}{d \log (R)} \]

Feature in source spectrum? Feature during propagation?
\[ \gamma = \frac{d \log (\Phi)}{d \log (R)} \]
SPECTRAL INDEX OF THE PROTON FLUX FOR 2011-2013
TRANSPORT MODELS IN THE AMS-02 ERA

Optimized for AMS-02

Optimized for PAMELA

proton spectrum $R^{2.7}$

B/C

AMS-02

Optimized for AMS-02

AMS-02

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Antiproton event: \[ R = -423 \text{ GV} \]
ANTIPROTON-PROTON RATIO

\[ \frac{\bar{p}}{p} \text{ ratio} \]

\[ 10^{-4} \]

\[ 10^{-5} \]

\[ 10^{-6} \]

\[ 100 \]

\[ 200 \]

\[ 300 \]

\[ 400 \]

\[ 500 \]

Kinetic Energy (GeV)

AMS-02

PAMELA

BESS
WHAT DO WE LEARN FROM THE NEW DATA?

Models based on 15 mio. DRAGON runs.

- **Proton spectrum**
  - *Pamela* model
  - $\sigma$ models (LIS)
  - $\sigma$ models
  - FF-modulated

- **Antiproton/proton**
  - *Pamela* model
  - $p_{CR} + p_{Gas} \rightarrow \bar{p} + ...$

- **Boron/carbon**
  - $C_{CR} + p_{Gas} \rightarrow B + ...$

- **Interaction rate of CRs**

- **AGE of CRs**
  - $^{10}\text{Be} \rightarrow B + e^+ + ...$
  - $^{9}\text{Be} \rightarrow B + ...$
WHAT DO WE LEARN FROM THE NEW DATA?

Models based on 15 mio. DRAGON runs.

1σ models (LIS)

1σ models
FF-modulated

Pamela

\[ p_{CR} + p_{Gas} \rightarrow \bar{p} + ... \]

\[ C_{CR} + p_{Gas} \rightarrow B + ... \]

B/C fixed
→ positrons fixed

\[ ^{10}\text{Be} \rightarrow B + e^+ + ... \]

\[ ^{9}\text{Be} \rightarrow B + e^+ + ... \]
AMS-02 COLLABORATION

16 countries, 56 institutes, ~500 physicists
95% of AMS was constructed in Europe and Asia
Protons ~90% He ~10%, heavy nuclei (mainly C) ~1%, $e^-$ ~1%, traces of $e^+$, anti-$p$, ...

Power law:

$$\Phi(E) dE \propto E^{-\gamma} dE$$

$$\gamma \approx 2.6 - 2.7$$

$$\gamma \approx 3, \ E > 10^{15} \text{eV}$$