Review on direct measurements of Cosmic Rays

May 22nd, 2018
Vulcano Workshop, Vulcano, Italy
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THE SPECTRUM OF COSMIC RAYS

all particle flux

Direct measurements

Indirect measurements

$\frac{dN}{dE} = [m^{-2} sr^{-1} s^{-1} GeV^{-1}]$

at first sight ... a featureless power law

L. Baldini, arXiv: 1407.7631
ISS: 400 km
AMS-02
CALET
ISS-CREAM

PAMELA: 350-600 km
DAMPE: 500 km
Fermi: 550 km

Modern balloons
~30 km

Kolhörster
9 km

CREAM launch, McMurdo

Antares
KM3NeT
IceCube, South Pole

Auger Observatory, Argentina

See A. Capone, M. Circella, C. Kopper
See V. de Souza today
PHYSICS QUESTIONS IN DIRECT COSMIC RAY MEASUREMENTS

- What is the origin of galactic cosmic rays and how do they propagate to us?

- Do we understand the diffuse galactic gamma-ray emission from cosmic ray interactions or is there room for new physics (e.g. Dark Matter)

- What is the nature of the elusive Dark Matter? Do we see annihilation/decay signals in cosmic rays? → Antimatter! Photons, neutrinos.

- Is there primordial antimatter left in our Universe?
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The “conventional scenario” of galactic cosmic rays

Cosmic ray fluxes below the knee can be described by a single power law, the spectral index being the result of the following processes:
- production
- acceleration
- propagation

Primary cosmic ray fluxes have universal (species independent) spectral indices.

Antimatter component is purely of secondary origin (no sources of CR antimatter).

Precise measurements provided by the current generation of CR detectors (PAMELA, AMS-02, Fermi-LAT, CREAM, CALET, DAMPE…) have been providing new insight to the physics of cosmic rays, by challenging the previous statements.

P. Serpico ICRC2015
L. Drury ICRC2017
see also G. Morlino today
see also F. Aharonian today
SOME RECENT SPACEBORNE DETECTORS
AMS-02: A TeV PRECISION SPECTROMETER

Transition Radiation Detector
Identify $e^+$, $e^-$

Particles and nuclei are defined by their charge ($Z$) and energy ($E$) or rigidity ($R=p/Z$)

Silicon Tracker
$Z$, $R$

Electromagnetic Calorimeter
$E$ of $e^+$, $e^-$

Time of Flight
$Z$, $E$

Magnet
$\pm Z$, $R$

Ring Imaging Cherenkov
$Z$, $E$

Charge and energy are measured independently by many detectors
For every positron there are $10^3$-$10^4$ protons and $\sim10$ electrons.

It took AMS 2 years to perform this measurement.

Major challenge:
selection purity → proton background, charge confused electrons.
ELECTRONS AND POSITRONS.... *a few years ago*

![Graph showing electron and positron flux vs energy](image-url)
The spectra of $e^-$ and $e^+$ different. There is a maximum in the $e^+$ flux around 300 GeV.
The data are consistent with a symmetric contribution in $e^+$ and $e^-$. 
Interpretation of the positron data

The data are consistent with a symmetric contribution in $e^+$ and $e^-$. Could be explained by:

- **Dark Matter annihilation**
  $\rightarrow O(100)$ papers

- **Astrophysical point sources like pulsars**
  $\rightarrow O(100)$ papers

- **Secondary $e^+$ production**
  $\rightarrow$ a few papers

\[\text{PRL. 113, 121102 (2014)} \rightarrow 500 \text{ GeV Prelim. Data} \rightarrow 700 \text{ GeV} \]

\[\text{P.L. Biermann et al. [arXiv:1803.10752]} \]
SOME HIGHLIGHTS FROM SPACE: ANTIPROTONS

There is only 1 antiproton for 10,000 protons.

→ A percent precision experiment requires a background rejection close to 1 in a million.

It took AMS 5 years to perform this measurement.

Major challenge: purity of selection and tracker unfolding.
Model expectation for secondary $p$ production.

$[PRL \ 102, \ 051101 \ (2009)]$

$\frac{\bar{p}}{p}$ vs kinetic energy (GeV)
The antiproton/proton ratio is flat.

The $\bar{p}/p$ ratio has a slope of $(-0.7\pm0.9) \times 10^{-7}$ GV$^{-1}$. It is consistent with 0.

$3.49 \times 10^5$ antiprotons
$2.42 \times 10^9$ protons

$[\text{PRL 117, 091103 (2016)}]$
Interpretation of anti-p data

Anomaly in antiprotons?

Uncertainties in the astrophysical background predictions are reducing with the new results of AMS-02, however the x-section uncertainties in some cases are 20-50% or higher. Stay tuned …

G. Giesen+(2015)

N. Tomassetti+(2017)
The rigidity dependence of $e^+$, $\bar{p}$, $p$ is identical from 60-500 GV.
What we are learning from cosmic rays antimatter:

-There is an excess of positrons.
Positron measurements are inconsistent with pure secondary hypothesis. We do need a nearby source to reproduce the data. We have many ideas how to explain this, including pulsars and dark matter.

-Excess of antiprotons?
A flat antiproton-to-proton ratio is unexpected, however it is not sure there is an anomaly. The astrophysical background is affected by large uncertainties that may reduce in view of latest CR data, but x-section uncertainties are ~20-50%. Be ready for surprises ...

-The spectra of protons, positrons and antiprotons have identical rigidity dependence above 60 GV.
Currently very few ideas.
Cosmic ray proton and helium fluxes

until a few decades ago…

Issues:
• large uncertainties
• small energy range covered by a single experiment
Cosmic ray measurements until a few decades ago…

1970-2000 Issues:
• large uncertainties
• small energy range covered by a single experiment
hints of surprises ...

When the GeV-TeV region became to be explored with sufficient precision … hints of possible features emerged in p, He but also in heavier nuclei and antimatter!

CREAM results [Ahn+2010]

Change in spectral index suggested around 200 GeV/n

Both the energy range and the flux uncertainties prevented a clear claim for a break in p,He spectra
1st Evidence for a broken power law in CR fluxes

PAMELA Science 2011

Proton flux

Helium flux

A single instrument covering the whole energy range was solving the puzzle
Proton and helium flux

- Based on 300 million events (2011-2013)
- The proton flux cannot be described by a single power law.
- A transition in the spectral index occurs around 200 GV.

- Based on 50 million events (2011-2013)
- The helium flux cannot be described by a single power law.
- A transition in the spectral index occurs around 200 GV.

Proton flux
PRL 114, 171103 (2015)

Helium flux
PRL 115, 211101 (2015)
p/He flux ratio

AMS: this ratio is not flat.

He spectrum is harder

Theoretical prediction

AMS-02

Single power law fit (R>45 GV)

Traditional Models


non-universality

this ratio is not flat.
Latest Cosmic ray measurements (since 2014)
Latest Cosmic ray measurements (since 2014)

Galactic cosmic ray fluxes cannot be described as a single power law. The spectral features are the “fingerprints” of their origin and propagation.
Identical rigidity dependence of He, C and O

They all deviate from a single power law above 200 GV and harden in an identical way.

\[ \text{Flux} \times \tilde{R}^{2.7} \left[ \text{m}^2\text{s}^{-1}\text{sr}^{-1}(\text{GV})^{1.7} \right] \]

\[ \text{Rigidity } \tilde{R} \left[ \text{GV} \right] \]

PRL 119, 251101 (2017)

p/C and p/O ratio show identical behaviour as p/He
Primary-to-primary ratios

PRL 119, 251101 (2017)
Summary on spectral breaks

PRL 120, 021101 (2018)
How to investigate the spectral hardening

• **Spectral hardening at high energy observed in primaries and secondaries.**

• **Plausible explanations include:**
  
  – **Hardening of the injected spectrum from the source**
    
    • Same hardening expected for secondaries and primaries
    • No hardening of the Sec./Prim. ratio

  – **Changes in the propagation properties in the Galaxy**
    
    • Stronger hardening expected for Secondaries
    • Hardening of the Sec./Prim. Ratio
Secondary nuclei are only produced via collisions in the ISM

$$\Phi_s = Q_s \tau_{diff} \propto \sigma_{p \rightarrow s} \Phi_p \tau_{diff}$$

The secondary to primary flux ratios provide informations about the diffusion process:

$$\frac{\Phi_s}{\Phi_p} \propto \tau_{diff}(E) \propto E^\delta$$

Usually
studied with B/C
Secondary to primary ratios

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Usually studied with B/C
The Boron-to-Carbon flux ratio disfavours several CR models predicting a rise at high energies.

PRL 117, 231102 (2016)
• Using cosmic-ray boron to carbon ratio (B/C) data we find indications for a diffusive propagation origin for the broken power-law spectra found in protons (p) and helium nuclei (He).
• The result is robust with respect to currently estimated uncertainties in the cross sections, and in the presence of a small component of primary boron, expected because of spallation at the acceleration site.
• Reduced errors at high energy as well as further cosmic ray nuclei data definitely confirm this scenario.
Measurement of Li, Be, B
PRL 120, 021101 (2018)

- Based on 5 million nuclei (2011-2016)
- A transition in the spectral index occurs around 200 GV also for secondaries.
- Secondary fluxes harden more than primaries.
- The transition in the spectral index is confirmed.
What we are learning from cosmic ray nuclei:

The observational improvements occurred during the past decade challenge the ‘conventional’ model for cosmic ray origin/propagation.

A new precision level in the GeV to TeV energy region has been reached.

Transition in the spectral index of primary nuclei (p, He, C, O) observed around 200 GV. Li, Be and B fluxes also show a hardening. However, the secondaries harden more than the primaries.

Precise measurement of B/C together with other secondary-to-primary ratios provides important clues to understand the nature of spectral breaks.

It is now time to combine these high quality data to establish an updated conventional model for CRs below the knee.
Recent results from CREAM-III and NUCLEON did confirm the scenario up to about 100 TeV but with large uncertainties.

Current missions like CALET and DAMPE have the needed resolution to check the break region and determine the spectral behaviour up to more than 100 TeV.
DAMPE AND CALET WITH FIRST RESULTS!

There is a lot more to come......

[DAMPE]
Proton flux (prelim.)
[Yue et al. PoS (ICRC 2017) 1076]

[CALET]
Heavy nuclei (prelim.)
[Shoji Torii, AMS Days 2018]

Gamma-ray sky (prelim.)
[Lei et al. PoS (ICRC 2017) 616]

B/C (prelim.)
[Shoji Torii, AMS Days 2018]

[see also P. S. Marrocchesi @ Vulcano]
THE COMBINED ($e^+ + e^-$) FLUX

The combined $e^+ + e^-$ flux is a difficult measurement and it is difficult to interpret. The results of the space experiments are not consistent. They come in two groups: (AMS and CALET) ↔ (Fermi and DAMPE).
WHERE WE ARE

Few decades ago …

A “standard paradigm” for cosmic ray transport (with some problems).

You are here

The accuracy of the data challenges the “standard paradigm”.

Future

CALET, DAMPE, ISS-CREAM,…

● Statistics!
● High energies!
● New answers and new questions!
● Only matter.
Summary

Direct CR measurements are a gateway to some of the most fundamental questions in our universe, like the understanding of the nature of dark matter and the baryon asymmetry in our Universe. The answers to these questions requires, as a first step, a detailed understanding of cosmic ray sources and transport in our galaxy.

The observational improvements occurred during the past decade brought to light a lot of unexpected features below the knee reveal new physics phenomena that should be incorporated in a coherent model for cosmic ray origin/propagation.

The uncertainties in the isotopic x-sections are still 20-50% or even larger, and this affect the uncertainty on the astrophysical background, that is the fundamental key for discovery of new physics. Indirect search for dark matter with charged cosmic rays is a powerful tool, but so far no clear consensus. Stay tuned for antideuterons ....

The accuracy achieved by PAMELA and AMS-02 measurements brought CR physics to a precision level.

The new experiments are CALET, DAMPE and ISS-CREAM all equipped with powerful calorimeters. They will collect unprecedented statistics and improve our knowledge on CR matter.