A New Era for Galactic Cosmic Rays

Veronica Bindi
Physics and Astronomy Department
University of Hawaii at Manoa
Honolulu, Hawaii, US
Over the last 15 years the number of experiments in space and on ground looking at GCRs and gamma rays is increased dramatically.

- Interest in the field
- New data
- New discoveries
Open questions to address:

• Indirect search of Dark Matter in multiple channels (e+, antiP, antiD, gammas …)
• Anti-matter in space
• GCR composition, acceleration and their maximum energy
• GCR propagation in the galaxy and in the heliosphere
• GCR sources and anisotropies -> Gamma rays (Fermi and ground experiments)

Talk Covers:
Balloon and space particle detectors

Leaves out: Gammas and ground experiments (covered by various talks at TeVPA)
Status at the beginning of 2000s

In the past, extensive campaign of daily balloon flights has been done: Wizard (MASS, TS, CAPRICE), BESS, HEAT, IMAX…,

High-statistics measurement of antiP@low energy->BESS-Polar

antiP and $e^+$ measurement @ high energy

Conflicting results!

Charge-dependent solar modulation

$GCR + ISM \rightarrow p-bar + x$

$GCR + ISM \rightarrow \pi^+ + x \rightarrow \mu^+ + x \rightarrow e^+ + x$

$GCR + ISM \rightarrow \pi^0 + x \rightarrow \gamma + \gamma \rightarrow e^+ e^-$
Balloon and Space experiments: protons

Measurements from balloons in the past have been mostly limited in statistics due to the short observation time.

Space experiments (or Long duration balloon flight) with long exposure time and large acceptance are the new standard.

The need of precise measurements led to PAMELA and AMS.
PAMELA (2006 - 2015)

Time-Of-Flight
- plastic scintillators + PMT:
  - Trigger
  - Albedo rejection;
  - Mass identification up to 1 GeV;
  - Charge identification from dE/dX

Electromagnetic calorimeter
- W/Si sampling (16.3 X0, 0.6 λl)
  - Discrimination e+ / p, anti-p / e-
  (shower topology)
  - Direct E measurement for e-

Neutron detector
- plastic scintillators + PMT:
  - High-energy e/h discrimination

Spectrometer
- microstrip silicon tracking system + permanent magnet
  It provides:
  - Magnetic rigidity \( R = pc/Ze \)
  - Charge sign
  - Charge value from dE/dx

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AMS (2011-2024)

Acquisition rate [Hz]

GF ~ 0.45 m² sr (450 cm² sr with ECAL)
MDR ~ 2 TV
Current Positron Fraction

The excess is really there and now we have the new challenge:
Dark Matter annihilation or contribution from nearby young pulsars?

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->Talk D. Gaggero TeVPA 2017
Cui et al. ’17 and Cuoco et al. ‘17 use AMS-02 antiproton data and B/C or the Helium flux to set limits on DM annihilation. Both papers claim detection of a possible excess due to DM annihilation.

Stay tuned!
Antiproton at low energy

BESS Flights

BESS confirms PAMELA and AMS data and extends the measurements at low energy.
Anti-nuclei

Most stringent limit of AntiHe/He paced so far from BESS-Polar II on anti-He

After all selection

No He candidate

-14 GV

BESS-Polar II

Sasaki @ Antideuteron 2014

Abe et al. PRL 131301 (2012)

He/He Limit (95% C.L.)

BESS-Polar II

PAMELA

ALL BESS Results
Anti-Helium from AMS

- To date AMS has observed 5 Anti-He events, with mass around $^3$He, at a rate of ~1 antihelium in 100 million helium.

- It will take a few more years of detector verification and to collect more data to ascertain the origin of these events. At a signal to background ratio of one in one billion, detailed understanding of the instrument is required.

- Studies on anti-deuteron are ongoing.
Anti-Deuteron

GAPS
Dark matter search using low-energy antimatter

Long-duration balloon (LDB) flight in Antarctic – low geomagnetic cutoff.

Now approved by NASA for funding and launch in late 2020
GAPS will make precision measurement of the low energy **antiprotons**.

GAPS is expected to have x10 more statistics @0.25 GeV than BESS/ PAMELA and AMS.

GAPS has also the capability for detection **anti-He** and studies to estimate the sensitivity are on going.

->Talk K. Perez TeVPA 2017
CREAM - is there an hardening in the spectra?

CREAM spectra harder than prior lower energy measurements: P, He and heavy nuclei.

Seven Balloon Flights in Antarctica: ~191 days Cumulative Exposure


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Confirmation of P and He hardening

- PAMELA measured a break for P and He around ~ 200 GV
- Consistent with high energy CREAM data.
- AMS measured a smooth hardening above 230 GV for both H and He.


Aguilar et al. PRL 115, 211101 (2015)
FERMI-LAT protons

P hardening confirmed by FERMI-LAT
Using 7 years of LAT 2008-2015
Extend space-based measurement to 9.5 TeV
AMS measured a smooth hardening above 230 GV for heavier elements at the same rigidity.

Why the hardening? re-acceleration at the source? propagation? nearby source?
The B/C ratio does not show any significant structures and it is described by a single power law. (Exclude some propagation models). Other secondaries/primaries will be studied.

Protons and helium are both primaries and produced by the same source, therefore their flux ratio should be flat. The ratio varies with rigidity.

**P and He have different slopes. Why?**
Isotopes

AMS-02

-> Talk F. Giovacchini TevPA 2017

$^{3}\text{He}/^{4}\text{He}$

BESS Polar II

Same solar modulation with PAMELA: good agreement $^{1}\text{H}$ and $^{4}\text{He}$

$^{2}\text{H}$ and $^{3}\text{He}$ significantly higher

PAMELA

$^{7}\text{Be} / (^{9}\text{Be} + ^{10}\text{Be})$

AMS-02

M. Boezio Workshop Solar Modulation Hawaii 2015
Isotopes: HELIX $^{10}\text{Be}/^{9}\text{Be}$

To fly in 2019 with LDB

$^{10}\text{Be}$: Unstable isotope w/ known half life of $1.5 \times 10^6$ yr

- $^{10}\text{Be}/^{9}\text{Be}$ ratio provides strong constraints for the propagation models
Need to extend to higher energies

To search for spectral features from nearby/young sources and acceleration effects in the TeV range.
Launched: December 2015 with a rocket
Lifetime: greater than 3 years
Electrons and photons: 5 GeV – 10 TeV
Protons and heavy ions: 100 GeV – 100 TeV
DAMPE: 3 years

DAMPE collaboration ICRC 2017

Simulations assuming AMS-02 fit

Simulations assuming AMS-02 fit

Simulations assuming AMS-02 fit

Simulations assuming AMS-02 fit

->Talk S. Zimmer TeVPA 2017

Lifetime: more than 5 years

Vessel:
Weight ~360 kg
Power consumption ~160 W
Telemetry ~10 GB/day
NUCLEON: 2 years of data (preliminary)

New preliminary data for several species of GCRs from a few TeV till 100 TeV.

Are there hardening or structures?

Two different methods of measuring of the energy of particles are implemented in the NUCLEON experiment:

1. The kinematic method KLEM (Kinematic Lightweight Energy Meter) - for the first time (main)
2. The calorimetric method - usual and well studied
CALET

- 15 months of observation from December 1st, 2015 to February 28th, 2017
- subset of total acceptance: acceptance $A$ (fiducial) with $S\Omega = 416$ cm$^2$ sr
- Assessment of the systematic errors: IN PROGRESS

CALET Energy reach in 5 years:

- Proton spectrum to $\approx 900$ TeV
- He spectrum to $\approx 400$ TeV/n
- Spectra of C, O, Ne, Mg, Si to $\approx 20$ TeV/n
- B/C ratio to $\approx 4 - 6$ TeV/n
- Fe spectrum to $\approx 10$ TeV/n
CALET

CALET collaboration ICRC 2017

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CALET (5 years)

Nicely bridge the low energy measurements with the high energy measurements and extend them close to the PeV.

CALET collaboration ICRC 2017
ISS: new cosmic ray observatory

AMS Launch
May 16, 2011

ISS-CREAM

CALET Launch
August 19, 2015
ISS-CREAM

Protons to iron individual energy spectra from 1 TeV to 1 PeV

The CREAM payload has been transformed for accommodation on the International Space Station, in order to increase the exposure by one order of magnitude with respect to balloon flights.
HERD: High Energy cosmic Ray Detector

CSS (2022-2025) E~10 GeV to the PeV

Large acceptance, deep, 3D calorimeter, equipped with silicon tracker and plastic scintillators, onboard the CSS for long duration mission.

<table>
<thead>
<tr>
<th>Item</th>
<th>HERD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range(e/y)</td>
<td>10 GeV - 10 TeV (e/y)</td>
</tr>
<tr>
<td>Energy range (CR)</td>
<td>30 GeV - PeV</td>
</tr>
<tr>
<td>Angle resolution</td>
<td>0.1 deg@10 GeV</td>
</tr>
<tr>
<td>Charge measurement</td>
<td>0.1-0.15 c.u</td>
</tr>
<tr>
<td>Energy resolution (e)</td>
<td>1%@200 GeV</td>
</tr>
<tr>
<td>Energy resolution (p)</td>
<td>20%@100 GeV,PeV</td>
</tr>
<tr>
<td>e/p discrimination</td>
<td>~10^-4</td>
</tr>
<tr>
<td>Geometric factor (e)</td>
<td>3.8 m^2sr@200 GeV</td>
</tr>
<tr>
<td>Geometric factor (p)</td>
<td>2.6 m^2sr@100 TeV</td>
</tr>
</tbody>
</table>

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| Experiment | $e^+ | e^-$ (present data) | $e^+e^-$ (Energy range) | CR nuclei (Energy range) | charge | Gamma-ray | Type | Launch        |
|------------|-----------------------|-------------------------|-------------------------|--------|------------|------|---------------|
| PAMELA     | $e^+ < 300 \text{ GeV}$ $e^- < 625 \text{ GeV}$ | 1-700 GeV (3 TeV with cal) | 1 GeV-1.2 TeV (extendable -> 2 TeV) | 1-8   | -          | SAT  | 2006 Jun 15   |
| FERMI      | -                     | 7 GeV – 2 TeV           | 50 GeV-1 TeV            | 1      | 20 MeV – 300 GeV GRB 3 KeV – 35 MeV | SAT  | 2008 Nov 11   |
| AMS-02     | $e^+ < 500 \text{ GeV}$ $e^- < 700 \text{ GeV}$ | 1 GV-1 TV (extendable)  | 1 GV-1.9 TV (extendable) | 1-26 ++| 1 GeV-1 TeV (calorimeter) | ISS  | 2011 May 16   |
| NUCLEON    | -                     | 100 GeV-3 TeV           | 100 GeV-1 PeV            | 1-30   | -          | SAT  | 2014 Dec 26   |
| CALET      | -                     | 1 GeV-20 TeV            | 10 GeV-1 PeV             | 1-40   | 10 GeV-10 TeV GRB 7-20 MeV | ISS  | 2015 Aug 19   |
| DAMPE      | -                     | 10 GeV-10 TeV           | 50 GeV-500 TeV           | 1-20   | 5 GeV-10 TeV | SAT  | 2015 Dec 17   |
| ISS-CREAM  | -                     | 100 GeV-10 TeV          | 1 TeV-1 PeV              | 1-28 ++| -          | ISS  | 2017          |
| CSES       | -                     | 3-200 MeV               | 30-300 MeV               | 1      | -          | SAT  | 2017          |
| GAMMA-400  | -                     | 1 GeV-20 TeV            | 1 TeV-3 PeV              | 1-26   | 20 MeV-1 TeV | SAT  | ~2023-25     |
| HERD       | -                     | 10(s) –10^4 GeV         | up to PeV                | TBD    | 10(s) –10^4 GeV | CSS  | ~2022-25     |
| HELIX      | -                     | -                       | < 10 GeV/n light isotopes | -      | -          | LDB  | proposal      |
| HNX        | -                     | -                       | ~ GeV/n                  | 6-96   | -          | SAT  | proposal      |
| GAPS       | -                     | -                       | < 1 GeV/n                | -      | -          | LDB  |              |

and many more ... ACE/CRIS, TIGER, SUPERTIGER ... it is a very exciting time!
Low Energy Spectra

Exciting time also at low energy! Voyager 1 is outside the heliosphere. First measurements of the LIS at low energies.
Monitor solar activity from Space

Understand GCR propagation into the heliosphere
Decrease uncertainties in DM indirect search
Look for new phenomena at low energy

Lots of new measurements from current and future experiments (HEPD, Solar Probe, Solar orbiter..) are expected. Stay Tuned!

O. Adriani PRL 116, 241105 (2016)
Conclusions

• Precise measurements from space experiments provided answers and opened new questions. => Positron excess, antiproton spectrum, change in the power law slope of proton helium and heavy nuclei, different slopes for primary elements, anti helium candidates… The results challenge the standard paradigm of GCR origin and propagation.

• Current experiments and new ones will make significant progress in understanding GCR => sources, acceleration and propagation, new physics over GCR background.

• Measurements from Voyager of the LIS at low energies and continuos observation from space of the solar modulation activity => propagation into heliosphere, LIS, constrain in DM search and look for new phenomena.