Charged Cosmic Rays, measurements in orbit

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NOW 2018
Particle ‘beam’

Chemical composition energy spectra of primary \( \text{(and secondary)} \)

CR origin and propagation in the galaxy
Measurements not requiring the identification of the charge sign

- Up to $\sim 10^{20}$ eV;
- Energy density $\approx 1$ eV / cm$^3$;
- Luminosity, $L > 10^{40}$ erg/s;

$$\Phi(E)dE = kE^{-\gamma}dE \quad \gamma \approx 2.6 - 2.7$$

- energies much higher than reachable on ground;
- to investigate the spectral and chemical composition accurate detector (‘a la particle physics’) are needed;
- to reach higher energies, bigger and bigger detectors are needed;
Primary cosmic rays carry information about their original spectra and propagation: high energy $e^-$, due to their energy loss $\approx E^2$ are sensitive probes to nearby sources.

C, O, ..., Fe + ISM $\rightarrow$ Li, Be, B + X

Secondary cosmic rays carry information about propagation of primaries, secondaries and the ISM.
Anti-particles: the quest for Dark Matter

\[ p, \text{He} + \text{ISM} \rightarrow e^+, \bar{p} + \ldots \]
\[ \chi + \chi \rightarrow e^+, \bar{p} + \ldots \]

E.g. the excess of \(e^+, \bar{p}\) with respect to expected secondary production as a probe for Dark Matter (\(\chi\))

[Image of cosmic rays and particle interactions]

I. Cholis et al., arXiv:0810.5344

Collision of Cosmic Rays

\[ e^+/(e^+ + e^-) \]
The experimental challenge

No atmosphere: Stratospheric Balloons
Space

Limits on size / weight / time

- Detector design focused on specific measurements

$p, He, e^-, anti-particles$

Primary spectra, Nuclei, $e^\pm$

Magnetic spectrometers
Energy reach on anti-particles limited by
Maximum Detectable Rigidity

Calorimeters
Energy reach limited by statistics

HEP detectors adapted to space!

$$\Delta N = \Phi(E) \times \Delta(E) \times A \times T$$
**Spectrometer vs Calorimeter**

**Magnetic spectrometer**

- Spatial resolution: 3 – 10 µm

**Calorimeter**

- Charged particle resolution: 30 – 70 µm

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HEP detectors in Space

Mechanical stress at launch:
- Static acceleration
- Random vibration
- Sinusoidal vibration
- Pyroshock

Life in space:
- Thermal stresses due to Sun-light (seasonal / day-night effects)
  - Vacuum
  - Radiation

Careful Design, Model validation and Qualification are needed to ensure *highest possible reliability*
Technology Readiness Level

<table>
<thead>
<tr>
<th>Transition phases</th>
<th>TRL levels</th>
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<tbody>
<tr>
<td>System Test, Launch and Operations</td>
<td>TRL 9 Actual system “flight proven” through successful mission operations</td>
</tr>
<tr>
<td>System/Subsystem Development</td>
<td>TRL 8 Actual system completed and “flight qualified” through test and demonstration</td>
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<td>Technology Demonstration</td>
<td>TRL 7 System prototype demonstration in a space environment</td>
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<tr>
<td>Technology Development</td>
<td>TRL 6 System/subsystem model or prototype demonstration in a relevant environment</td>
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<td>Research to Prove Feasibility</td>
<td>TRL 5 Component and/or breadboard validation in relevant environment</td>
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<td>Basic Technology Research</td>
<td>TRL 4 Component and/or breadboard validation in laboratory environment</td>
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<td></td>
<td>TRL 3 Analytical and experimental critical function and/or characteristic proof-of-concept</td>
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<tr>
<td></td>
<td>TRL 2 Technology concept and/or application formulated</td>
</tr>
<tr>
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<td>TRL 1 Basic principles observed and reported</td>
</tr>
</tbody>
</table>

Source: Adapted from NASA and Mankins (1995)

Exported to space
Well established technology on ground
Tracking with silicon microstrip detectors: heritage of LEP experiments (L3):

Main advantages:

→ Excellent spatial resolution
→ Absolute charge measurement from multiple dE/dX
→ Light weight / minimum material along track trajectory
→ No HV
Direct measurements in space

Alpha Magnetic Spectrometer - 01 (AMS-01)
- Same orbit of the ISS and of AMS-02
- 10 days of mission on board the Space Shuttle Discovery mission STS-91 (1998)

Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA)
- 470 Kg
- In orbit since 15 June 2006
The experimental program

- Acceptance ($m^2 \text{sr}$)
- Livetime (s)

- Green circles: No B field, different techniques with main focus on Z
- Red circles: No B field, different techniques with main focus on $e, \gamma$
- Blue circles: Magnetic spectrometers
- Orange circles: Balloon
- Black circles: Space
- Gray circles: Space (planned)
Space

Long missions (years)
Small payloads
Low energies

IMP series < GeV/n
ACE-CRIS/SIS Ekin < GeV/n
VOYAGER-HET/CRS < 100 MeV/n
ULYSSSES-HET (nuclei) < 100 MeV/n
ULYSSSES-KET (electrons) < 10 GeV
CRRES/ONR < (nuclei) 600 MeV/n
HEAO3-C2 (nuclei) < 40 GeV/n

Short missions (days)/ Larger payloads

CRN on Challenger
(3.5 days 1985)

AMS-01 on Discovery
(8 days, 1998)
Transition Radiation Detector (TRD)
Identify $e^+$, $e^-$

Silicon Tracker
$Z, P$

Electromagnetic Calorimeter (ECAL)
$E$ of $e^+, e^-, \gamma$

Time of Flight (TOF)
$Z, E$

Magnet (0.15 T)
$\pm Z$

Ring Imaging Cherenkov (RICH)
$Z, E$

Particles and nuclei are defined by their charge ($Z$) and energy ($E$)

$Z, E, R, \beta$
are measured independently by the Tracker, RICH, TOF and ECAL for the same CR

AMS-02: A TeV precision, multipurpose spectrometer
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AMS

- Dimensions: 5m x 4m x 3m
- Weight: 7.5 tons
- GF ≈ 0.5 m²sr
The DAMPE detector, launched in 2015

- Charge measurement (dE/dx in PSD, STK and BGO)
- Tungsten converter (pair production)
- Precise tracking (silicon strips)
- Thick calorimeter (BGO bars)
- Hadron rejection (neutron detector)

high energy γ-ray, electron and cosmic ray telescopes
The DAMPE detector

PSD: IMP

STK: IHEP, UG, INFN Perugia

BGO: USTC & PMO

NUD: PMO
DAMPE satellite
CALET Payload

Kounotori (HTV) 5

Launched on Aug. 19th, 2015 by the Japanese H2-B rocket

Emplaced on JEM-EF port #9 on Aug. 25th, 2015
(JEM-EF: Japanese Experiment Module-Exposed Facility)

CGBM (CALET Gamma-ray Burst Monitor)

FRGF (Flight Releasable Grapple Fixture)

ASC (Advanced Stellar Compass)

Calorimeter

GPSR (GPS Receiver)

MDC (Mission Data Controller)

- Mass: 612.8 kg
- JEM Standard Payload Size:
  1850mm(L) × 800mm(W) × 1000mm(H)
- Power Consumption: 507 W (max)
- Telemetry:
  Medium 600 kbps (6.5GB/day) / Low 50 kbps
AMS-02 Positrons & Electrons

28.1 million electrons

1.9 million positrons

Preliminary Data. Please refer to the AMS forthcoming publication in PRL.
AMS-02 Positron fraction

- 1.9 million positrons

Positron fraction $= \frac{e^+}{(e^+ + e^-)}$

Collision of Cosmic Rays + Collision of Dark Matter

1.2 TeV

Preliminary Data. Please refer to the AMS forthcoming publication in PRL.

DAMPE ‘all electron’ spectrum (e^+ + e^-)

- Three different PID methods give very consistent results on event-by-event level.
- Direct detection of a spectral break at ∼1 TeV with 6.6σ confidence level.

530 days of data
2.8 billion events
1.5 million e+e- (>25 GeV)
CALET ‘all electron’ spectrum ($e^+ + e^-$)

DAMPE: Nature 552 (2017) 63, 7 December 2017
AMS-02 all electron \((e^+ + e^-)\)

Preliminary Data.
Please refer to the AMS forthcoming publication in PRL.
AMS-02 ‘all spectra’
AMS-02 He C O spectra

results based on:
- ~ 90 million helium nuclei
- ~ 8.5 million carbon nuclei
- ~ 7 million oxygen nuclei
AMS-02: high energy spectra, different species
DAMPE Proton spectrum

Data set
Jan 1, 2016 – Dec 31, 2017

5% systematic error
(three independent analyses ongoing)

TEVPA-2018 S. Vitillo
DAMPE Helium spectrum

Data set
Jan 1, 2016 – May 31, 2017
2.6 Billion events

p contamination < 1.5%

preliminary summary

(three independent analyses ongoing)
Large acceptance, deep, 3D calorimeter, equipped with silicon tracker (STK) and plastic scintillators (PSD) for primary identification, onboard CSS for a long duration mission.

One order of magnitude jump in exposure wrt current generation CR experiment: 15 m² sr yr
HERD: performance

Precise measurement of the "discrepant" hardening

Reaching the knee(s)
Conclusions

• excellent instruments in orbit to measure CR
• charged CR have a lot to tell us
• current direct measurements are pushing the limit to the $O(10 \text{ TeV})$
• future experiment will reach $O(\text{PeV})$ for the direct CR measurements

• Stay tuned for new results

Apologies for all the missing items