Penetrating Particle Analyzer: PAN

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Genesis of the project

- Informal discussions among colleagues working on Galactic Cosmic Rays (AMS-02, DAMPE)
- Interest in the Space Weather activities
- Positive feedback at the presentation at the ESA DSG (LOP-G) Workshop, Dec. 5-6, 2017
- Positive feedback at the presentation at the NASA DSG (LOP-G) Workshop, Feb 27-Mar. 1, 2018

Penetrating particle ANalyzer (PAN)


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Introduction to PAN

• PAN is a scientific instrument for deep space and interplanetary missions
  – Precisely measure and monitor in real time the flux, composition, and direction of penetrating particles (> ~100 MeV/nucleon) in deep space.

• Science goals: multi-disciplinary and cross-cutting
  – Cosmic ray physics: fill an in situ observation gap of galactic cosmic rays (GCRs) in the GeV region in deep space, crucial for the understanding of the origin of the GCRs, and their interplay with solar activities.
  – Solar physics: provide precise information on solar energetic particles for studying the physical process of solar events, in particular those producing intensive flux of energetic particles.
  – Space weather: gather data to develop space weather models from the energetic particle perspective.
  – Planetary science: measure and monitor energetic particles to develop a full picture of the radiation environment of a planet, in particular as a potential habitat.
  – Deep space travel: PAN can monitor the flux and composition of penetrating particles during a space voyage. PAN can become a standard on-board instrument for deep space travel.
Radiation environment in deep space

- **Plasma environment**
  - Mainly low energy protons and electrons from solar wind
    - Unperturbed solar wind plasma (<10 keV)
    - Effectively stopped by multilayer insulation (MLI) sheets (up to 100 keV)

- **Particle radiation sources**
  - Particles trapped in the Geomagnetic field
    - Negligible in deep space
  - **Transient flux: Solar Energetic Particle (SEP)**
    - Particles from solar eruptions (flare and Corona Mass Ejection)
    - Dominant at low energy (< 100 MeV)
      - “GeV” Solar Particle Events rare but potentially damaging/dangerous
  - **Steady flux: Galactic Cosmic Rays (GCR)**
    - Dominant at high energy (> 100 MeV), peak at ~1 GeV/n
    - Modulated by solar activities
    - Important contribution to TID for long missions (shield?)

~GeV particle flux have not been precisely measured in situ in deep space
Deep space mission: low energies, E –dE/dx technique, cherenkov, no e⁺/⁻ separation

LEO CR mission: higher energies, spectrometers e⁺/e⁻ separation

PAN/MINI-PAN: covering a gap in energy/time
Deep space mission: low energies, E –dE/dx technique, particle rates

LEO CR mission: higher energies, calibrated fluxes

PAN/MINI-PAN : covering a gap in energy/time
Example of existing measurements

AMS-02 data on time structure in the cosmic rays fluxes
Electrons measurements: the energy spectrum

$J(E) \text{ (particle/m}^2 \text{ s sr/GeV)}$

- ISEE3 / MEH
- Voyager-1 / LET+HET
- Voyager-2 / LET+HET
- Resurs-DK1 / PAMELA
- Ulysses/KET
- STS-91/AMS-01
- ISS/AMS-02
- Fermi-LAT

kinetic energy (GeV)

V1 out of the heliosphere
deep space
in the heliosphere

LEO

V1 out of the heliosphere
Proton measurements: the energy spectrum

J(E) (particle/m² s sr GeV)

kinetic energy (GeV)

- Voyager-1 / LET+HET
- SOHO / EPHIN
- Voyager-2 / LET+HET
- Ulysses-COSPIN / KET
- STS-91 / AMS-01
- Resurs-DK1 / PAMELA
- ISS / AMS-02
- IMP8 / CPME

2012-now

1999

1996

1993

1999

2008

1999

2008

1999

2008

1999

2008

1999
PAN Instrument proposal (LOP-G or satellite)

- Light weight (20 kg) low power (20 W) spectrometer with permanent magnet

  ![Diagram of spectrometer]

- 4 Halbach permanent magnet sectors, $\phi = 10$ cm, $L = 10$ cm each, provide a dipole magnetic field of $\sim0.2$ Tesla, total weight $\sim11$ kg
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PAN detector modules

- 5 tracker modules, 2 TOF modules, 2 pixel modules

**Tracker module**
- 2 StripX: 25 µm readout pitch, 150 µm thick, **2 µm resolution**, to measure both bending radius and bending angle, 40k channels, total power budget 8W
- 1 stripY: 500 µm readout pitch, 150 µm thick, high dynamic range ASIC for Z = 1 – 26, trigger signal, time stamp (<100 ps resolution), 1k channels, total ~1 W

**TOF module**
- 3 mm thick scintillator, read out on all sides by SiPM: trigger, particle counter (max. ~10 MHz), charge measurement (Z = 1 -26), time (<100 ps), total ~1 W

**Pixel module**
- Avoid measurement degradation for high rate solar events
- Issue to be resolved: total (static) power consumption ~2-4 W, for ~190 cm²
PAN measurement principle

- Measure momentum by both radius and bending angle, to have large acceptance
  - GF: $\sim 32, 10, 5, 3 \text{ cm}^2\text{sr}$ (x2 for isotropic sources), for crossing 1, 2, 3, 4 sectors
  - Open angle 25, 33, 47, 80°

- Energy resolution <10% for protons of 0.4 – 20 GeV for 4-sector acceptance
  - <20% for protons of 0.2 – 2 GeV for 1-sector acceptance
The key of the PAN design is to optimize resource utilization for both long term low rate (GCR) and short term high rate (SEP) operation

- At high rate (S5 SEP events)
  - Improve measurement of triggered events: TOF pileup and Si layer multi-hits
    - Pixel, no pileup: provide unambiguous charge and 3d points
  - Non-triggered pixel hits, ~2.4 MHz
    - Pixel is working "standalone", so energy information limited, but at least can provide an integrate flux measurement for >20 MeV
    - Requirement: up to 5-10 MHz (~95 cm²) → ~1.5-3 Hz/pixel
- At lower rate (up to S4 SEP events)
  - 1 extra 3d point
    - With 4-10 µm position resolution, improve energy resolution
    - With ~100 µm position resolution, help pattern recognition
  - 1 extra charge measurement
    - At least for lower Z, effective limit to be investigated
Mini.PAN for planetary missions

- Smaller device for in-situ radiation measurement and monitoring
  - 2 Halbach permanent magnet sectors, each $\phi = 5$ cm, $L = 5$ cm, provide a dipole magnetic field of $\sim 0.4$ Tesla, magnet weight $\sim 2$ kg, total $< 5$ kg
  - GF: $\sim 6.3$ or $2.1$ cm$^2$sr (x2 for isotropic sources, for crossing 1 or 2 sectors)

Energy resolution $<20\%$ for $p$ of $0.2 - 10$ GeV for 2-sector acceptance

Shorter sector length compensated by stronger $B$ field

Can be simplified further with only one-side sensitive

Can add a few layers of Si detectors to measure $10$ MeV – $20$ MeV with the classical $\Delta E - E$ method ($\sim 2.4$ mm of Si) $\Rightarrow$ full range energetic particle monitor

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Conclusion

- Magnetic spectrometer is the most suitable measurement technique in the range 100 MeV/n – 20 GeV/n and we have a detector design
  - Principle and technologies demonstrated by AMS-01, PAMELA and AMS-02
  - High precision strip detector are available, high rate low power active pixel sensors are becoming available
- Direct measurements of penetrating particles (100 MeV/n – 20 GeV/n) in deep space are important
  - Fill a gap in cosmic ray observation
  - Possibly open a new window for solar physics
  - Unique input to space weather modeling and forecasting
  - Indispensable for human deep space missions
  - Important for planetary exploration
- PAN is suitable for LOP-G or medium to large solar missions, while mini.PAN is suitable for planetary exploration missions
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mini.PAN has been founded by H2020 FET_OPEN for the design and construction of a ground demonstrator: in 3 year we will have a ready-to-fly detector!