REAL-TIME PENETRATING PARTICLE ANALYZER (PAN).
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Introduction: Using a magnetic spectrometer with particle identification capability, it is possible to measure and monitor the flux, composition, direction and time variation of highly penetrating particles (> ~100 MeV/nucleon) in deep space, to a precision that has never been achieved before. Deploying such a device on the Deep Space Gateway (DSG) will allow real-time monitoring and long term measurements over a full solar cycle (~11 years). These precise measurements will improve our understanding of the connection between the high energy particle environment in deep space and the solar activities, and bring new insight to the origin and the propagation of these particles. The real-time monitoring of the penetrating particles is crucial for future deep space human travel since these particles are difficult to shield, therefore needed to be constantly monitored. In the baseline version, the proposed instrument, called the Real-Time Penetrating Particle Analyzer (PAN), weighs about 20 kg and consume about 20 W. But the instrument is highly scalable.

Radiation environment in deep space: In space, particle radiation comes mainly from 3 sources: particles trapped in the geomagnetic filed, particles from solar flares (Solar Cosmic Rays or SCRs), and Galactic Comics Rays (GCRs). In deep space, the trapped particle contribution can be neglected, leaving only the SCR and the GCR as main contributors. SCRs are burst of energetic particles produced by solar flares, consisting of mainly electrons below 1 MeV, but also protons and Helium nuclei, mostly with energy below 30 MeV. GCR is the dominant particle source above few hundred MeV, consisting of mainly protons and Helium nuclei, but also heavier nuclei produced in nucleosynthesis and through the interactions of GCRs with the interstellar medium. In deep space the GCR flux below a rigidity of ~20 GV is strongly affected by solar activities, through solar winds and through the modulation of the interplanetary magnetic field.

Science objectives: The energetic particle environment at the LEO has been studied in great details, in particular since the launch of the PAMELA [1] satellite in 2006 and the installation of the AMS-02 [2] spectrometer at the ISS in 2011. In deep space, however, only the non-penetrating particle (< ~100 MeV/n) environment has been precisely measured, and indeed continuously monitored over more than 17 years by the CRIS instrument [3] on NASA's ACE mission. While the particle flux above 20 GV, predominantly from GCR, is largely unaffected by the geomagnetic field and the solar modulation, thus allowing the AMS measurement to be extrapolated into deep space, the same is not true for particles below this threshold. A precise measurement of particle flux between ~100 MeV/n to ~20 GeV/n in deep space is therefore missing (for a review of the current and planned particle observation missions, see e.g. [4]). The science objective of PAN is to fill this gap of observation, allowing to measure the particle flux in deep space in this energy range with unprecedented precision in terms of energy, composition and short and long term time variations, profiting from the unique orbit and the expected long lifetime of the DSG. PAN will open up a new window of observation for multiple disciplines of space science, including solar physics, space weather and cosmic ray physics, and their interplay in the interstellar radiation environment. For example, the precise flux and composition measurements of the GCR at 100 MeV/n – 20 GeV/n will help to resolve fundamental questions concerning the GCR production, acceleration and propagation in the Galaxy. However, solar modulation effects on these measurements should be evaluated and corrected. Another example is detailed studies of the rare "GeV" solar storms (solar flares that produce GeV particles), an interesting topic for solar physics, space weather and radiation protection.

Energetic particle monitoring for deep space human travel: Energetic particles above about 100 MeV/n, in particular proton and nuclei, cannot be shielded easily, thus become "penetrating". At LEO, the geomagnetic field is a natural shield for particles up to 20 GV. In deep space however, without the geomagnetic shield, penetrating particles represent a serious radiation hazard for long term space travelers. The precise and long term measurements of the flux and composition of these particles are indispensable for the assessment of the related health risk, and the development of an adequate mitigation strategy. PAN will also provide valuable experience for the crew to operate a real-time penetrating particle monitoring tool.

Detection principle: Magnetic spectrometer (MS) is a proven detection technology for particles between 100 MeV/n and 20 GeV/n (e.g. Pamela and AMS-02). In this energy range, the classical $\Delta E - E$ method (e.g. ACE) is not optimal, because a very thick and heavy calorimeter is needed to measure the total energy of the particle. In a MS, the momentum resolution, thus the energy resolution, has 2 contributions: one, related to the magnetic field (strength and length) and the tracker precision, increases with momentum; the other, due to the multiple Coulomb scattering (MCS), decreases with momentum. With appropriate instrument design, it is possible to mitigate these two effects to achieve a good energy resolution over the desired energy range. Figure 1 shows the energy resolution obtained with the baseline PAN design described below, estimated with the Gluckstern formulas [5]. For protons, the energy resolution is ~5% between 1-5 GeV, and ~15% at 100 MeV and 20 GeV. Note that a 20 GV rigidity is equivalent to ~9 Gev/n for nuclei heavier than proton.

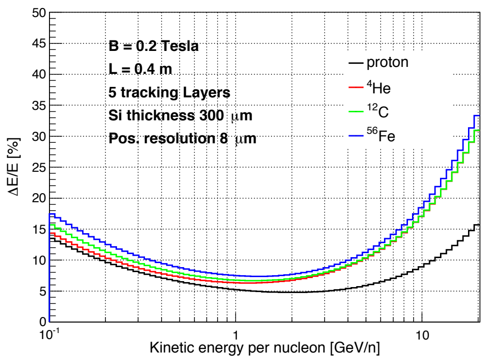

Figure 1. Energy resolution as a function of energy per nucleon for proton, Helium, Carbon and Iron nuclei from 100 MeV/n to 20 GeV/n, with the baseline PAN design.

The charge (Z) of the particle can be determined by measuring the energy deposited in the tracking layers and in the Time-of-Flight detector, using the dE/dx method. A large dynamic range is needed to measure the dE/dx for Z up to ~30. Also at 100 MeV/n, the βγ of the particle is only ~0.5, which leads to a dE/dx that is ~3 times of the Minimum Ionization. A possible option to optimize charge measurement is to add a dedicated charge detector, using e.g. silicon pixel detectors. On the other hand, the low βγ value can provide isotope identification for low energy particles with the dE/dx – E method. The identification of electrons is straightforward since they bend in the MS to a direction opposite to that of the nuclei.

Baseline instrument design concept: The baseline design concept of PAN is shown in Figure 2. It consists of a cylindrical MS, with a TOF detector at each end to determine the entering direction of the particle. The instrument is symmetric, effectively doubling the geometrical acceptance. The data processing of the MS is straightforward, allowing for real-time calculation and display of particle fluxes that can be monitored by the crew, who can decide to point the PAN to a particular direction if the situation requires.

The MS consists of a magnet made from blocks of NdFeB permanent magnets arranged according to the Halbach scheme. The baseline layout uses a magnet assembly weighing below 10 kg to provide a dipole magnetic field of 0.2 Tesla, in a cylindrical cavity of 15 cm in diameter and 40 cm long. The total geometrical acceptance is about 2x18 cm^{2}sr.

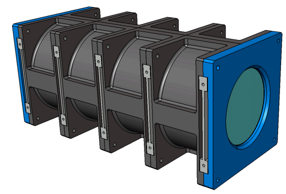

Figure 2. Sketch of the baseline design concept of PAN.

The MS is instrumented with 5 equal-distance tracking planes made of 300 μm thick Si micro-strip sensors, with 50 μm readout pitch, to provide a position resolution of ~8 μm. This layout achieves the energy resolution shown in Figure 1. A plastic scintillator TOF with SiPM readout can achieve a time resolution of 150 ps, sufficient for determining the particle entering direction in the energy range of interest.

A preliminary estimate of resource requirements is given in Table 1. The baseline design uses technologies with high TRL. It can easily be scaled up or down depending on available resources. More recent technology such as silicon pixel detector can also be adopted. By design the instrument is highly modular, with replaceable modules, to provide an extra safety margin for very long operation period.

Resources	Requirement
Mass	~20 kg
Power	~20 W
Cost	~10 M$
Volume	~25 cm×25 cm×50 cm
Crew intervention	Setup and monitoring

Table 1. Preliminary estimated resource requirements.

PAN should be mounted at an external site that facilitates maximal sky coverage. The operation mode includes automatic full sky scan and pre-programmed pointing observation, but the crew can take control of the instrument for instantaneous monitoring in specific directions.

References:

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