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Space Radiation Characterization for a Safe Human Space Exploration and Colonization

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Abstract

All the space agencies are working to restart the human exploration of space outside the Low Earth Orbit (LEO). Crewed space missions in this and the next decade will see the presence of humans on the Moon and Mars surfaces. One of the main showstoppers to be investigated for a safe exploration and colonization is the ionizing radiation biological effects that can compromise the health of astronauts/space workers. The characterization of the space radiation fields on the Moon and Mars surface, as well as in the Beyond Low Earth Orbit space, will be the first step toward an accurate description of the radiobiological effects, and continuous monitoring of the radiation level will allow a safe permanence of the humans in the Moon and Mars habitat. In this vital task, the astroparticle experiments presently operating in space could play a principal role. Such experiments are a source of information crucial to improving the knowledge of radiobiology effects in space. This paper will review some of the most successful astroparticle space missions (AMS-02, Pamela, …) and their results, the planned ones for the next decades as well as the critical technologies derived from these instrumentations that will be crucial for on-surface and on-orbit radiations levels monitoring and surveillance systems design. Further the current activities and the future perspectives of the AMS INFN Roma Sapienza research group in this topic are described.

Keywords: Space Radiation, Human Space Exploration, Space Radiobiology, Cosmic Rays, AstroParticle Experiments, Cosmic Rays Detectors

Acronyms/Abbreviations

AMS - Alpha Magnetic Spectrometer
APE – Astro-Particle Experiment
BLEO – Beyond Low Earth Orbit
CME – Coronal Mass Ejections
CP - Charged Particle
CR – Cosmic Ray
CRD – Cosmic Ray Detector
CSS – Chinese Space Station
DEM– Dose-Effects Model
ECAL- Electromagnetic CALorimeter
GCR – Galactic Cosmic Rays
HN – Heavy Nuclei
ISS – International Space Station
LEO – Low Earth Orbit
LET – Linear Energy Transfer
MC – Monte Carlo
NEO – Near-Earth Object

PAN– Penetrating particle ANalyzer
RAD–The Radiation Assessment Detector
RBE– Relative Biology Effectiveness
RICH – Ring Image Cherenkov Counter
SEP – Solar Energetic Particle
SF – Solar Flares
SP – Space Radiation
TRD – Transition Radiation Detector

1. Introduction

The space environment Beyond low Earth orbit (BLEO) contains several types of ionizing radiation. Most of the energetic particles in interplanetary space are from the solar wind, producing a constant flux of low linear energy transfer (LET) radiation. In that space region, the galactic cosmic radiation (GCR) will also contribute a significant portion of the radiation dose accumulated by astronaut crew members. GCR ions originate outside our solar system and contain mostly highly energetic protons and alpha particles, with a small component of high charge and energy (HZE) nuclei moving at relativistic speeds and energies [1]. In addition to GCR, unpredictable and intermittent solar particle events (SPEs) can produce large plasma clouds containing highly energetic protons and some heavy ions that may cause a rapid surge of radiation both outside and within a spacecraft. Future human spaceflight missions include Moon bases and settlements on the surface of Mars. For current space missions in LEO, the shielding provided by the Earth's magnetic field attenuates the significant biomedical effects of space radiation exposures. However, the risks of space radiation will become more onerous as future spaceflight missions to the Moon or Mars require extended transit beyond the protection of the Earth's Magnetosphere. Near the Earth's surface, cosmic rays (CR) approaching our planet interact with the Earth's magnetic field and atmosphere, and such interaction protects humans living on the Earth's surface. The Magnetosphere rejects most particles (99%) while the rest lose most energy going through the atmosphere before reaching the Earth's surface. Completely different is the situation in space where the CR interacting with the human body releases some energy and can be dangerous for human health. In this regard, this is one of the main concerns for safe space exploration as planned for the coming years by all the national space Agencies. In a Mars mission, the long distance between Earth and Mars will make the total mission duration 800–1,100 days, of which approximately 500 days will be spent on the planet's surface, depending on the final mission design [2]. As a result, radiation exposure is expected to be more significant when compared with that of a 6-month mission on the ISS. One primary health concern in such prolonged missions is the amount of radiation exposure that accumulates over the duration of the lives of the astronauts. Therefore, health risks associated with exposure to space radiation are an essential topic in a human Moon and Mars mission. In 2006, the National Council on Radiation Protection and Measurements (NCRP) issued a report entitled "Information Needed to Make Radiation Protection Recommendations for Space Missions Beyond Low-Earth Orbit" [3]. The report contains a comprehensive summary of the current evidence for radiation-induced health risks and recommends areas requiring further experimentation to enable future space missions in BLEO. Moreover, the NCRP report emphasizes the need for identifying and validating biomarkers for reliable early detection of adverse effects, improving radiation biodosimetry by providing accurate estimates of cumulative radiation doses and identifying increased personal risks for individual astronauts due to genetic predisposition to the effects of space radiation (SP).

1.1 The AMS INFN Roma Sapienza Research Group

The Alpha Magnetic Spectrometer (AMS02) is a particle physics experiment mounted on the International Space Station (ISS) and is also recognized as a CERN experiment. AMS02 is a cosmic rays (CRs) detector that can measure all the charged components of the CRs. This information is needed to understand the formation of the Universe and search for evidence of dark matter and primordial anti-matter. The INFN Roma and the Sapienza university joined the AMS collaboration in 2001. The Roma Sapienza group-built part of the AMS02 experiment participating in the construction of the Transition Radiation Detector (TRD), having as its main task the responsibility to develop the slow control electronics module of the GAS System of the TRD. This module was part of a safety-critical system, and the group took care of all the phases of the development (Design–Test-Integrate-Fly) following NASA requirements[4,5].

The Roma-Sapienza research group are participating in the data-taking operations at CERN and the data analysis. In 2017 the group started to investigate the possible use of AMS02 data for research in space life sciences, space radiobiology (SPRB), and dosimetry. SPRB is an interdisciplinary science that examines the biological effects of ionizing radiation on humans involved in aerospace missions. The knowledge of the risk assessment of the health hazard related to human space exploration is crucial to reducing damages induced to astronauts from Galactic Cosmic Rays (GCRs) and sun-generated radiation. To address such problems, at that time, was created a tight synergy with the medical physics research group headed by Lidia Strigari, currently at IRCCS University Hospital of Bologna, Italy. Since 2018, the INFN Roma Sapienza AMS group has collaborated with researchers and scientists to investigate the possibilities of using the CRD to improve the radiation health risk assessment for humans in space missions. In 2019 we organized at INFN Roma Sapienza a thematic meeting with participants from ESA and Thales Alenia Space. Collaborations focused on creating synergy within different scientific communities (radiobiology, medical physics, radiotherapy, and nuclear medicine) and Institutions playing a crucial role in human space exploration (Research, Universities, and National Space Agencies). We also studied the capabilities and possibilities in that direction, especially regarding the AMS02. We also identify many opportunities for improvement [6,7,8].

A pillar was also the publication in 2021 of a review paper on the Dose-Effects Model (DEM) for SPRB [9]. The article had a substantial impact on the scientific community. It ius and will be the base for the actual and future research group activity

1.2 Paper Structure

The focus of this paper is space radiation characterization. We will initially discuss the environment of space radiation (Par.2). Then we will review the actual next generation Astro-particle experiment space missions as well as the space radiation detection technologies derived from (Par.3). In the end we will describe the enabling research that are ongoing in such field at INFN Roma research group.

2. Space Radiation Characterization

Space radiation (SP) differs from the radiation we experience on the Earth's surface. Also, it comprises hazardous charged particles and atoms in which electrons have been stripped away, and only the atom's nucleus remains. Space radiation consists of three kinds by origin: particles trapped in the Earth's magnetic field, particles generated by the Sun and shot into space during solar flares or other solar events, and galactic cosmic rays whose origin is astroparticle sources from outside the solar system. Also different are the radiation species present in spaces that comprise very light elementary particles like electrons and protons but also low ($Z<8$), medium ($8 <Z<14$) and high ($Z>14$) charge nuclei. All these kinds represent a radiation environment of quality unique and with no equivalent for any human exposition scenario on the Earth.

One of the most significant hazards for astronauts travelling beyond Earth's protective atmosphere will be overcoming exposure to high energy radiation from the solar wind, solar storms, and galactic cosmic rays that originate outside our solar system. Beyond Low Earth Orbit (BLEO), space radiation may place astronauts at significant risk for radiation sickness and increased lifetime risk for cancer, central nervous system effects, and degenerative diseases. Research studies of exposure to various doses and strengths of radiation provide strong evidence that cancer and degenerative diseases are to be expected from exposures to galactic cosmic rays (GCR) or solar particle events (SPE).

2.1 Solar Radiation

The Sun play a crucial role in the LEO and BLEO radiation environment since part of the radiation components are generated by the Sun's activity during SPE and create radiation emission of high intensity and not predictable. Moreover, the Sun's magnetic field interferes with the Cosmic Rays arriving from our galaxy, modulating their fluxes and creating a long-term space radiation environment that is always variating in intensity and is tightly bound to the solar magnetic activity cycle (aka sunspot cycle)[10].
Two phenomena closely related to Sun-generated radiation are Coronal Mass Ejections (CME) and Solar Flares (SF).

- **CMEs** are large expulsions of plasma and magnetic fields from the Sun's corona. They can eject billions of tons of solar corona material and carry an embedded magnetic field more robust than the background solar wind interplanetary magnetic field (IMF) strength. CMEs travel outward from the Sun at speeds ranging from slower than 250 kilometres per second (km/s) to as fast as nearly 3000 km/s. The fastest Earth-directed CMEs can reach our planet in as little as 15-18 hours. Slower CMEs can take several days to arrive. They expand as they propagate away from the Sun, and more significant CMEs can reach a size comprising nearly a quarter of the space between Earth and the Sun by the time it reaches our planet.

- **SFs** are intense localized eruptions of electromagnetic radiation in the Sun's atmosphere. The duration of an SFs ranges from approximately tens of seconds to several hours with a median duration of about 6 and 11 minutes, and the frequency of occurrence of SFs varies with the 11-year solar cycle, ranging from several per day during solar maximum activity periods to less than one every week during solar minimum.

During CMEs or SF, SPEs are produced due to high-energy processes associated with and corresponding shocks and are typically dominated by protons, but composition can vary substantially. SEPs events are sporadic and difficult to predict, with onset times on the order of minutes to hours and durations of hours to days, and associated element fluxes can vary by several orders of magnitude and are typically dominated by protons, but composition can vary substantially.

2.2 Trapped Radiation (Van Allen Belt)

The Earth's magnetosphere shields the Earth from solar storms and the constantly streaming solar wind and GCRs that can damage technology and people living on Earth and, in doing this, traps high-energy radiation particles. These trapped particles form two belts of radiation, Inner and Outer, known as the Van Allen Belts (IVAB and OVAB), surrounding the Earth like enormous doughnuts and consisting of relativistic electrons and protons. Their intense radiation can cause satellite anomalies in space through deep-dielectric charging.[11] The OVAB comprises billions of high-energy particles that originate from the Sun, and the IVAB results from interactions of cosmic rays with Earth's atmosphere. The IVAB is produced by a combination of Cosmic Ray Albedo Neutron Decay, which occurs when cosmic rays scatter off the neutral atmosphere producing neutrons that decay with a 15-min half-life. Solar energetic protons associated with flares and coronal mass ejections also become trapped in the Earth's magnetic field. These energetic solar protons are the primary source at low-energy (<50 MeV) for the IVAB and sometimes produce a long-lived proton belt distinct from the inner zone [12]. Astronauts must fly through the VABs to reach outer space, so they must pass through this region quickly to limit their radiation exposure, or the flight path through the VAB has to be carefully designed to avoid the exposition that can be of the order of tens of mSv even under Aluminum shield protection[13].

2.3 Galactic Cosmic Ray Radiation

The GCRs represent that part of the CRs present in the solar system that originates outside our galaxy's solar system. Different astrophysical sources (e.g. Active Galactic Nuclei, Supernova Stars) produce such CRs, usually named primary (PCR), to distinguish from the other that originates from the interactions of the PCRs with other objects during their travelling into the galaxy or inside the solar system regions (e.g. the interstellar medium, the planet's atmosphere) for this reason referred as secondary CRs (SCR). Direct measurement of CR is one of the main tasks of many astroparticle experiments on the Earth's surface or in space. Their measurements could shed light on many unsolved problems of fundamental physics (e.g. dark matter composition, primordial anti-matter existence). GCR are composed of light particles, bare nuclei of different species, and a wide energy range from a few KeV up to TeV and can cause atoms they pass through to ionize. GCR are of interest since are present continuously in BLEO and can pass practically unimpeded through a typical spacecraft or the skin of an astronaut. This SR components is a min concern for BLEO space mission requiring long travelling periods.

2.4 Anomalous Cosmic Rays

Another component of the space radiation are the Anomalous Cosmic Rays (ACRs), usually defined as those particles in the energy spectra of cosmic rays that originate as interstellar neutral gas flowing into the heliosphere, become ionized, and are eventually accelerated at the solar wind termination shock . As a result, the ACRs at low energies are mostly singly charged particles that can reach also the soalr system planets surface.[14]

2.5 The Moon and Mars Radiation Environments

A comprehensive understanding of the lunar radiation environment is essential in preparing for future human exploration of the Moon. The radiation environment on the Moon is essentially shaped by the absence of an authentic atmosphere (it's very thin and composed mainly of hydrogen, neon and argon) and of a weak respect o the one present on the Earth's dipolar magnetic field that can represent a shield towards the charged particle coming from the space. Hence, the charged particle radiation environment on the lunar surface consists of GCR, a small contribution from ACR, and a highly variable, sporadic contribution from SEPs. In addition, secondary albedo particles are created primarily by the GCR interaction with the lunar regolith, including neutrons and protons. Some of these particles can escape from the soil and be measured as albedo particles. They will also contribute to the radiation exposure of astronauts on the lunar surface.

Similarly, to the Moon also, Mars has no magnetic field, and the atmosphere is not only different in composition (carbon-dioxide based vs nitrogen and oxygen) to the Earth's and so not breathable for humans but also much thinner with an atmospheric volume of less than 1%. Again, the shield effects against SP are strongly reduced or negligible. Current estimation will forecast a factor of exposition to the Mars Surface with respect to the Earth's due to SP 10^2 to 10^3.

The space radiation on the Moon measured is a crucial concern for human space flight and may pose limits on long-term crewed missions to the Moon[15] or Mars[16,17].

3. AstroParticle Experiments: Actual and Future Space Missions

In the last two decades, many astroparticle experiments have been built and deployed in space to investigate many open questions in fundamental physics and cosmology, for example, the dark matter and dark energy existence and composition or the existence of primordial antimatter. A particular class of experiments, the Cosmic Ray Detectors (CRD), is designed to produce a complete inventory of charged particles and nuclei in CR since the knowledge of this information is crucial to solving the above physics open problems. The fundamental *questions* of cosmic rays' physics are related to their origin and mechanism of their acceleration to the high energies associated with them and their composition, that is, the abundance of each particle of nuclei [18].

3.1 Principal Operating Cosmic Ray Detector in Space

The principal CRDs operating in space are AMS02, CALET, and ISS-CREAM, for what regard the ones installed on the ISS and ACE and DAMPE that instead are based on satellite space missions.

AMS02: The Alpha Magnetic Spectrometer is a high-energy particle physics experiment in space designed to measure CRs. The primary purposes of the experiment are the indirect search of dark matter from its annihilation products, the search for relic antimatter and the precise measurement of all CRs species spectra, and their variation in time for the precise estimation of radiation doses for space exploration (see Fig.2).

Fig. 2. The AMS02 was installed on the ISS on 19-May-2011 (courtesy of AMS collaboration)

The AMS02 spectrometer consists of a permanent magnet and several instruments (subdetectors), a Silicon Tracker, a Time of Flight (TOF), a Ring Image Cherenkov Counter (RICH), and an Electromagnetic Calorimeter (ECAL), an Anticoincidence Counter (ACC) and a Transition Radiation Detector (TRD). AMS02 provides excellent particle identification capabilities. It measures the charge of the traversing particle independently in Tracker, RICH, and TOF subdetectors. The TOF, TRD, and RICH sub-detectors also measure particle velocity. AMS02 was launched and installed on the International Space Station (ISS) in May 2011 and has been continuously operating since then [19-25]. The experiment is planned to be operative until 2030. Recently, the AMS collaboration has presented a proposal for a detector upgrade that will increase the acceptance of the AMS detector by 300% via spacewalks and robotic operations. The upgrade has planned to be installed in 2025 [26].

DAMPE: the Dark Matter Particle Explorer (DAMPE) is a satellite-based space mission whose primary purpose is the detection of cosmic electrons and photons up to energies of 10 TeV. The DAMPE instruments also can measure the fluxes and the elemental composition of the galactic cosmic rays' nuclei up to 100 TeV. It has been in data taking since 2015 and consists of: a double layer of Plastic Scintillator Detector, a Silicon-tungsten Tracker-converter; an electromagnetic calorimeter; and a Neutron Detector. In the first years of operations, DAMPE has collected and sent more than 6 billion cosmic ray events [27].

CALET: the CALorimetric Electron Telescope has been in operation since 2015 on the external platform of the ISS's Japanese experimental module (KIBO/JEM). The instrument is optimized to precisely study the properties of extreme energy cosmic electrons up to dozens of TeV. It can also measure the relative composition and abundance of nuclei from space, from protons to the heaviest elements up to Z=40. In the first three years of operation, CALET collected and sent more than 1.8 billion cosmic rays' events [28].

ISS-CREAM: The Cosmic Ray Energetics and Mass for the International Space Station was successfully installed and activated on the Japanese Experiment Module Exposed Facility as an attached payload in 2017. The instrument is configured with complementary particle detectors capable of measuring elemental spectra for Z=1 up to Z=26 nuclei in the energy range from 1 up to 1000 TeV, as well as electrons at multi-TeV energies add the CREAM instrument [29].

ACE: the Advanced Composition Explorer is a satellite-based space mission that started its operation in 1998, intending to observe particles of solar, interplanetary, interstellar, and galactic origins, spanning the energy range from solar wind ions to galactic cosmic ray nuclei. It is located at the L1 Lagrange point, about 1.4 million kilometres from the Earth. ACE can measure particle and nuclei elements up to Z=30 in an energy range of up to hundreds of MeV thanks and is composed of 9 different instruments (see Fig. 3) that share the satellite infrastructure for power, control, and data communications [30].

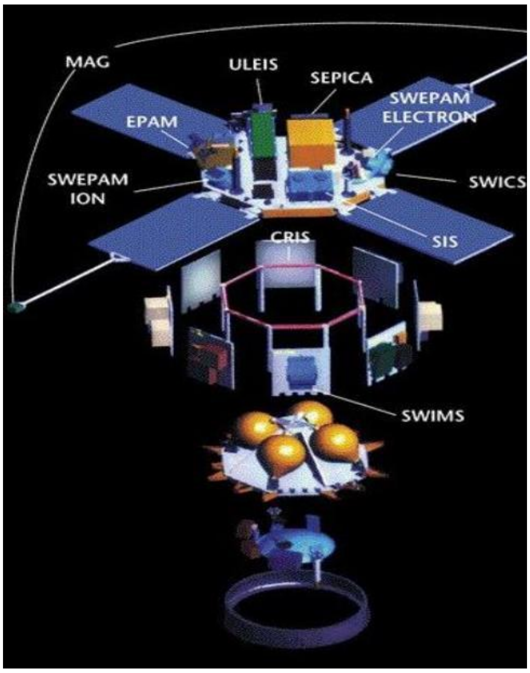


Fig. 3. Advanced Composition Explorer (ACE), satellite architecture and on-board instruments (credit NASA)

Relevant for IR measurements are:
- the **Cosmic-Ray Isotope Spectrometer (CRIS)** can cover the energy interval, from 50 to 500 MeV/nucleon, with an isotopic resolution for elements from Z ≈ 2 to 30. The nuclei detected in this energy interval are predominantly cosmic rays originating in our Galaxy. Charge and mass identification with CRIS is based on multiple measurements of dE/dx and total energy in stacks of silicon detectors and trajectory measurements in a scintillating optical fibre trajectory (SOFT) hodoscope. The instrument has a geometrical factor of 250 cm2 (39 sq in)-sr for isotope measurements.

- The **Ultra-Low-Energy Isotope Spectrometer (ULEIS)** on the ACE spacecraft is an ultra-high-resolution mass spectrometer that measures particle composition and energy spectra of elements He–Ni with energies from ~45 keV/nucleon to a few MeV/nucleon [31].

Other ACE instruments also provide near-real-time solar wind information over short periods. When reporting space weather, ACE can provide a warning (about one hour) of geomagnetic storms that can overload power grids, disrupt communications on Earth, and present a hazard to astronauts. An instrument used for such purposes is the Electron, Proton, and Alpha-particle Monitor (EPAM), designed to measure a broad range of energetic particles over nearly the full unit-sphere at high time resolution. Such measurements of ions and electrons in the range of tens of keV to several MeV are essential to understand the dynamics of solar flares, co-rotating interaction regions (CIRs), interplanetary shock acceleration, and upstream terrestrial events. Another instrument is the Real-Time Solar Wind (RTSW) system, which uses low-energy energetic particles to warn of interplanetary shocks approaching and to help monitor the flux of high-energy particles that can produce radiation damage in satellite systems [32]. The end of its operation is forecast not before 2024.

Another important CRD, no more in operation, was the Payload for Antimatter Matter Exploration and Lightnuclei Astrophysics (PAMELA). **PAMELA** operations started in 2006 and 2016, producing accurate measurements of the cosmic ray components (particle and light nuclei up to Z=6) [33].

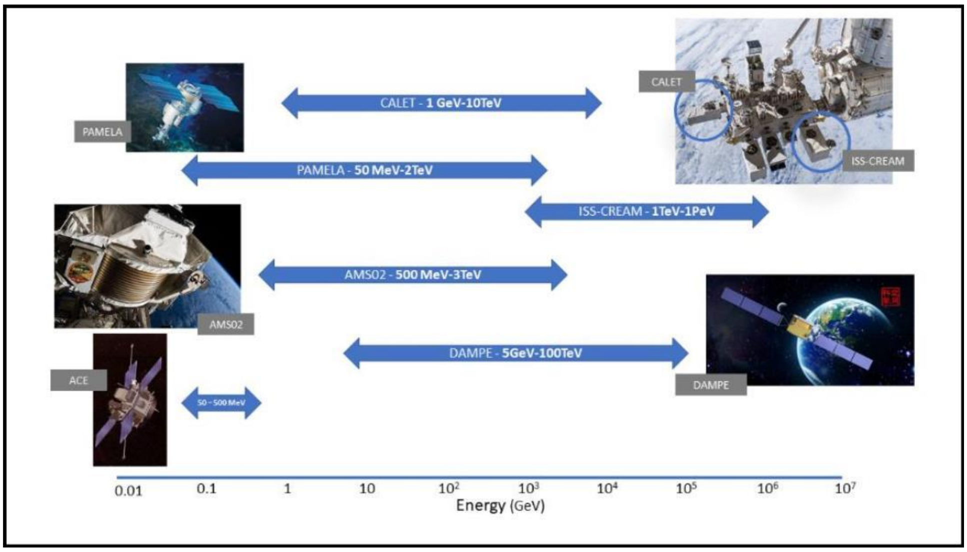


Fig. 4. Measurement's energy range of some Cosmic Ray Detectors operating in space.

3.2 CRD Operations and Measurements

The characteristics of the operations of the CRD space missions that last for several years are optimal for improving our knowledge of the IR health effects on humans in space. It will be possible to use vast amounts of data (on average, a CRD registers more than a billion CR events per year, i.e., AMS02 have registered since the start of data taking in 2011 more than 190 billion events). The more crucial characteristics associated with such data can be summarized in the following aspects [34]:

- **Complete CR components identification**: They can measure the abundances and spectral distribution of the CRs particles (protons and electrons) as well as the CRs nuclei from the light one like the Helium up to heavier ones like the Iron (Z=25), with a precision and accuracy never reached so far.

- **High Energy Range Spectra**: As shown in figure 4, the data taken from the operating CRDs ranges from a few MeV up to hundreds of TeV.

- **CR Solar Modulation**: one of the most important aspects to be evaluated is the differences in IR exposition due to the interference of the solar activities and cycles with the GCR part of the space radiation. In this regard, the CRDs took data during cycles 23 and 24, and some will continue for the 25th. In figure 5, the solar modulation is evident for protons at lower energies comparing the measurements done by the AMS02 in the earth nearby with the ones done by the Voyager probe in the Heliosphere.

The variation of CRs flux in time is crucial for investigating the effects of IR during space missions. In figure 6, the Protons flux variation at the low energy is reconstructed by the AMS02 since May 2011.

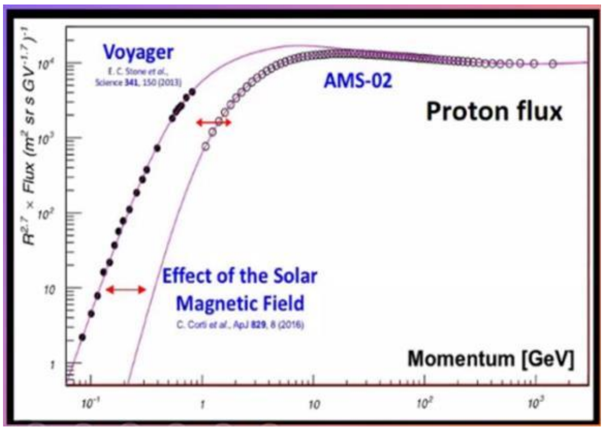


Fig. 5 The effects of the Solar Magnetic Field action are evident in the CRs protons flux in the low energy spectrum. (Figure Courtesy of AMS Collaboration)

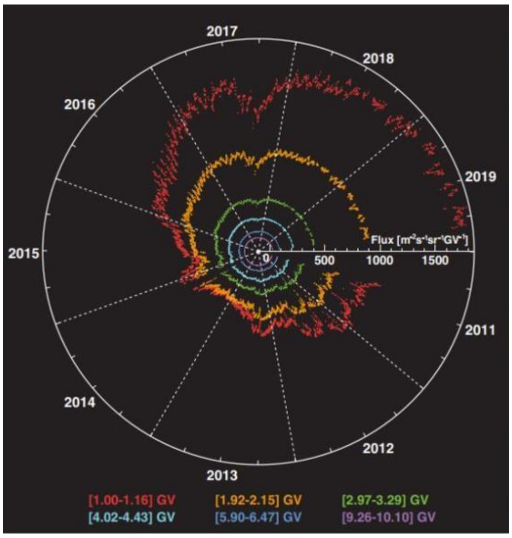


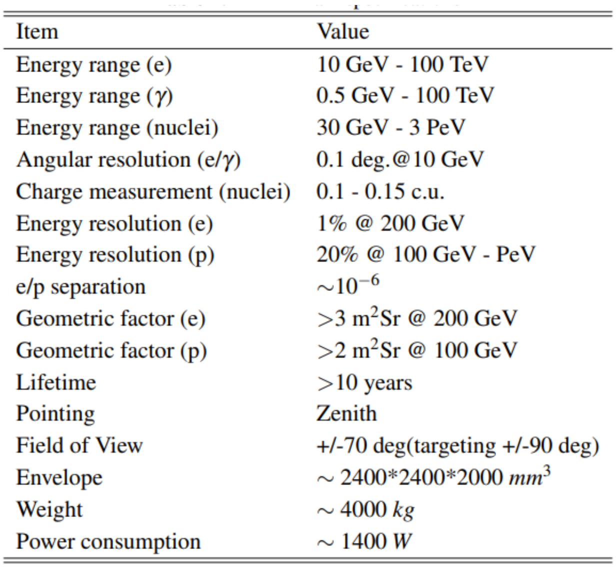
Fig. 6 The daily AMS proton fluxes for six typical rigidities from 1.00 to 10.10 GV measured from May 20, 2011, to October 29, 2019, which includes a significant portion of solar cycle 24 (from December 2008 to December 2019) (Figure Courtesy of AMS Collaboration in [23])

3.3 CRDs in space what next?

For space exploration and to be able to live somewhere other than Earth (Moon or Mars or even beyond of solar system), we need to increase our knowledge about space radiation more and more, but also to improve our knowledge on some crucial aspect regarding the Cosmo behaviour is still necessary to improve the measurements of the CR. Actually, many project are in the progress for developing new generation of CRDs to accomplish this scientific goal and to probe further on direct measurements of cosmic rays flux and composition up the very high energies regions, to monitor the gamma-ray components of the sky, to probe further the indirect measurements of the dark matter and dark energy components of the universe and also to probe the presence of primordial antimatter and shed light of its origin. We highlight in the following two work in progress CRDs that can be representative of the possible future approaches to CRDs design and development one in LEO and the other in BLEO, the High Energy Cosmic-Radiation Detection facility (HERD) and the AMS-100 experiment that is an example of a proposal for a CRDs to be installed in the BLEO. HERD[36] is a probe for high-energy cosmic rays' physics and multi-messenger astronomy planned to be installed and in operation after the 2025 for about 10 years on the Chinese Space Station (CSS). It is a multi-instruments CRD that will be capable to measure all the components of the CR with the characteristics as indicated in Fig 7.

HERD is composed of 4 scientific instruments. The main one is a homogeneous, almost cubic calorimeter made of about 7500 LYSO scintillation crystals and capable of accepting particles incident on its top face and four lateral faces. Each sensitive face is instrumented with a silicon tracker and covered by a plastic scintillator detector to separate gamma rays from charged particles. Additionally, a TRD is located on one lateral face for energy calibration of TeV particles.

The target is to improve the CRD acceptance and energy measurements range while maintaining the full capability to measure all CR components This design results in an effective geometric factor more than one order of magnitude larger than that of previous missions, and excellent lepton/hadron separation capabilities thanks to the 3D nature of the calorimeter.



Item	Value
Energy range (e)	10 GeV - 100 TeV
Energy range (γ)	0.5 GeV - 100 TeV
Energy range (nuclei)	30 GeV - 3 PeV
Angular resolution (e/γ)	0.1 deg.@10 GeV
Charge measurement (nuclei)	0.1 - 0.15 c.u.
Energy resolution (e)	1% @ 200 GeV
Energy resolution (p)	20% @ 100 GeV - PeV
e/p separation	$\sim 10^{-6}$
Geometric factor (e)	>3 m^{2}Sr @ 200 GeV
Geometric factor (p)	>2 m^{2}Sr @ 100 GeV
Lifetime	>10 years
Pointing	Zenith
Field of View	+/-70 deg(targeting +/-90 deg)
Envelope	$\sim$ 2400*2400*2000 mm^3
Weight	$\sim$ 4000 kg
Power consumption	$\sim$ 1400 W

Fig. 7. The High Energy Cosmic-Radiation Detection facility (HERD) main specification as reported in [35].

Completely different is the approach used to design the next generation magnetic spectrometer in space, AMS-100. In such case still an improvement on the geometrical acceptance (up to 100 m^2 sr) is planned but is the operational location completely new and disruptive since it is moved at the Sun-Earth Lagrange Point 2, 1.5 million Km fer from the Earth in the opposite direction with respect to the Sun. Compared to existing experiments, it will improve the sensitivity for the observation of new phenomena in cosmic rays, and in cosmic antimatter, by at least a factor of 1000. The magnet design is based on high temperature superconductor tapes, which allow the construction of a thin solenoid with a homogeneous magnetic field of 1 Tesla inside (see Fig.8) [36]. The inner volume will be instrumented with a silicon tracker reaching a maximum detectable rigidity of 100 TV and a calorimeter system that is 70 radiation lengths deep, equivalent to four nuclear interaction lengths, which extends the energy reach for cosmic-ray nuclei up to the PeV scale, i.e., beyond the cosmic-ray knee. Covering most of the sky continuously, AMS-100 will detect high-energy gamma rays in the calorimeter system and by pair conversion in the thin solenoid, reconstructed with excellent angular resolution in the silicon tracker. Such class of CRDs could be represent a breakthrough technology for continuous and precision monitoring of the CR characteristics of the deep space radiation environment, especially for the GCR component.

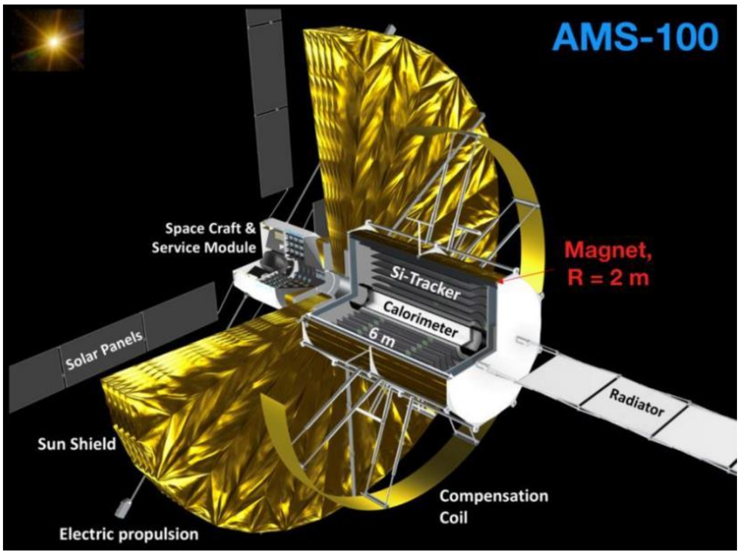


Fig. 8. The AMS-100 CRD Concept as reported in37. It will be in the "Lagrange Point 2" of the Earth-Sun system far from the Earth surface 1.5 million Km and more that 150 million from the Sun where it could be used as an excellent platform for the continuous high-precision measuring of the CRs Galactic Cosmic Ray component.

The future generation of CRD will be an excellent coadjutant of the initiative focused to build dosimeters system to know the to the amount of dose that reaches the human body during a space journey. Therefore, it is necessary to use active and passive dosimeters that collect data with high accuracy.

Actually, the NASA's Artemis program represents the refence in this field. The purpose of this program is to explore the surface of the moon and send the first woman and the first person of color to the moon and to obtain the necessary knowledge and experience to send the first astronaut to Mars [37]. On November 2022, NASA launched Artemis 1. In the spacecraft, there were two female phantoms covered with many dosimeters. The spacecraft was in space for several weeks and circled around the moon before finally returning to Earth in December 2022. Undoubtedly, such missions provide very valuable dosimetry data for researchers [38].

3.4 CRDs derived enabling technologies: the magnet-based energy measurements case study

On multiple instruments for space radiation detection that can follow up from the CRDs detectors an interesting one is the possibility to measure the high-energy CRs spectra using a technique no requiring that the CR particle stops inside the detector. In fact, the use of the magnet to bend the particle trajectory can be used to measure the energy.

Most of the actual and past instruments used to detect space radiation are based on solid state detector an example is the Radiation Assessment Detector (RAD) [39] used to characterize the full spectrum of energetic particle radiation at the surface of Mars, including galactic cosmic rays (GCRs), solar energetic particles (SEPs), secondary neutrons and other particles created both in the atmosphere and in the Martian regolith. The RAD instrument consists of a charged particle telescope comprised of three solid-state detectors and a cesium iodide (CsI) calorimeter. An additional BC-432 scintillating plastic channel is used together with the CsI calorimeter and an anti-anticoincidence shield to detect and characterize neutral particles (i.e., neutrons and gamma rays). The outputs of the various photodiodes, used with the CsI and scintillating plastic, and solid-state detectors are converted to digital pulse height discriminated signals for further processing. The energy measurements ranges are summarized in Table 1.

Table 1. RAD energy coverage for both charged and neutral particles(rielaborated from [39].

Particle types	Energy Range in (MeV)/n
P, He	5 - 1500
Ions (Li – O)	7 - 1500
Ions (Mg – Fe)	10 - 1500
Neutrons	5 - 100
γ-rays	0.5 - 8
Electrons	0.2 - 25
Positrons	0.2 - 1

An improvement can be reached using the proven detection principle of a magnetic spectrometer and an example of an R&D activity on this topic is the Penetrating particle ANalyzer (PAN) project [40, 41].

PAN is a scientific instrument, under development, suitable for deep space and interplanetary missions. It can precisely measure and monitor the flux, composition, and direction of highly penetrating particles (>100 MeV/nucleon) in deep space, with the main aim to fill an observation gap of galactic cosmic rays in the GeV region, and will provide precise information of the spectrum, composition and emission time of energetic particle originated from the Sun. PAN detection technology, based on the magnetic spectrometer principle, has the potential to become a crucial technology for on-board instrument for a safe human space exploration and colonization.

4. Enabling Space Radiation Research at the AMS INFN Roma Sapienza group

Safety is of utmost importance to space missions. One of the prime concerns in human exploration and development of space is protecting astronauts and future settlements against the hazards of deep space radiation. Enabling radiation protection and cost-reduction technologies are vital for deep space exploration. At the INFN Roma AMS group, we have started to develop enabling technologies for predicting the possible damage induced by space radiation to the astronaut's/space workers' health over multi-segmented missions involving multiple work and living areas in the transport and different exposition scenarios of space missions. Also, we are approaching another crucial aspect of space radiobiology investigation: the possibility of having low-cost and easy-access technologies for pre-clinical study. In this case, the space radiation analogue generator can be mimicked using the Laser Plasma Accelerators (LPA) instrumentations and facilities.

4.1 Dose Effects Models for Space Radiobiology.

In the following is describe the path the we used to address the problem of improvements the filed of space radiobiology and the results currently achieved

4.1.1 GCR sensitivity analysis: A case study on AMS02 capability

In 2019 we identified which components of the CR are of interest for the computation of possible risks associated with the crewed exploratory space missions in LEO and BLEO scenarios. In this regard, using as reference some existing space radiation sensitivity studies [42], we also recognized that they correspond with the data taken by the CRDs operating in space, and in particular, the energy range crucial for the risk assessment mostly corresponds to the capability of measurements of the AMS02 detector [43]. This study was the first step of an analysis focused on identifying possible improvements from the CDR data to the radiation health risk assessment for human space missions [44,45]. Such analysis was also confirmed recently by Corti et al. [46], showing the capabilities of AMS02 and other CRD to measure CP and HN in the windows energy range that is primarily of interest for the "Human Radiation Hazard" (see Fig. 9).

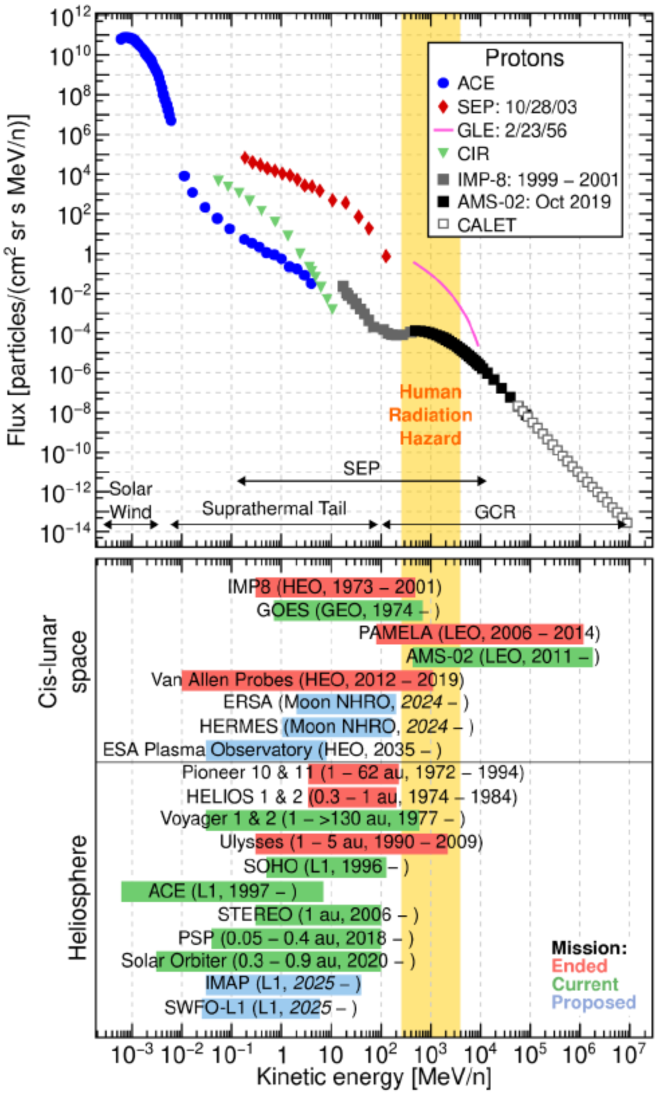
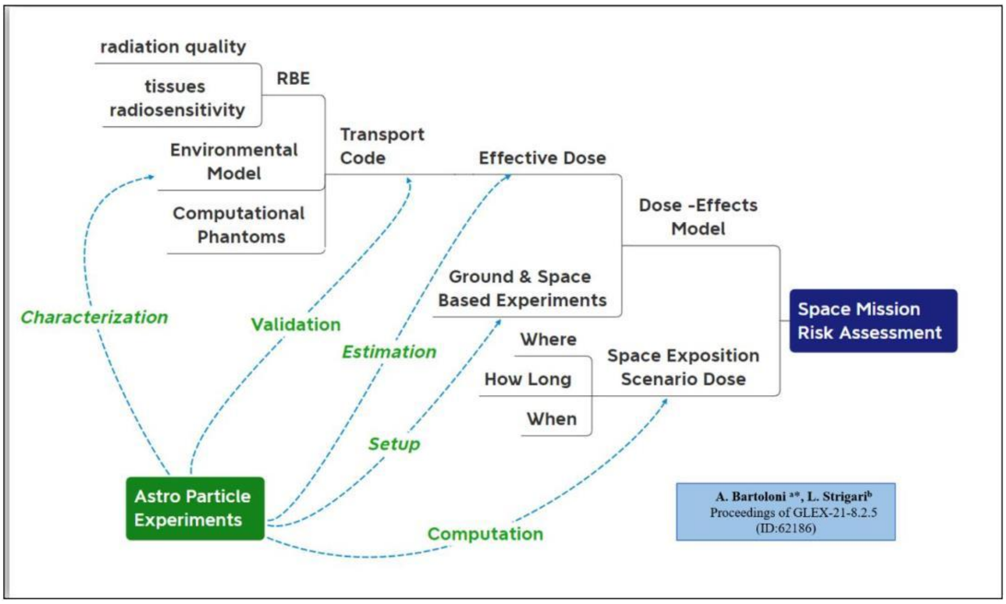


Fig. 9. Flux vs Energy ranges of protons as seen by different CRDs, and probes operating in the last decades or planned soon. The yellow band range is the most relevant for human radiation exposure (Figure courtesy of Corti et al. [46])

4.1.2 Improve the Radiation Health Risk Assessment for Humans in Space Missions

In the second step, we perform a literature search of published dose-effect relationships identifying the reported endpoints from space missions, including acute and late effects, published in a separated manuscript [8]. In this study, we highlight the significant improvements in the risk assessment capability thanks to the possibility to have information in energy ranges never explored before and in the complete species of CR - from elementary particles (electrons, protons) to light and heavy nuclei (Helium to Iron and beyond) - that could be of concerns in space missions. Figure 10 shows the identified possible improvements. In this regard, once that the space mission exposition scenario is fixed, that means that are identified with accuracy all the details of the space mission concerning the expected duration, destination, and forecast period latter in order to evaluate the Solar activity conditions that modulate the GCR radiation components, the risk assessment will calculate the possible damages deriving from the space mission and to do that will benefit from an accurate dose effects models for each scenario.

Five possible actions, described in the following, have been identified to pursue this scope.



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(ID:62186)

Fig. 10. Human Health Risk Assessment in exploratory space missions: possible improvement using astroparticle experiments operating in space [45].

4.2 Environmental Model Characterization:

Current environmental models used in the risk assessment process are based on a subset of the CR spectrum poor in the information of CR components of energy > 1GeV due to limited information collected in the past years. This affects the accuracy and precision of the risk assessment, potentially underestimating the actual damage. Indeed, space radiation for LET higher than several keV/µm causes more severe damage than low-LET radiation to living cells/tissues.

Many successful CR observatory space missions have been collecting crucial data in the last decade, and they will continue in the years. These data have an unprecedented precision on the spectrum and LET distribution of charged particle fluxes that compose the CRs. This precision is essential for improving the risk assessment models thanks to monitoring the CR fluxes and their variation over time (including the frequency and duration of solar events). In that direction, Slaba and Witham report [47] a possible improvement using the AMS02 and Pamela CRDs data of the BadhwarO'Neill GCR model.

4.3 Equivalent Dose Estimation

Measurements only of absorbed doses, by passive dosimeters, are insufficient for investigating biological effects or assessing radiation risk for astronauts. Dose equivalents need to consider the whole LET distributions, their QFs (up to 30), and RBE of high-LET particles constituting the space radiation environment. So, the CRDs data could be used to complete the absorbed dose measurements related to the installation site/area. Recently an example of possible use of the AMS02 for implementing a radiation monitoring system in the external environment of the ISS was presented [48]. This type of system could be a useful resource to plan space walks or space missions involving human crew in the Low Earth Orbit, in a smart-system approach that combines, analyses, and provides feedback and alarms based on the inputs from instruments inside [49,50] and outside the ISS and on satellites in different orbits.

4.4 Transport Code Validation

Based on the detailed information obtained from the CRD, Monte Carlo (MC) simulation code can be further implemented to better describe the interaction with the matter of GCR environments thanks to the improvement of accuracy of cross-sections at high energy of elementary particles (electrons, protons), light and heavy nuclei (Helium to Iron and beyond). Implementing transport code at these energies allows predicting the particle interactions with the known geometries of installed detectors. The determination of ray/particle tracking, energy spectrum, and deposited energies collected in several materials can serve for a subsequent MC transport code validation (e.g., through a possible Bayesian approach). The calculations of dose equivalents allow generating an accurate and precise database for subsequent MC simulation codes validation applied to human tissues. Moreover, MC codes can be used for designing ad hoc shielding of spacecraft and space landers Considering the importance of radiation dosimetry and awareness of biological damage caused by the collision of space radiation on human body tissue, it is necessary to use Monte Carlo simulation codes for the study of the transport of particles in materials.

4.4.1 Space Exposition Scenario Dose Computation

MC codes can be implemented to calculate the dose and so predict/describe the effects of GCR particles interacting with cells, tissues/organs, and astronauts, which can be modelled as geometries with increasing details and complexities. The CRD data could be used as input data of the MC codes for determining the absorbed dose in the forecast exposition scenario (e.g., lunar gateway/lander or spacecraft).

4.4.2 Ground or Space based Experiment definition

Ad hoc measurements in the biophysical laboratory of lunar gateway/lander or spacecraft are expected to further boost the knowledge of RBE and QFs for space missions. Space-based Experiment setup can be identified and improved by replicating ad hoc experiments on Earth for endpoints considered relevant for future space missions. The possibility to conduct ad hoc experiments on the Earth can allow overcoming the uncertainties due to the limited number of subjects involved in space missions and pave the way to the era of lunar or MARS missions using more accurate risk models. The CDRs data are mandatory to set up the experiments concerning the particle types and abundancy.

4.4.3 Other possible improvements

There are many other aspects of IR health effects on humans that could be investigated prior to long-term space missions outside the protection of the Earth's geomagnetic sphere will begin, and that can benefit from the information contained in the CRD data.

Among the others, the so-called bystander IR non target effects [51] is to be intended as the damage generated in tissue not directly irradiated. This topic is unknown mainly due to the scarcity of animal models for tissues that dominate human radiation cancer risk. The individual radiosensitivity that it is crucial when the number of people traveling/working in space will be orders of magnitude higher than the actual one. To this aim we started in 2021 to develop a tool for modelling and predicting the Non-Target Effect (NTE) due to GCR and the induced carcinogenesis risk for humans in space exploration.

The software tool, NTE-DEM, was developed using the RStudio Integrated Development Environment and was initially applied to the proton data collected from AMS02. The result of such analysis was published in 2023 [52].

4.5 *LPA an analogue for space radiation investigations.*

Space radiobiology (SPRB) is an interdisciplinary science that examines the biological effects of ionizing radiation on humans involved in aerospace missions. One of the crucial points in advancing the knowledge in this field is enhancing the possibility of generating experimental data; to that, space radiation reproduction is mandatory. Using the analogue approach that in many other areas of space research is of great success, it could be possible to use Laser Plasma Accelerators (LPA) to reproduce the space radiation condition in ground experiments and design radiobiology investigations in the space environment. LPA is capable of robust generation of particle beams such as electrons, protons, neutrons, and ions, as well as photons, having a wide range of accessible parameters. Several facilities exist in the world equipped with LPAs, however to full understand the radiobiology mechanism and models ad hoc tuning of all the LPAs parameters to reproduce the exposure conditions are mandatory. This is way the AMS Roma group has started fostering synergies and collaboration from different scientific communities (Space Radiation , Medical Physics, LPAs Expert) to produce a common understanding of the problem and define protocols to mimic appropriately space radiation exposure conditions depending of the exposition scenario. The aim of such collaboration is the identification of exposure protocols and methodologies for improving Space Radiation testing analogues using LPAs using also the

Alpha Magnetic Spectrometer (AMS02) detector Cosmic Rays fluxes and spectra measurements. Development : Foster collaboration from different scientific communities (Space Radiation , Medical Physics, LPAs Experts). Further we want to fill a technological gap in coupling the existing LPAs technologies with a platform including all the relevant dose effects information and exposure conditions necessary for better characterize and investigate target and non-target effects in SPRB. The result will enable greater usability of these new technologies for the SPRB and hence for a safe space exploration.

5. Conclusions

In the coming years, there will be a great interest in human space missions non-only to explore and for a permanent presence of humans outside the geo-magnetosphere. Further, technological advancements might realize the dream of human space exploration, and crewed spaceflights to explore and colonize the Moon and Mars are on the agenda of space agencies. Possible exposition to space radiation is the primary concern and the first showstopper in many human exploration scenarios. In this context, a great benefit could derive from the data acquired over a decade by the Astroparticle experiments operating in space. Such data contains crucial information on the composition and the radiation quality of the CR in LEO and BLEO environments and could improve essential topics related to the human health effects due to ionizing radiation expected in space during the planned space exploration missions. Many space radiobiology dose-effects models have been proposed for target effects, while other topics (e.g., non-targeted effects, individual radiosensitivity) demand further investigation. Characterizing the space radiation environment is essential for evaluating space travel exposure, improving space missions' safety, and improving the risk assessment model.

In recent years, significant improvements have been made in the absorbed dose-effect estimation for predicting risks for human health in space exploration. Unfortunately, the number of events helpful in modelling the radiobiological effects still needs to be increased. On-Earth experiments may reinforce knowledge of cancer and non-cancer space-radiation-induced effects. In this task, a valuable complementary technology can be the Laser Plasma Accelerators facilities, but clear protocols for using such technologies to mimic SP are mandatory before acting. The AMS Roma Sapienza group is part of the scientific community investigating this crucial research topic for safe human exploration of space, putting in place the necessary expertise in the field of cosmic rays measurements, space radiobiology and space radiation as well as creating synergies and collaboration with the people and institution eager to participate in such researches.

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References

[1] Simpson, J.A. Elemental, and isotopic composition of the galactic cosmic rays. Ann. Rev. Nucl. Part. Sci. 1983, 33, 323–381.

[2] B. G. Drake, Human exploration of mars design reference architecture 5.0, National Aeronautics and Space Administration, 2009.

[3] National Council on Radiation Protection and Measurements (NCRP). Information Needed to Make Radiation Protection Recommendations for Space Missions Beyond Low-Earth Orbit; NCRP: Bethesda, MD, USA, 2006.

[4] A. Bartoloni, B. Borgia, S. Gentile, F.R. Spada (2014) The Slow Control System for the TRD Gas Circuit of the Alpha Magnetic Spectrometer, Nuclear Instruments and Methods in Physics Research Section A, 738, 61-73,, doi.org/10.1016/j.nima.2013.11.080.

[5] A. Bartoloni (2004) The AMS02 transition radiation detector (TRD) gas control system , Nuclear Instruments and Methods in Physics Research Section A, 518, 6143-144, doi:10.1016/nima.2003.10.044.

[6] Bartoloni A, Strigari L, Can high energy particle detectors be used for improving risk models in space radiobiology? in proceedings of the Global Space Exploration Conference 2021 (GLEX2021), Jun 2021.

[7] Bartoloni A, Strigari L, AMS02 e radiobiologia nello spazio., Annual Conference of the Italian Physical Society (SIF) L'Aquila 27/09/2019, wiki.infn.it/ media/strutture/roma1/experiments/ams2/ams sprb sif 2209 breve eng.pdf (accessed 31.08.22) 2019.

[8] A. Bartoloni, N. Ding, G. Cavoto, C. Consolandi, L. Strigari (2023)., Astroparticle Experiments to Improve the Biological Risk Assessment of Exposure to Ionizing Radiation in the Exploratory Space Missions: The research topic initiative Nucl.Instrum.Meth.A 1047 167738, doi:10.1016/j.nima.2022167738

[9] L. Strigari, S. Strolin, A. G. Morganti, A. Bartoloni (2021). Dose-Effects Models for space radiobiology: an overview on dose effect relationships, Front. Public Health 9, 733337. Doi:10.3389/fpubh.2021.733337.

[10] L. J. Gleeson, W. I. Axford, (1968). Solar modulation of galactic cosmic rays. Astrophys. J. 154, 1011, doi: 10.1086/149822.

[11] F. Satoshi, N. Aiko, N. Mitsuru, and et. Al., (2020). Space Radiation Biology for "Living in Space", BioMed Research International Volume 2020, Article ID 4703286, doi.org/10.1155/2020/4703286.

[12] W. Li, and M.K. Hudson, (2019). Earth's Van Allen Radiation Belts: From Discovery to the Van Allen Probes Era, doi.org/10.1029/2018JA025940.

[13] A. Marki, (2020). Radiation Analysis for Moon and Mars Missions International Journal of Astrophysics and Space Science 8(3), 16-26, doi:/10.11648/j.ijass.20200803.11.

[14] A.C. Cummings, E.C. Stone, C.D. Steenberg (2002). Composition of Anomalous Cosmic Rays and other Heliospheric Ions The Astrophysical Journal , 578,194-210

[15] X. Zigong, G. Jingnan, F. Robert, Wimmer-Schweingruber, I. Mikhail, Dobynde, K. Patrick, K. Salman, and Z. Shenyi, (2022). Primary and albedo protons detected by the Lunar Lander Neutron and Dosimetry experiment on the lunar farside, Astronomy and Space Sciences, 10.3389/fspas.2022.974946.

[16] M. Daniel, M. H. Donald, Wouter de Wet, E. Bent, and et. al., (2017). The radiation environment on the surface of Mars - Summary of model calculations and comparison to RAD data, doi.org/10.1016/j.lssr.2017.06.003.

[17] M. H. Donald, Z. Cary, F. Robert, Wimmer-Schweingruber, and et. al., (2016). Mars' Surface Radiation Environment Measured with the Mars Science Laboratory's Curiosity Rover, http://science.sciencemag.org/, VOL 343, 1244797.

[18] T. K. Gaisser, R. Engler, E. Resconi, (2016). Cosmic Rays and Particle Physics - second edition (Cambridge University Press).

[19] M. Aguilar, L. Ali., Cavasonza, L. Ambrosi, G. Arruda, L.N. Attig, F. Barao, L. Barrin, A. Bartoloni, S. Başeğmez-du Pree, and et al. (2021). The Alpha Magnetic Spectrometer (AMS) on the international space station: Part II — Results from the first seven years. Phys. Rep 894, 1-116. 10.1016/j.physrep.2020.09.003.

[20] M. Aguilar, L. Ali., Cavasonza, M. S. Allen, B. Alpat, G. Ambrosi, L. Arruda, N. Attig, F. Barao, L. Barrin, A. Bartoloni, and et al. (2021). Properties of Iron Primary Cosmic Rays: Results from Alpha Magnetic. Phys. Rev. Lett 126, 041104. 10.1103/PhysRevLett.126.041104.

[21] M. Aguilar, L. Ali., Cavasonza, M. S. Allen, B. Alpat, G. Ambrosi, L. Arruda, N. Attig, F. Barao, L. Barrin, A. Bartoloni, and et al. (2021). Properties of heavy Secondary Fluorine Cosmic Rays: Results from Alpha Magnetic Spectrometer. Phys. Rev. Lett 126, 081102. 10.1103/PhysRevLett.126.081102.

[22] M. Aguilar, L. Ali, Cavasonza, B. Alpat, G. Ambrosi, L. Arruda, N. Attig, F. Barao, L. Barrin, A. Bartoloni, (2021). Erratum: Properties of a New Group of Cosmic Nuclei: Results from the Alpha Magnetic Spectrometer on Sodium, Aluminum, and Nitrogen. Phys. Rev. Lett 127, 159901. 10.1103/PhysRevLett.127.159901.

[23] M. Aguilar, L. Ali, Cavasonza, G. Ambrosi, L. Arruda, N. Attig, F. Barao, L. Barrin, A. Bartoloni, S. Başeğmezdu Pree, R. Battiston, (2021). Periodicities in the Daily Proton Fluxes from 2011 to 2019 Measured by the Alpha magnetic Spectrometer on the International Space Station from 1 to 100 GV of Daily Helium Fluxes. Phys. Rev. Lett 127, 271102. 10.1103/PhysRevLett.127.271102.

[24] M. Aguilar, L. Ali, Cavasonza, G. Ambrosi, L. Arruda, N. Attig, F. Barao, L. Barrin, A. Bartoloni, S. Başeğmezdu Pree, R. Battiston, (2022). Properties of Daily Helium Fluxes. Phys. Rev. Lett 128, 231102. 10.1103/PhysRevLett.128.231102.

[25] M. Aguilar et al., M. Aguilar et al Properties of Heavy Nuclei in South Atlantic Anomaly region, in the Conference proceedings of the COSPAR 2022 44th Scientific Assembly 16-24 July 2022, Athens Greece.

[26] K. Bollweg on behalf of the AMS Collaboration Upgrade of AMS for the next Ten Years, in the Conference proceedings of the COSPAR 2022 44th Scientific Assembly 16-24 July 2022, Athens Greece.

[27] A. De Benedittis for the DAMPE Collaboration, The DAMPE experiment: performance and results, proceedings of EPS-HEP 2019.

[28] Y. Asaoka, O. Adriani, Y. Akaike, K. Asano, Bagliesi, M. G. Berti, E., G. Bigongiari, W. R. Binns, S. Bonechi, M. Bongi, and et al. (2019). The CALorimetric Electron Telescope (CALET) on the International Space Station: Results from the First Two Years on Orbit. J. Phys. Conf. Ser, 1181. 10.1088/1742-6596/1181/1/012003.

[29] E.S. Seo, T. Anderson, D. Angelaszek, S.J. Baek, J. Baylon, M. Buénerd, M. Copley, S. Coutu, L. Derome, B. Fields, and et al. (2014). Cosmic Ray Energetics and Mass for the International Space Station (ISS-CREAM). Adv. Space Res 53, 1451-1455. 10.1016/j.asr.2014.01.013.

[30] E. C. Stone, A. M. Frandsen, R. A. Mewaldt, E. R. Christian, D. Margolies, J. F. Ormes, F. Snow, (1998). The Advanced Composition Explorer. Space Sci. Rev 86, 1–22. 10.1023/A:1005082526237.

[31] R. E. Gold, S. M. Krimigis, S. E. Hawkins III, D. K. Haggerty, D. A. Lohr, E. Fiore, T. P. Armstrong, G. Holland, L. J. Lanzerotti, (1998). Electron, Proton, and Alpha Monitor on the Advanced Composition Explorer Spacecraft. Space Sci. Rev 86, 541–562. 10.1023/A:1005088115759.

[32] R. D. Zwickl, K. A. Doggett, S. Sahm, W. P. Barrett, R. N. Grubb, T. R. Detman, V. J. Raben, C. W. Smith, P. Riley, R. E. Gold, R. A. Mewaldt, T. Maruyama, (1998). The NOAA Real-Time Solar-Wind (RTSW) System using ACE Data. Space Sci. Rev 86, 633–648. 10.1023/A:1005044300738.

[33] O. Adriani, G. C. Barbarino, G. A. Bazilevskaya, R. Bellotti, M. Boezio, E. A. Bogomolov, M. Bongi, V. Bonvicini, S. Bottai, A. Bruno, (2017). Ten years of PAMELA in space. Riv. del Nuovo Cim 10, 473-522. 10.1393/ncr/i2017-10140-x.

[34] A. Bartoloni, S. Strolin, L. Strigari, 2020 Virtual IEEE Nuclear Science Symposium and Medical Imaging Conference http://wiki.infn.iroma1/experiments/ams2/ieee-nss-mic_bartoloni5.pdf (accessed 30.10.2022).

[35] Y. Dong, S. Zhang, G. Ambrosi, on behalf of the HERD collaboration (2019) Overall Status of the High Energy Cosmic Radiation Detection Facility Onboard the Future China's Space Station on Proceedings of the 36th International Cosmic Ray conference (ICRC2019), DOI: https://doi.org/10.22323/1.358.0062.

[36] S. Schael, A. Atanasyan, J. Berdugo, T. Bretz, M. Czupalla, B. Dachwald, et al (2019). AMS-100: The Next Generation Magnetic Spectrometer in Space - An International Science Platform for Physics and Astrophysics at Lagrange Point 2. arXiv. https://doi.org/10.1016/j.nima.2019.162561.

[37] Websites: NASA, Artemis program. https://www.nasa.gov/specials/artemis/

[38] Websites: NASA, Artemis 1. https://www.nasa.gov/artemis-1

[39] Websites: The Radiation Assessment Detector (RAD), RAD for Scientists | RAD – NASA Mars Exploration

[40] X. Wu, G. Ambrosi, P. Azzarello, B. Bergmann, B. Bertucci, F. Cadoux, and et. al., (2019). Penetrating particle ANalyzer (PAN), Advances in Space Research 63, 2672–2682, https://doi.org/10.1016/j.asr.2019.01.012

[41] Websites: PAN - Département de physique nucléaire et corpusculaire (DPNC) - UNIGE

[42] T. Slaba, S. Blatting, GRC environmental model I: Sensitivity analysis for GCR environments, Space Weather 12:4 (2014) 217-224.

[43] A. Bartoloni, L. Strigari, AMS02 e radiobiologia nello spazio, Book of Abstract of the Annual Conference of the Italian Physical Society (SIF) L'Aquila 27/09/2019, wiki.infn.it/_media/strutture/roma1/experiments/ams2/ams_sprb_sif_2209_breve_eng.pdf (accessed 31.08.22)

[44] A. Bartoloni, L. Strigari, *Can high energy particle detectors be used for improving risk models in space radiobiology?* in proceedings of the Global Space Exploration Conference 2021 (GLEX2021) Jun 2021.

[45] A. Bartoloni, G. Della Gala, A.N. Guracho, G. Paolani, M. Santoro, L. Strigari, S. Strolin, (2022). High energy Physics Astro Particle Experiments to Improve the Radiation Health Risk Assessment for Humans in Space Missions. EPS-HEP2021 398, 106. 10.22323/1.398.0106.

[46] C. Corti, K. Whitman, R. Desai, J. Rankin, D. T. Strauss, N. Nitta, D. Turner, T. Y. Chen, (2022). Galactic Cosmic Rays and Solar Energetic Particles in Cis-Lunar Space: Need for contextual energetic particle measurements at Earth and supporting distributed observation. Preprint at Arxiv, https://doi.org/10.48550/arXiv.2209.03635.

[47] T. C. Slaba, K. Whitman, (2020). The Badhwar-O'Neill 2020 GCR model. Space Weather 18, e2020SW002456. 10.1029/2020SW002456.

[48] Faldi, F. (2022). Real time monitoring of the radiation environment on the ISS with AMS-02. IL Nuovo Cimento 45 C, 1-8. 10.1393/ncc/i2022-22079-6.

[49] M. C. Morone, C. Berucci, P. Cipollone, C. De Donato, L. Di Fino, M. Iannilli, La Tessa, C. Manea, G. Masciantonio, R. Messi, and et al. (2019). A compact Time-Of-Flight detector for radiation measurements in a space habitat: LIDAL–ALTEA. Nucl. Instrum. Methods Phys. Res. A 936, 222-223. 10.1016/j.nima.2018.09.139.

[50] T. Berger (2008). Radiation dosimetry onboard the International Space Station ISS. Z. Med. Phys 18, 265–275. 10.1016/j.zemedi.2008.06.014.

[51] F.A. Cucinotta, E. Cacao, (2017). Non-Targeted Effects Models Predict Significantly Higher Mars Mission Cancer Risk than Targeted Effects Models. Sci Rep 7, 1832. 10.1038/s41598-017-02087-3.

[52] Guracho AN, et. Al., Space Radiation Induced Bystander Effect in Estimating the Carcinogenic Risk Due to Galactic Cosmic Rays (2023), in publication on the Journal of Mechanics in Medicine and Biology.