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Astroparticle Experiments to Improve the Radiation Health Risk Assessment for Humans in Space Missions

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Abstract

In the near future, 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 surface. One of the main showstoppers to be investigated for safe exploration and colonization is the biological effects of ionizing radiation that can compromise the health of astronauts/space workers. The Astroparticle experiments presently operating in space (e.g., AMS02, ACE-Explorer, ...) could play a principal role in this vital task. Such experiments are actual cosmic ray observatories and a source of information crucial to investigating the fundamental physics open problems (e.g., Dark Matter, Antimatter) and improving the knowledge of radiobiology effects in space. In this paper, a review of the past, present, and planned Astroparticle experiments operating would be presented and highlighted some of the possible contributions and improvements in the space radiobiology research field. Also, will be presented some examples of progress in understanding the biological effects of radiation in space using the pieces of information acquired for astronomy and Astroparticle science and where such information has been used to enhance the space radiation field characterization and, consequently, improve crucial radiobiological issues in space (e.g., dose-effect models). Finally, the use of the vast amounts of data taken from such experiments will open a new era of studies performed in different exposure scenarios that will allow a safe human space exploration outside of the Low Earth Orbit by addressing important radiation protection open questions, such as the dose relationship for cancer and non-cancer risk, the possible existence of dose threshold(s) for different biological systems and endpoints, and the possible role of radiation quality in triggering the biological response.

Keywords: Human Space Exploration, Space Radiobiology, Space Radiation, Cosmic rays, Astroparticle

Acronyms/Abbreviations

AMS - Alpha Magnetic Spectrometer
APE – Astro-Particle Experiment
BLEO – Beyond Low Earth Orbit
CP - Charged Particle
CR – Cosmic Ray
CRD – Cosmic Ray Detector
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
RBE Relative Biology Effectiveness
RICH – Ring Image Cherenkov Counter
SEP – Solar Energetic Particle
TOF – Time Of Flight
TRD – Transition Radiation Detector

1. Introduction

Cosmic rays (CR) approaching our planet interact with the Earth's magnetic field, and atmosphere and such interaction protect humans living on the Earth's surface. The magnetosphere rejects most of the particles (99%) while the rest lose most of their energy going through the atmosphere before reaching the Earth's surface [1]. In particular, the geo magnetosphere stops/deflects 99.9% of charged particles while the Earth's atmosphere is equivalent to a metal shielding 1 meter thick. Completely different is the situation in space where the CR interacting with the human body release 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 [2, 3]. In this context, all the different components of space radiation have been extensively studied and measured during the last decades by several astroparticle experiments operating in space, and the information contained in the data taken by such experiments can be used to improve the radiation health risk assessment for humans in space missions.

1.1 The Space Radiation Environment

The space radiation environment (Figure 1) is a complex mixture of radiation species dominated by highly penetrating charged particles from different sources. In this regard, three different types of particles are present: particles emitted by the Sun (SEP) due to the solar activities, particles trapped in Earth's magnetic field (i.e., Radiation Belt), and Galactic Cosmic Rays (GCRs) coming from outside the solar system.

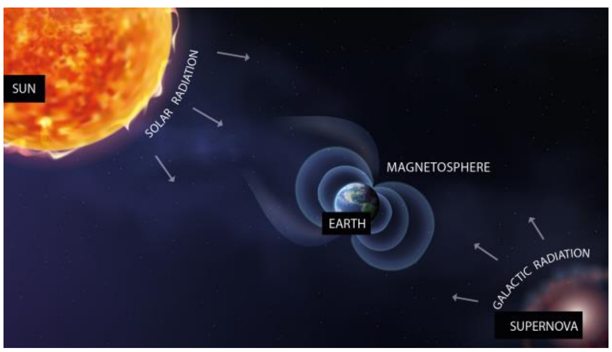

Fig. 1. The Space Radiation Environment is a complex mixture of radiation species coming from outside the solar system, generated by the sun and trapped in the Magnetosphere (credit IAEA)

The energy spectrum and abundances of radiation species are modulated by planetary magnetic fields and long-term solar activity and characterized by short-term solar particle events.

In addition, shielding on space stations or spacecraft modifies the incident spectrum and related exposure due to particles generated by the interaction (spallation) with such structures.

Such particles can penetrate several tens of centimetres of materials such as aluminium or tissue/water producing lower Z secondary particles through nuclear interactions. The secondary particles are characterized by lower linear energy transfer (LET), which confers a higher penetration range than the primary particles [1].

In ionizing radiation protection, several technical solutions are generally applied to reduce worker exposure: increasing the distance from the radiation source, reducing exposure time, and implementing ad hoc shielding [4].

Distance is not helpful in space, being GCRs substantially isotropically distributed. Time in space is accurately reduced as low as possible according to exploration and colonization plans or decreasing flight time. Therefore, shielding materials cannot fully absorb all space radiations due to a very high-energy component of the GCR spectrum. In addition, shielding needs to be optimized considering its efficacy and cost to reduce the unavoidable exposures to the minimum acceptable level. More in detail, passive or active shielding may significantly reduce radiation exposure, considering the time variable contribution of GCR. Nevertheless, astronauts' dose- and equivalent dose-rates are around 0.3–0.6 mGy/day, corresponding to 1–1.8 mSv/day, respectively [5].

1.2 CR charged particle interaction with cells and tissues

Charged particles penetrating living matter have physical and radiobiological properties, including giving rise to a sharp maximum in ionization near the end of the penetration range (Bragg peak). This implies that their effects indicated using the Relative Biology Effectiveness (RBE) quantities are enhanced compared with reference radiation (usually X-rays or γ-rays). In other words, for a given experimental observation, absorbed doses lower than that released from the reference radiation will produce an equal level of biological effect. Indeed, the complex RBE depends not only on the dose levels but also on other factors, including the radiation quality (such as the dose rate, the LET, ...) and the biological characteristics (such as species, tissues, and the endpoint under consideration, etc.) In addition, the damage to human organs and tissues depends on the radiosensitivity of cells and the functional architecture of organs and tissues.

The biophysical models play a crucial role in understanding the mechanism of the interaction between radiation and organism. Many radiobiological models have been proposed to explain the survival fraction and estimate the RBE in clinical applications, while estimating the radiation quality factor is mandatory for improving the space radiation risk assessment in interplanetary missions [6].

1.3 Health hazard of astronauts

Both acute and late effects in the space radiation environment are the most frequent and important life-threatening adverse events associated with ionizing radiation exposure. Acute radiation syndrome (i.e., short-term effects) is caused by intense and short exposure to SPEs in case crews cannot reach areas with adequate shielding.

Late radiation morbidity (e.g., carcinogenesis or central nervous system or cardiovascular induced damage) is associated with chronic exposure to GCR, which is substantially different both qualitatively and quantitatively from the Earth's radiation natural background depending on various above-described factors (i.e., long-term or short-term solar activity and magnetic field features).

In addition, ionizing radiation can also induce the potential detrimental health effects associated with secondary cancers as side effects. Cellular radiosensitivity can provide important insights into identifying the different responses of normal tissues.

Thus, the subject radiosensitivity can be used to screen individuals (like astronauts) to elect suitable candidates for long-term work in a space radiation environment.

In exploratory space missions, the radiation health hazard assessment requires evaluating the dose effects relationships/models to quantify the expected damage in the forecast astronaut's exposition scenario.

Dose-effect relationships/models have been proposed to explain and predict clinical and subclinical effects registered during spatial missions mainly on human subjects and confirmed in "in vitro"/"in vivo" studies. In addition, the possibility to use clinical diagnostic or radiotherapeutic devices is recognized as an essential tool for improving the radiobiological model understanding of space exposure due to the similarity of dosage and available type of particles. Moreover, the complete understanding of non-targeted effects induced by charged particles becomes mandatory[7] due to the interaction of secondary particles with several healthy human tissues. In addition, dose equivalents must be calculated considering the QFs and RBE of high-LET particle distributions, which should be measured in the space radiation environment[8]. Another ongoing approach considers the possibility of hibernating astronauts for a guarantee as additional protection against space radiation effects, given the radioprotective action of hypothermia[9].

An accurate estimation of the health hazard of astronauts due to exposure to ionizing radiation is mandatory to plan and implement safe exploratory space missions. In addition, dose-effect models are mandatory to pose more appropriate counter measurements such as local shielding and improve the routine dosimetry future development is seen in bio-dosimetry as one of the most exciting developing directions [10].

2. Astroparticle Experiments Operating in Space

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[11].

2.1 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.

Fig. 2. The AMS02 was installed on the ISS on 19-May-2011 (photo 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 [12-18]. 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 [19].

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 [20].

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 [21].

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 [22].

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 [23].

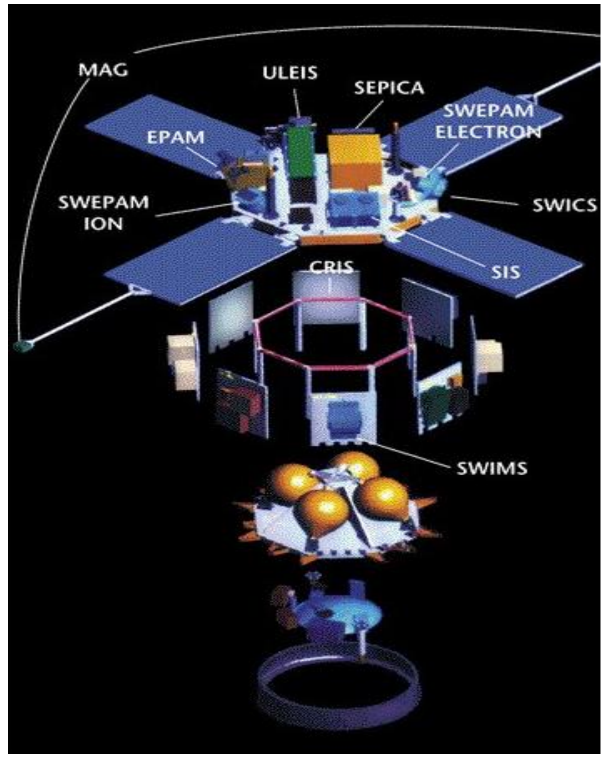

Fig. 3. Advanced Composition Explorer (ACE), satellite architecture and on-board instruments (credit NASA)

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 [24].

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. [25] 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 Light-nuclei 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) [26].

3 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 [27]:

- **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.

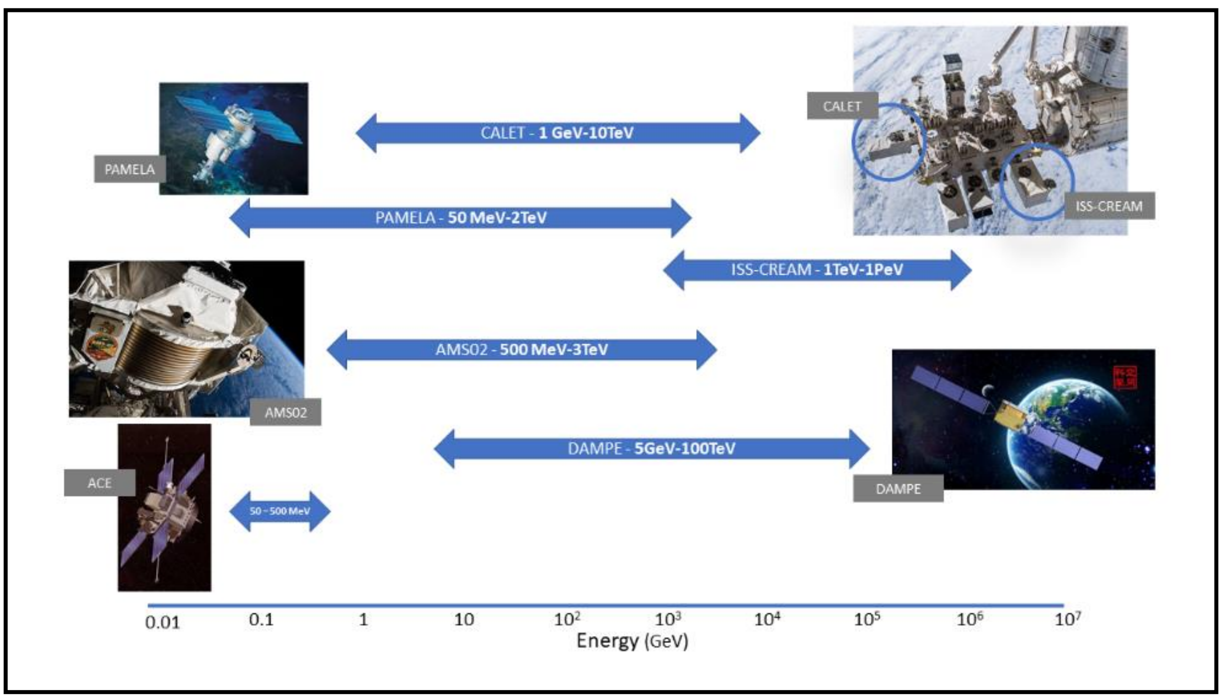

Fig. 3. Measurement's energy range of some Cosmic Ray Detectors operating in space

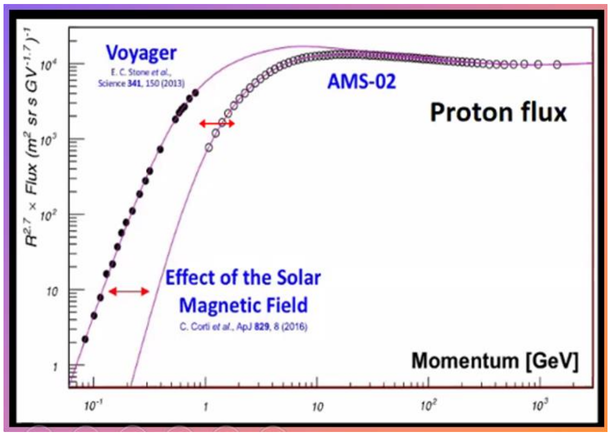

Fig. 5 The effects of the Solar Magnetic Field action are evident in the CRs protons flux in the low energy spectrum. (Figure Courtesy of AMS Collaboration)

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.

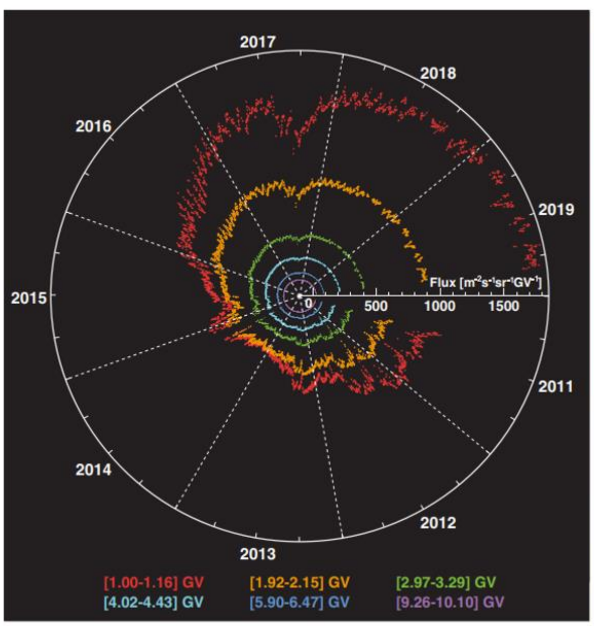

Fig. 6 The daily AMS proton fluxes for six typical rigidity from 1.00 to 10.10 GV measured from May 20, 2011, to October 29, 2019, which includes a significant portion of solar cycle 24 (from December 2008 to December 2019) (Figure Courtesy of AMS Collaboration in [16])

3.1 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 [28], 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 [29]. 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 [28-31]. Such analysis was also confirmed recently by C. Corti et al. [32], 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. 7).

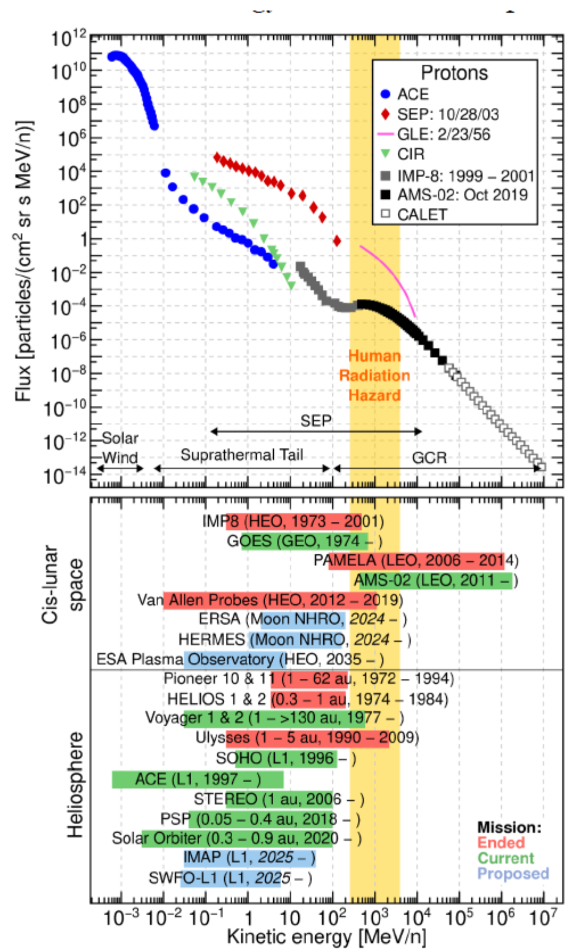

Fig. 7. Flux vs Energy ranges of protons as seen by different CRDs and probes operating in the last decades or planned soon. The yellow band range is the most relevant for human radiation exposure (Figure courtesy of C. Corti et al. in [31])

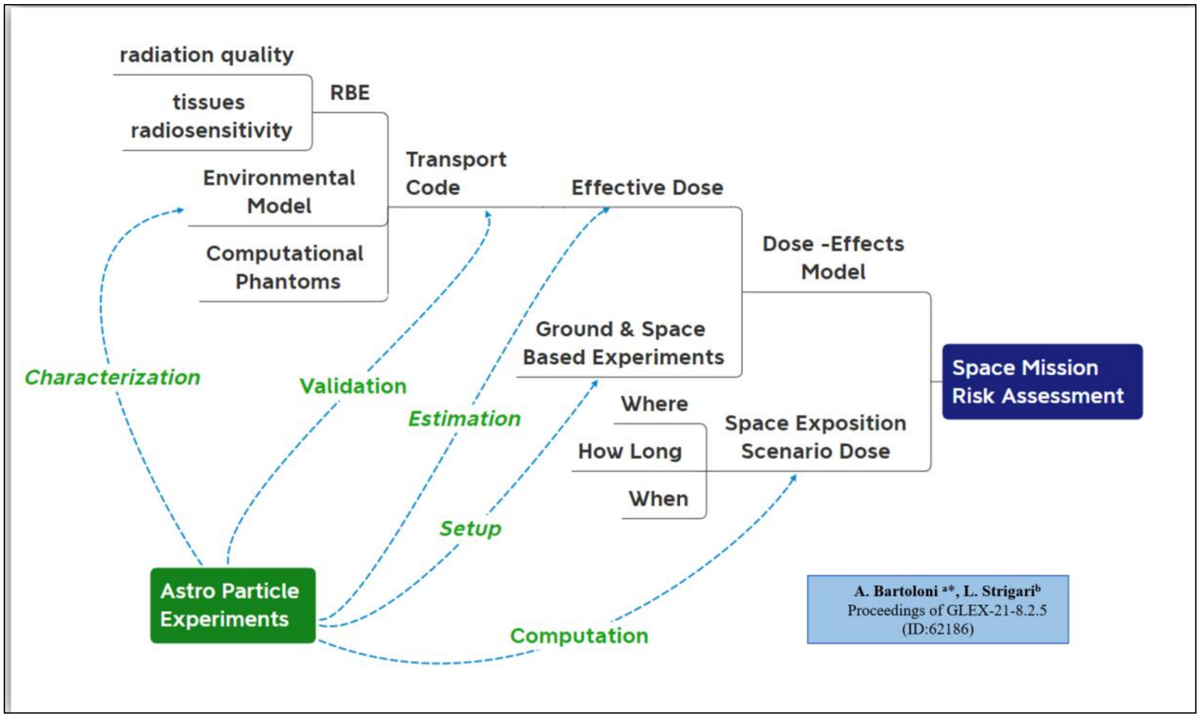

Fig. 8. Human Health Risk Assessment in exploratory space missions: possible improvement using astroparticle experiments operating in space [30]

4. 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 [33].

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 8 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.

4.1 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 [34] a possible improvement using the AMS02 and Pamela CRDs data of the Badhwar-O'Neill GCR model.

4.2 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 [35]. 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 [36,37] and outside the ISS and on satellites in different orbits.

4.3 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.

4.4 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).

4.5 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.

4.6 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* [38] 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

5. Conclusions

In the coming years, there will be a great interest for space human mission non only to explore and for a permanent presence of humans outside the geo-magnetosphere. 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 considerable amount of data acquired for more than a decade by the Astroparticle experiments operating in space. Such data constrains 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. In particular, improvements in the efficacy of space radiobiology dose-effects models is possible, while many other topics till not Completely investigated (non-targeted effects, individual radiosensitivity, …) could be further investigated. The characterization of the space radiation environment is essential for evaluating space travel exposure, improving space missions' safety, and improving the risk assessment model.

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