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Editorial

Advances in Space Astroparticle Physics: Frontier Technologies for Particle Measurements in Space

Matteo Duranti [1,*] and Valerio Vagelli [1,2,*]

1 Istituto Nazionale Fisica Nucleare (INFN)—Sezione di Perugia, IT-06123 Perugia, Italy
2 Agenzia Spaziale Italiana (ASI), IT-00133 Roma, Italy
* Correspondence: matteo.duranti@infn.it (M.D.); valerio.vagelli@asi.it (V.V.)

In the last decades, breakthrough advances in understanding the mechanisms of the Universe and fundamental physics have been achieved through the exploitation of data on cosmic rays and high-energy radiation gathered via orbiting experiments, in a synergic and complementary international effort that combines space-based instrument data with ground-based space observatories, accelerator, and collider experiments.

Cosmic ray space-borne detectors, such as PAMELA [1], AMS-02 [2], DAMPE [3], and CALET [4], have been providing high-precision data on cosmic ray spectra and composition, uncovering unexpected features that could not be explained by the consolidated models of the origin, acceleration, and propagation mechanisms of cosmic rays. These achievements have been indicating the need to revise the pillars of the established theories. In reaching this results, high-precision experimental measurements from the most recent generation of space-borne particle detectors have been a game changer.

Today, advancing our understanding of cosmic ray physics mainly requires to concurrently investigate several observational frontiers.

Measurements of all cosmic ray species with energies larger than TeV to shed light on the origin and composition of the "knee" of cosmic ray fluxes is the main objective of the planned HERD experiment [5], which for the first time will operate in space an innovative isotropic 3D-imaging calorimeter to maximize the faint statistics of supra-TeV cosmic rays. Extending the precision and range of cosmic-ray nuclear and isotopic composition measurements is also one largely pursued scientific target, currently tackled by the HELIX [6] and TIGER [7] ballon-borne instruments, that requires relevant improvements in the techniques for high-dynamic range charge measurements and high-resolution velocity measurements, and that will be possibly implemented in future space-borne extensions of the previous missions [8].

Finally, one of the most ambitious objectives of space-borne particle physics is to precisely measure the faint components of antimatter in cosmic rays, possibly providing striking evidence of heavy anti-nuclei in cosmic radiation and revealing signatures of dark matter annihilation, thus helping to narrow down the origin and properties of dark matter particles. To take over the legacy of the PAMELA and AMS-02 detectors, the scientific community is envisioning large-area, high-precision magnetic spectrometers to be operated in deep space, such as the proposed AMS-100 [9] or ALADInO [10] instruments. The technological roadmap for operating such instrumentation in space combines what already being developed for high energy and high precision charge and velocity measurements with the need to develop high-temperature superconducting magnets for space applications. Besides this approach based on magnetic spectrometric measurements of particles in space, independent techniques to identify nuclear antimatter in space has been pioneered by the GAPS instrument [11], to be soon flown on a balloon, and further investigated by other proposed instruments.

Improving the understanding of the physical properties of low-energy and highly penetrating cosmic radiation is also a major requirement for enhancing radiation risk models and developing countermeasures to minimize the risks posed by radiation exposure

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to humans and instrumentation in space, ultimately enabling safe space colonization [12]. Most recent advances leverage on readapting particle detector technologies and approaches from the heritage of general-purpose high-energy space detectors to MeV-GeV cosmic-ray measurements (such as, e.g., the HEPD detectors onboard the CSES satellites [13]) and to instrumentation for dosimetric energy releases onboard and outside spacecrafts (such as the ALTEA-LIDAL detector onboard the ISS [14]). Novel scientific results are achieved by taking advantage of technologies developed for complementary applications and optimized for applications in space, as demonstrated by the successful experience of the Timepix hybrid pixel detectors [15]. Fundamental new information can also be extrapolated by monitoring long-term and short-term disturbances in cosmic ray fluxes due to their interaction with the dynamic heliospheric environment, with the prospects of improving the predictive models of cosmic-ray flux intensities for space weather forecasting and developing prompt alarm systems in case of abrupt increases in flux exposures.

Our understanding of the high-energy sky has also been completely revolutionized by the successful operation of gamma-ray observatories, such as Fermi [16] and AGILE [17], whose data have been providing accurate information on the most energetic and exotic phenomena in the Universe, from very powerful distant sources such as blazars to the local Galaxy. The potential of gamma-ray observatories has been additionally enriched when, in 2017 and 2018, the very-high-energy emission from extreme sources has been concurrently observed from space in correlation with the ground-based detection of gravitational emissions [18] and neutrino emissions, starting the era of multi-messenger astronomy. Very recently, the IXPE telescope [19] finally demonstrated the feasibility of precision X-ray polarimetry astrophysics measurements, de facto opening a new window for investigating most classes of high-energy events in the Universe.

Ultra-high-energy cosmic rays and neutrinos may provide information about the most energetic phenomena in the Universe, and several technological developments are ongoing to enable their observation from space for the first time, where a large-field telescope, such as, e.g., the proposed POEMMA space observatory [20], could complement and integrate the measurements made by ground-based observatories.

In the field of cosmic ray and high-energy detection in space, the reach of current observations is, in general, largely constrained by the limitations in technology and approaches. Historically, state-of-the-art level ground-based particle detectors established since several years have been adapted and optimized for space operations. Building on the experience gained from operating the current generation of instrumentation, conceiving follow-up opportunities has become largely demanded by the scientific community. In view of this, the scientific community is pushing research efforts and resources in developing novel approaches to step forward beyond the current paradigm of radiation measurement in space, possibly re-inventing the experimental investigation strategies. New frontiers in astroparticle physics can be tackled only with breakthrough advances in technological solutions and observational approaches. The development of novel technologies and techniques for the measurement of particles and high-energy radiation in space shares common heritage and approaches in detection techniques and data handling, despite being probes that historically differ in terms of observational strategies and in the scientific information they provide. The success of particle and radiation detectors operated in space is also rooted in the common, strong heritage of particle detectors first developed for ground-based accelerator or collider experiments, subsequently specialized and optimized for the harsh space environment, although this paradigm could gradually move towards an approach in which space applications will drive novel technological solutions.

Most importantly, current opportunities in the new space economy era for next-generation astroparticle and high-energy radiation observatories have significantly diversified from the previous decade. Access to small- and nano-sat platforms has become increasingly diffused, while the prospect of accessing novel platforms, such as new orbiting laboratories, planetary gateways, or bases, is driving the community to rethink the standard paradigm upon which current operating space instrumentation has been developed.

Nonetheless, the stringent requirements on mass, volume, power budget, and operation safety strongly define the constraints on mission instrumentation.

The international conference "Advances in Space AstroParticle Physics: Frontier technologies for particle detection in space (ASAPP 2023)" has aimed in reviewing the progresses in design, development, integration and test of instrumentation for measurement of particles and high-energy radiation in Space, gathering the scientific community to pave the road to future astroparticle missions for investigations of fundamental physics and the Cosmos, applications for monitoring of the space radiation environment, and investigations of the impact of low energy ionizing particles on instrumentation, Space Weather, and Earth sciences. The contributions included in this Special Issue provide a snapshot of many arguments discussed during the conference. The collection of papers covers and reports on the most recent technological developments for high-energy and low-energy cosmic rays as well as high-energy X and γ radiation, including proposals, developments, and tests of novel sensors or measurement approaches, front-end electronics and data acquisition systems, and space mission payloads and instruments. This overview largely demonstrates the advances achieved in recent years by a vivid community that targets ambitious scientific objectives to breach the frontiers of current knowledge on the origin and mechanisms of the Universe and to provide cutting-edge solutions for precise monitoring and diagnostic of the radiation environment in space. The pioneering technological solutions that are being investigated, developed, and consolidated today through collaborative international research efforts will form the foundations for next-generation space instruments, paving the way for future groundbreaking discoveries.

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