



Publishable Summary for 21GRD02 BIOSPHERE

Metrology for Earth Biosphere: Cosmic rays, ultraviolet radiation and fragility of ozone shield

Overview

One of the most significant – yet unexplored – ecological challenges facing EU member states and beyond is the impact on human and environmental health of the increasing atmospheric ionisation caused by extra-terrestrial radiation (cosmic rays and solar UV radiation) boosted by anthropogenic emissions. This project aims to develop the necessary tools, methodologies and measurement infrastructure needed to evaluate the mutual impact of cosmic rays and biologically active UV radiation on the Earth's biosphere, and to support EU policy makers with scientific assessments and information that have the potential to substantially improve policies on climate, health and anthropogenic emission activities.

Need

Cosmic rays, along with UV radiation and the Earth's natural radioactivity, are one of the main sources of atmospheric ionisation, contributing to the electrification of the lower atmosphere and, thus, to the climate system in general. Attempts to quantify the changes this radiation causes in climate processes (e.g., cloud formation and thunderstorms), however, are debated and remain poorly understood. Over millennia, living organisms have been continuously exposed to cosmic rays and solar UV radiation. Biological actions of many kinds have evolved to deal with such exposures and a balance between beneficial and harmful effects of these radiation fields has been established. In recent years, however, this balance has been disturbed due to anthropogenic (man-made) emissions and environmental pollution creating an urgent need to study how these combined radiation fields are shaping our natural habitat, affecting the evolution of the biosphere, and impacting on our health. To achieve this, a combination of observations is needed using modern satellite technologies and ground-based *in situ* and remote sensing in environmental biology, chemistry and also radiation protection, to start the evaluation of cosmic and solar radiation effects on the biosphere.

Ionisation of the biosphere by cosmic radiation is known to correlate significantly with disease prevalence in humans, infectious disease mortality, and overall mortality. This is in addition to the harmful effects caused by UV radiation alone, which increases the incidence of skin cancer by about 2 % for every one percent reduction in ozone. Genomic, epigenetic, transcriptomic, and metabolomic changes potentially responsible for cellular radio-sensitivity and possible long-term dysfunction remain, however, largely unknown. The lack of understanding of these effects is exacerbated further by ozone depletion-induced overexposure to UV radiation and its implications for cellular defence mechanisms. Therefore, monitoring, modelling, and correlating cosmic rays, terrestrial solar radiation, and ozone thickness is critical not only to understand the radiological sensitivity of cells, but also to make informed decisions regarding the global challenges facing our society.

Traceable metrological data on cosmic ray fluxes, solar UV spectra, and the total ozone column are key to assessing the role of cosmic rays as climate drivers but quantification of correlations between them is required to inform new approaches to chemistry-climate models that will help clarify current ambiguities in the scientific community related to climate variability. Cosmic rays entering the top of the Earth's atmosphere, or primary cosmic rays (PCR), interact with atmospheric constituents to produce secondary cosmic rays (SCR), which are measured by ground-based instruments. The generation of an improved understanding of the role of PCR and SCR in ozone depletion, would provide a better assessment of biological implications due to natural UV overexposure. Quantification of ionisation and the production rates of charged molecular fragments and other reactive species is needed to extend present-day models that are currently limited to ionisation and the nonspecific energy loss values required to produce an ion pair. The interaction cross sections for these

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European Partnership



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processes need to be examined and measured experimentally to improve the reliability of the ionisation data of natural atmospheric and anthropogenic gases relevant to ozone layer chemistry. Implementation of these cross sections into simulation codes for space radiation propagating through the atmosphere leads to refined radical, ion and slow electron production rates, which are needed to enable a more accurate estimation of the effectiveness of the cosmic ray model compared to the photochemical model in depleting the ozone layer. This is important for predicting future trends in ozone hole dynamics and for assessing the role of new chemicals in the ozone depletion.

Therefore, it is necessary to identify and quantify the relationship between cosmic radiation, ozone depletion and anthropogenic emission with the help of simultaneous modelling and traceable measurements of (i) ground-level muon and neutron fluxes, (ii) terrestrial solar UV-irradiance, and (iii) total ozone column (Objective 2). To achieve this, this project will characterise and calibrate novel SCR instrumentation – including an upgraded LIDAR system. Since generation and decay of SCR depend on air density, knowledge of atmospheric profile parameters such as temperature, density, and aerosols are needed to establish an accurate relationship between SCR and PCR fluxes (Objective 1). For the first time, this project will determine fundamental data on the interaction of low-energy cosmic-ray induced electrons with atmospheric gases of both natural and anthropogenic origin (Objective 3). This includes collision cross sections for the molecular processes such as dissociative electron attachment, molecular fragmentation and ionisation needed for the evaluation of mitigation strategies for the effects of anthropogenic emissions for the greater protection of human, animal and ecological health, and the development of policies that support these strategies. The impact of combined cosmic and UV irradiation on human health will be assessed by investigating structural and functional damages inflicted by such mixed radiation fields in human normal cells such as primary skin fibroblasts and keratinocytes, blood monocytes and lymphocytes and endothelial cells (Objective 4). Genomic, epigenetic, and transcriptomic changes that might be responsible for cell radiosensitivity and possible long-term dysfunction will be assessed, in this project, in connection with the fate of irradiated cells in terms of viability, morphology and functions.

Objectives

The overall aim of this project is to develop metrological methodologies to establish the correlations between primary and secondary cosmic rays (PCR and SCR), solar UV radiation and ozone layer thickness, and to assess their mutual impact on the Earth's biosphere.

The specific objectives of this project are:

1. To determine the dependence of SCR on PCR and atmospheric parameters (e.g., temperature, density, aerosol concentration), based on field measurements made using well characterised and traceable modified mobile SCR muon and neutron detectors, a novel semiconductor detector and adapted and/or existing LIDAR systems for vertical atmospheric profiling.
2. To identify and quantify the correlation between PCR and solar UV radiation on the ground including their dependence on anthropogenic gas emissions using simulations and traceable measurements of (i) ground-level muon and neutron fluxes, (ii) terrestrial solar UV-irradiance, and (iii) total ozone column.
3. To determine the molecular processes affecting ozone depletion and atmospheric dynamics, and to provide a complete database of collision cross-sections for natural atmospheric and anthropogenic gases. This is to be based on simulations and experimental validations that quantify molecular ionisation (absolute ionisation, excitation, dissociation cross section energies and projectile energy loss) and production rates of charged molecular fragments of both natural and anthropogenic atmospheric gases including CFCs and CH_2Cl_2 from interactions with low and medium energy (<10 eV - 2000 eV) electrons.
4. To assess the potential effect on human health from exposure at environmental levels to combined SCR and UV radiation fields using healthy human cell lines. This is to be based on simulating environmental level exposures under experimental conditions to establish correlations between radiation type and flux, and changes to cellular parameters (cell death, DNA damage and genomic instability, adhesion, and proliferation). In addition, to determine the expression profile of stress genes using established radiation effect models and systems biology approaches.

5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs and DIs, atmospheric monitoring networks), standards developing organisations (e.g. IEC, ISO, CENELEC, CCRI (I) and EURAMET Technical Committee for Ionising Radiation (TC-IR)) and end users (e.g., health and environment regulatory bodies, research institutions focused on environment, climate, medicine and biology, and radiological protection, and instrument manufacturers).

Progress beyond the state of the art and results

Cosmic ray-induced low energy electrons and solar UV radiation are major drivers for atmospheric chemistry. For quantitative description of atmospheric ionisation, interactions with anthropogenic gases, collision and chemical processes involving ozone, climate-chemistry models require reliable cross-sections for the interactions of gases in the stratosphere with low energy electrons as well as for the production of reactive species by those interactions. This project will determine for the first time the medium to low-energy electrons cross sections for ionisation and fragmentation-ion production of atmospheric constituents such as N₂, O₂, NO, NO₂, selected chlorofluorocarbons (CFCs), halogenated molecules (such as HCl, HF, HBr, SF₆), as well as aromatic and nitrogenated molecules (such as pyridines whose cations facilitate aerosol formation).

Determining the dependence of SCR on PCR and atmospheric parameters

The SCR flux measured at ground level is affected by the survival probability of the incoming parent PCR particles, the various atmospheric conditions such as air density and temperature, and the particle absorption rate down this path. Corrections which exploit the exponential dependence of pressure or temperature on altitude are currently used for these effects, but these do not consider the inhomogeneities of air density that affect the accuracy of the recorded SCR fluxes. This project will develop, for the first time, metrological methods to quantify the correlation between PCR and SCR using atmospheric profile parameters measured by LIDAR(s). These will include a novel mobile scintillator-based muon detector capable of measuring muon flux reaching the ground level with an energy distribution from a few hundred MeV to a few hundred GeV, a novel boron scintillator-based mobile neutron detector which can measure neutrons in a wide range of energies (from thermal up to several tens of MeV), and a spectral-tracking particle telescope assembled as stack array from 2 semiconductor pixel detectors (Timepix3) in miniaturised and portable architecture for high-angular resolution wide field-of-view mapping of SCR with resolving power of mixed-field components (muon, electron, proton, ion, gamma, X ray, neutron).

The function and light collection efficiency of the mobile muon detector has been characterized with ⁹⁰Sr beta source. The performance of the detector with ambient radiation and with photon gamma reference fields (⁶⁰Co and ¹³⁷Cs) has been commissioned. Data processing and analysis algorithm to obtain muon fluxes have been developed. The mobile neutron detector has been characterized with photon and neutron reference fields (¹³⁷Cs at various angles and H*(10) rates, ⁶⁰Co, X-rays narrow-series qualities, AmBe, ²⁵²Cf, thermal neutrons). The detection efficiencies were determined and the detector functionality was demonstrated. A customised particle tracker that consists of 2 synchronised Timepix3 detectors has been developed and calibrated. The detector and its spectral and tracking properties were tested in 31 MeV proton beam. A pulsed LIDAR system to provide the vertical profiles of aerosol concentration, as well as the atmospheric temperature and density in aerosol-free regions from the lower free troposphere up to 15-18 km height has been commissioned. Data processing and analysis algorithms to provide atmospheric profiling parameters has been developed.

The mobile muon and neutron detectors and a pulsed LIDAR system are being operated in the first measurement campaign (1 July to 31 August, 2023) at the NCSR-DEM station (near NTUA) in Athens, Greece.

Identifying and quantifying the relationship between cosmic radiation, UV radiation and anthropogenic emission

Side-by-side measurement of the terrestrial solar UV spectrum, total atmospheric ozone, and SCR flux rate has never been attempted so far due to the lack of the proper measurement framework. This project will provide such measurements for the first time and will go beyond the state of the art not only by measuring these parameters simultaneously, but also by supporting the ground-based measurements with satellite measurements such as satellite observations of energetic electron, proton and Helium-ion fluxes. Simultaneous measurement of SCR fluxes, UV radiation spectrum and ozone column, enabling a quantification of the relationship between them, will be carried out at four European sites (Greece, Belgium, Czechia, and Germany). This will provide the necessary infrastructure for an accurate measurement of atmospheric profiling

parameters and have different anthropogenic emission inventories to integrate the influence of anthropogenic emissions on ozone dynamics.

The first measurement campaign is currently running at the National Center for Scientific Research (NCSR)-Demokritos (DEM) station in Athens. The campaign started on June 1, 2023, and will run through August 31, 2023, with 10 instruments being used simultaneously: UVB pyranometer and GUV-511 multichannel filters radiometer, UV spectroradiometer BTS-Solar, ^3He neutron detector, portable neutron detector system based on liquid scintillators, mobile muon detector based on plastic scintillators, CIMEL Sun photometer, EOLE Multiwavelength Raman LIDAR, DEPOLE Depolarization LIDAR and temperature/aerosol/density LIDAR.

Molecular processes affecting ozone depletion and atmospheric dynamics

This project will produce for the first time a complete database of collision cross sections for natural atmospheric and anthropogenic gases relevant for ozone layer chemistry. The database will be in an open format and will also include the quantification of molecular ionisation and production rates of charged molecular fragments and other reactive species going beyond present-day models which restrict to ionisation and a nonspecific energy loss value per produced ion pair.

Fragmentation cross sections of several chlorofluorocarbons (CFCs) such as CHClF_2 , CClF_3 , CH_2Cl_2 , CF_4 , CH_2F_2 and CH_3Cl have been measured with a reflectron time-of-flight (rTOF). Differential elastic scattering cross sections (DCS) of electrons on ethanol were experimentally determined for electron energies between 30 and 800 eV for scattering angles θ of 30° to 150° in steps of 15° . The experimental data were compared to theoretical values calculated using the modified independent atomic model (MIAM) and the independent-atom method with screening-corrected additivity rule (IAM-SCAR). Absolute electron scattering cross sections on N_2O were measured and the measurements for the remaining oxides of nitrogen (NO_2 and NO) are in preparation.

Simulations using AtRIS Geant 4 code of the effects of the cosmic rays (primary and secondary), as well as solar energetic particle events, on the terrestrial atmosphere are being developed. The composition of the atmosphere, the geometry of the planet and the magnetic field model have been studied to determine their influence on the atmospheric dynamics. Cases of low and high solar activity levels, and Solar Energetic Particle events as observed by PROBA-V/EPT and GOES have been investigated to determine the long term and short-term variations of atmospheric ionization. The effects of solar protons on the flux variations in the terrestrial radiation belts observed from 2013 to mid-2023 have been investigated and published.

Effects of combined SCR and UV radiation fields on biological systems

Understanding the mutual impact of cosmic and ultraviolet radiation on human health is important not only for humans, but for all mammalian and plant species and the entire living ecosystem. This project will go beyond the state of the art by creating, for the first time, a database of results from irradiated and non-irradiated biological samples such as lung and primary skin fibroblasts, cerebral microvascular endothelial cells from the brain, and healthy blood monocytes. Through advanced bioinformatics and systems biology methodologies, a complex network of molecular changes related to cell death, DNA damage and genomic instability, adhesion and proliferation, and expression profile of stress genes will be established.

Experiments to assess the biological impact of a combined exposure of human normal proliferating CRL 9855 monocytes and primary lymphocytes (non-malignant) to SCR (energetic protons) and UVB radiation, in terms of cellular viability and proliferation, DNA damage and stress gene expression as measure of the cellular damages have been performed at the PTB Ion Accelerator Facility. Human CRL 9855 monocytes were stored in liquid nitrogen. Lymphocytes were isolated from blood of healthy donors. Monocytes were unfrozen at PTB and were cultivated for 9 days to stabilize the cell culture and multiply the cells through passages at 2-3 days by adding fresh culture medium and periodic adjustment of cell concentration at 500000 cells/mL. CRL 9855 prepared for experimentation were then exposed to energetic protons (0.25 Gy and 0.5 Gy) followed within 15-20 min by exposure to UVB radiation in the range of fluences between 100 J/m² and 800 J/m². Unexposed cells (kept in the lab or in the irradiation room) and cells exposed only to protons or to UVB were considered as controls. In total, 9 exposure experiments were performed, 6 with 0.25 Gy protons and 3 with 0.5 Gy protons, combined with various UVB fluences, as described above. Part of the exposed cells and the corresponding controls were processed for assessing complex DNA damage, using the NTUA established gammaH2AX immunofluorescence methodology at post-irradiation times: T0 (0' hrs), and part were further cultivated for 24 h at 37 °C to follow the response of cells to the specific stress. Cellular viability and proliferation were measured using the MTS reduction assay, while the rest of the cells were processed for evaluating the level of DNA damage and stress-response gene expression at 24 h. Processed samples were transferred to

NTUA and IVB for final evaluation of DNA damage and stress gene expression. Preliminary results show a severe detrimental biological effect for UV radiations and synergy between protons and UV for the induction of cell death, decreased viability and chromosomal breaks.

Outcomes and impact

The advances of BIOSPHERE were presented at (1) the EURAMET Annual Meeting, Technical Committee for Ionising Radiation (TC-IR) in February 2023, (2) the 48th Annual Meeting on Radiation Protection in Gyula, Hungary, April 2023, (3) 25th Nuclear Medical Defense Conference, ConRad 2023-Global Conference on Radiation Topics-Preparedness, Response, Protection and Research held in May 2023 in Munich, Germany, and (4) the European Radiation Dosimetry Group (EURADOS) Annual Meeting, WG3 (Environmental dosimetry) and WG11 (High energy radiation fields), held in June 2023, Porto, Portugal.

An invited talk on solar wind acceleration was given at the 16th International Solar Wind Conference in Pacific Grove, California, in June 2023, organized by the Space Sciences Laboratory at the University of California Berkeley. The progress made about space radiation variations during Solar Energetic Particle events and geomagnetic storms was presented at the 11th International Conference on Radiation, Natural Sciences, Medicine, Engineering, Technology and Ecology was held at Herceg Novi, Montenegro, June 2023. Selective detection, spectrometry and particle tracking of protons, electrons, and muons with MiniPIX telescope were presented in Oslo (Norway), June 2023. An invited talk about the velocity distribution of solar particles was presented at the International Conference on Statistical Physics 2023 held in July 2023 in Chania, Greece

The objectives of the BIOSPHERE, including the operational capacity, needs and the impact, were presented at the Metrology for Climate Action 2022 that was organized by BIPM, WMO, and EURAMET and was held as an online workshop on 26-30 September 2022 (<https://www.bipmwmo22.org/>). During online sessions for recommendations on key technical challenge areas for metrology over the next decade, recommendations were given to WMO and BIPM workshop panel-chairs to investigate the need for and correct communities to support research into identifying and quantifying the relationship between cosmic radiation and ozone depletion and the impact this has on health and ecosystems. These recommendations were included in the workshop report that has been published on June 20, 2023 and is available on the BIPM website (<https://www.bipm.org/documents/20126/27085544/RapportBIPM-2023-03.pdf/57b00234-2bd0-09e1-8d4f-4aaed2ae45fd?version=2.4&t=1687244959519&download=true>).

Outcomes for industrial and other user communities

The project's data on the combined SCR and UV irradiation of human primary cell lines (such as primary skin fibroblasts, blood monocytes, brain cerebral microvascular endothelial cells) will be provided to enable key information on a plethora of biological effects such as DNA damage, genome instability, cell death, oxidative stress, subtle structural changes and transcriptomic changes. This information is crucial for assessing the impact of such radiation fields on human health. Therefore, European health groups and organisations such as ECCO (European Cancer Organisation), EORTC (European Organisation for Research and Treatment of Cancer), ESMO (European Society for Medical Oncology), and more globally World Health Organisation (WHO) will benefit from this project.

The cross-section data produced in this project will support worldwide monitoring programmes such as the Global Atmosphere Watch (GAW) of the World Meteorological Organisation (WMO) and the International Ozone commission (IO3C) of the International Association of Meteorology and Atmospheric Sciences (IAMAS). These data will also be a valuable input for the chemistry-climate models (CCM) such as, for example, SOCOL (SOlar Climate Ozone Links), MEZON (Model for the Evaluation of Ozone Trends), and CRAC:CRIL designed to study the impact of different external factors such as galactic cosmic rays (GCR) and solar proton events (SPE) on the Earth climate system and the ozone layer.

Outcomes for the metrology and scientific communities

The new metrological method for determining the dependence of the SCR flux to the ground on PCR and atmospheric profile parameters will greatly improve the prediction accuracy of the SCR rate at ground stations as a function of pressure and temperature, which is particularly needed during intercomparisons of environmental monitors. This would also lead to better quantification of ground level enhancements (GLEs) and subsequent radiation dose assessments. The participants will also provide input to BIPM Consultative Committee for Photometry and Radiometry on matters related to photometry and ozone dynamics. The metrology infrastructure and methods developed in this project will help estimate the on-ground magnitude of

cosmic events such as Solar Proton Events (SPE) and Gamma Ray Bursts (GRB) and will provide information for designing biomedical studies for assessing the impact of radiation exposure on human health, in relation to radiation dose and dose rates. In addition, quantifying the dependence of SCR on atmospheric profile parameters such as temperature would enable improvements to the tracking of short-term atmosphere dynamics such as Sudden Stratospheric Warmings and geoscience applications such as characterising the density structure of volcanoes. This would be of interest to organisations such as the European Geosciences Union (EGU) and the European Space Weather Community.

Traceable metrological data on cosmic ray fluxes, solar UV spectra, and the total ozone column generated by this project are key to assessing the role of cosmic rays as climate drivers. Quantifying the correlations between these three observables will contribute to new approaches to chemistry-climate models that will help clarify the ambiguities in the scientific community.

The new database of collision cross sections for natural atmospheric and anthropogenic gases will enable modellers, developers and end users to assess the role of low-energy cosmic electrons on the ozone depletion and atmospheric dynamics. The project's new database with results of irradiated and non-irradiated biological samples will enable modellers, developers and end users to assess the effects of combined SCR and UV radiation fields on human health.

Outcomes for relevant standards

The project will provide guidance for stakeholders and input to international standardisation bodies (ISO, IEC, CENELEC), for both ionising and non-ionising radiation protection via input to the following committees: ISO TC 85/SC 2/WG 2 (Radiological Protection, Reference radiation fields), IEC/TC45 (Nuclear Instrumentation, SC45B Radiation protection instruments, WG9 Detectors and systems), CENELEC/TC 45B (Radiation Protection Instrumentation). Thus, the project will support the harmonisation of procedures and methods for the measurement of cosmic rays and solar UV radiation in the environment and hence their inclusion into European and international standardisation.

Longer-term economic, social and environmental impacts

This project will provide data that will help assess the contribution of cosmic rays and UV radiation exposure in the risk for developing chronic diseases and cancer. The data and methods ensuing from the current project will be useful for ecological correlative studies, providing a first glimpse of some of the possible unexplored interactions between the environment and human health. Such findings will have significant economic implications, particularly in terms of public health, agricultural production and food security on a global scale. Policymakers and regulatory bodies will be able to make better informed decisions on climate and environmental policies by using an improved understanding of ozone depletion and its effects on the Earth's Biosphere.

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List of publications

Botek, Edith, Pierrard, Viviane, Winant, Alexandre (2023) "Prediction of Radiation Belts Electron Fluxes at a Low Earth Orbit Using Neural Networks With PROBA-V/EPT Data", *Space Weather*, 21(7) . Available at <https://doi.org/10.1029/2023SW003466>

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This list is also available here: <https://www.euramet.org/repository/research-publications-repository-link/>

Project start date and duration:		1 October 2022, 36 months
Coordinator: Faton Krasniqi, PTB		Tel: +49 531 592 6320
Project website address: https://euramet-biosphere.eu		E-mail: faton.krasniqi@ptb.de
Internal Beneficiaries:	External Beneficiaries:	Unfunded Beneficiaries:
1. PTB, Germany	8. ADVACAM, Czechia	20. CSIC, Spain
2. BFKH, Hungary	9. BIRA-IASB, Belgium	21. GGO, Germany
3. CEA, France	10. DTU, Denmark	22. IRM, Belgium
4. CMI, Czechia	11. DWD, Germany	
5. GUM, Poland	12. IFIN-HH, Romania	
6. IMBiH, Bosnia and Herzegovina	13. IVB, Romania	
7. TUBITAK, Türkiye	14. LZH, Germany	
	15. MPG, Germany	
	16. NOVA, Portugal	
	17. NTUA, Greece	
	18. Raymetrics, Greece	
	19. UJF CAS, Czechia	