The Doctoral Training Plan

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Student number: 2668165

Faculty: Faculty of Science

Research unit: Space Physics and Astronomy

Major & Doctoral Programme: Physics, Physics and Astronomy

Supervisors (Full name and title): Prof. Ilya Usoskin, Dr. Timo Asikainen

Follow-up Group members (Full names and titles): Doc. Dr. Jyrki Manninen (chair), Prof. Dr. Juergen Schmidt, Doc. Dr. Ilkka Virtanen

Title of the research and type of thesis (monograph or article-based): Extreme solar particle events and their effects, article-based thesis

Study rights start date, date of meeting with the Follow-up Group: 02.03.2020, 29.01.2021

Abstract

The thesis work will be focused on modelling of the atmospheric effects of extreme solar particle events, in the framework of the research project ESPERA (Extreme Solar Particle Events: Risk Assessment) funded by the Academy of Finland. It is known from indirect data that the Sun can occasionally produce extreme events, which are a factor of 10-100 stronger than anything we observed during the last decades of direct observations. Although the probability of such events to occur is low, a few per millennium, their severity would have a dramatic impact on modern technological society. However, these conclusions were obtained from indirect proxy (cosmogenic isotope concentrations in natural archives) data, which may be affected by complex and not fully understood processes of formation, transport and deposition of isotopes in the terrestrial system. Accordingly, our knowledge of the exact parameters of such past extreme events are not precise. However, it is crucially important to obtain the most accurate information on these events to be able to estimate the related societal risks. This work presents modelling of production, transport and deposition of cosmogenic isotopes in the Earth's atmosphere by applying chemical climate models (CCM) of the atmospheric chemistry and dynamics. The primary use of the CCM SOCOL model is planned, but other models, e.g., Whole Atmosphere Community Climate Model (WACCM), Sodankylä Ion Chemistry (SIC) model, etc. will be also considered. The CCM SOCOL consists of the dynamical core MA-ECHAM5 and the chemical core MEZON, interacting with each other every 2 modelling hours.

The main aim of the work is to identify patterns enabling precise reconstructions of the solar particle events in the past using measurements of cosmogenic isotopes (14C in tree trunks and 10Be in polar ice cores), for the last several millennia. This will be important for better evaluation of the possible 'worst-case' solar events, their occurrence and modelling of their impacts on both nature and society. Risk assessments and mitigation measures will be proposed.

1. Rationale

Background and significance of the research project in relation to current knowledge. Describe how the project is linked to previous international or national research (state of the art).

Nowadays, there are studies focused on the atmospheric effects of the extreme solar particle events also known as “superflares” and “super CMEs” (coronal mass ejection) [e. g., 1, 2]. However, the history of such studies in the context of measurements of cosmogenic isotopes on Earth and their connection with solar activity in the past covers only four decades. Detailed knowledge of the possible extremes of solar magnetic activity is important in several respects. On one hand, it can put an observational constrain on the theory of solar eruptive events. On the other hand, it may have a strong terrestrial effect. Satellite data reveals that solar magnetic activity and solar irradiance are positively correlated, a conclusion with important implications for climatology [e.g., 3]. Because of the complexity of variations in solar activity, a long record is necessary for understanding the mechanisms responsible for the heliomagnetic activity.

Attempts to reconstruct the events of solar particles in the past using measurements of cosmogenic isotopes have been repeatedly made. A pioneering note [4] was about intense fluxes of energetic solar protons that could produce Triton (or Tritium) and 14C isotopes in the terrestrial atmosphere at times near the maximum of the solar activity cycle. Calculations for the production of Beryllium and some other cosmogenic nuclides in the Earth's atmosphere for two components (galactic and solar) of primary cosmic-ray flux were made later in [5]. However, numerical simulations for calculating the production rates of terrestrial cosmogenic nuclides were made mainly for galactic-cosmic-ray particles while solar energetic particles have low energies. The different energy sensitivities of the various methods of cosmogenic isotope production along with the SPE (solar proton event) energy spectrum itself suggests a hierarchy of responses to SEP (solar energetic particles) events. Thus, SPEs detected by one method may not be seen using another and vice versa. This was considered by Usoskin et al. [6] who opened a new possibility to study extreme SPEs in the past based on differential energy spectra and the specific yield functions of isotope production using high-resolution 10Be and 14C data. In particular, a 5.5-year periodicity in the 10Be series was found due to a combination of GCR (galactic cosmic rays) and SPE signals. Later, Webber et al. [8] calculated, using the FLUKA Monte-Carlo tool of cosmic-ray cascade simulations [7], production of cosmogenic isotopes due to both SEP and GCR at lower energies where isotope production is a very sensitive function of energy. It was also suggested that 10Be may hold signatures of strong SPEs. Main problems of detection of the solar signal in 10Be ice data were discussed in [9]: (a) the difference in ice-core data due to the regional climatic differences in, e.g., atmospheric circulation or dust accumulation; (b) chronological and timing errors for the 10Be data, that at data comparison of 14C and 10Be can reach decades.

Partial solution of these problems is the use of models. The first cosmogenic isotope production model was LP67 [10]. It used an empirical approach based on fitting simplified model calculations to measurements of the isotope concentrations and inelastic nuclear collisions formations in the atmosphere. The LP67 model yields a reasonable agreement with measurements of stratospheric 7Be [11]. Next was the analytical model OB79 [12], which solved the problem of GCR-induced cascade in the atmosphere using an analytical stationary approximation in the form of Boltzman equation. Those models were based on calculating the rate of inelastic collisions and then applied the mean spallation yield per one collision. A new step in modelling of the isotope production was made by MB99 [1], who performed a full Monte Carlo simulation of the GCR-initiated cascade of the atmosphere and directly used cross-sections of spallation reactions instead of the average inelastic collision's efficiency. It used an approximation of the flat atmosphere and computed isotope production by galactic cosmic rays only and did not consider production by solar energetic particles (SEP). A subsequent model WH03/07 [14] was more flexibility computing an effect of SEP, but it WH03/07 model also contains simplifications and assumes a flat atmosphere and a vertical beam of primary GCR particles. These assumptions are crucial for the results in the stratosphere.

There is a full set of verified models, called CRAC (Cosmic-Ray Atmospheric Cascade) for modelling of cosmogenic isotopes and atmospheric impact on SEP and GCR. The CRAC model is based on the GEANT-4 tool [15] to perform a consistent and precise computation of the production of five cosmogenic isotopes, 7Be, 10Be, 14C, 22Na, and 36Cl, in the Earth's atmosphere. The first part of them was the model by [16], can compute production of 7Be isotope in the atmosphere, including altitude and geographical profiles. The flexibility of the model allows direct computation of the effect of SEP or other transient events. The effect of a severe solar energetic particle event shows that it enhances the production of 7Be in geomagnetic polar regions, accompanied by suppression in all other regions. It may relate to details of the tropospheric circulation and transport. These results were fully validated by comparing the model results with direct measurements of 7Be [17]. A combination of a numerical model of 7Be production and transport has been developed, using the GISS ModelE atmospheric circulation model, where in situ production of 7Be by cosmic rays is included explicitly. Using nudging from observed horizontal winds, the model correctly reproduced the overall level of the measured 7Be concentration near the ground and a great deal of the synoptic variability at timescales of 4 days and longer.

Early study had a systematic discrepancy between the results of theoretical models for the 14C production and the global average 14C production rate obtained from necessary inventory. This problem was solved in [18], using improved spectra of cosmic rays.

The question of how well the observed 10Be concentrations in ice cores reflect the global production changes was studied by the ECHAM5-HAM general circulation model [19]. The results suggest that the deposition fluxes of 10Be reflect well the changes in the global average 10Be production rate. They divided the 10Be production into different atmospheric source regions to be able to trace back the origin of the 10Be in polar regions. The most important source region was the stratosphere.

To quantify the relative importance of transport, microphysics processes related to aerosols, and radioactive decay [20] used the simulation of isotopes by a global 2-D (latitude-altitude) model. The model describing both the stratospheric circulation and the detailed formation and growth of stratospheric aerosols was used to simulate the stratospheric cycle of cosmogenic isotopes of beryllium, 7Be and 10Be. Calculations of the model budget show that the vertical transfer of these isotopes due to the aerosol sedimentation contributes to about half of the stratospheric 10Be flux into the troposphere but is negligible for the 7Be budget.

Cosmogenic Isotopes as proxies for Solar Energetic Particles was described in [15, 21, 22]. Extreme solar events may lead to detectable peak in the annual 10Be data. A combination of GCR and SEP signals may be responsible for a 5.5-year periodicity in the 10Be series found during some periods. Extreme events can be observed on an inter-annual scale, and this provides a possibility to study strong solar particle events in the past. The results should be interpreted as a conservative upper limit on the SPE occurrence near Earth. It was interpreted and applied in [23] for the SEP event of 774–775 AD. The study was based on 3-D CCM SOCOL modelling and observational data analysis, lead to good agreement between modelled and observed 10Be deposition variability. Since the analysed SEP event is the strongest known in the Holocene this result can serve as a realistic upper bound of the possible effect of SEP events on the atmosphere.

Based on the above our knowledges of the exact parameters of past solar extreme events are not perfect. During the PhD program we will perform modelling of production, transport and deposition of cosmogenic isotopes in the Earth's atmosphere by applying CCM models of atmospheric chemistry and dynamics in context solar extreme events conditions. This will be important not only for the scientific community as models give an opportunity to estimate solar impacts on nature and society. Risk assessments and mitigation measures will be proposed.

2. Objectives and expected results

Theoretical premise. Describe the theoretical premise of your research as well as its aims and objectives. Hypotheses or research questions. Expected research results and their anticipated scientific impact, potential for scientific breakthroughs and for promoting scientific renewal. Describe the impact of the research within the scientific community. What is the novelty value or added value of the research project from the perspective of science? Effects and impact beyond academia.

We are still far from the complete understanding of the physics of extreme solar events. How strong can a solar event be? How can it affect the Earth's atmosphere? In this regard, the main aim of the work is to identify patterns enabling precise reconstructions of the solar particle events in the past using measurements of cosmogenic isotopes (14C in tree trunks, and 10Be and 36Cl in polar ice cores), for the last several millennia. Possessing such information will help to significantly deepen our knowledge about solar flares and coronal mass ejections. By analysing the nature of extreme solar events and their impact on the Earth's atmosphere, we will also be able to assess and warn of potential risks associated with technology industries. Mission planning for manned space flight, for example, requires knowledge of the fluence distribution in SPEs and the possibility of the occurrence of such events.

We will divide the work into several stages, the first being the search for the longest and highest-quality series of measurements of cosmogenic isotopes, which forms a basis for comparison with model data. Next, we will select a global atmospheric model for further inclusion of the transport of cosmogenic isotopes. The exact choice is complicated by the fact the transport processes from the stratosphere to the troposphere are important that in the estimation of the mass flux of chemical species and the demonstration of global and small-scale aerodynamics in the atmosphere. There are a few models which are good in modelling the stratosphere-troposphere exchange. It gives us the opportunity to verify the models, comparing real data and simulation data [24]. When the first analysis of the simulated results is done, the main part of the work will begin. During this stage, we will model the process taking place in the atmosphere during strong solar events. This will help the scientific community to model solar processes and their influences on Earth. The planned work by combining several scientific fields, full-picture SPE impacts and already existing conclusions about distribution cosmogenic isotopes [e.g., 25].

3. Research methods and material

Data to be used. Describe what kinds of research material and data will be used as well as their significance for the project. Also describe justifications, how the data will be collected, acquired and used, and IPR and other relevant issues. Describe the research methods and how they will contribute to answering the research questions or confirming the hypotheses, or how they will support the chosen approach. If relevant for the project, also describe the statistical methods to be used.

In the course of the work, we will model production, transport and deposition of cosmogenic isotopes in the Earth's atmosphere by applying CCM models of atmospheric chemistry and dynamics. The primary use of the CCM SOCOL model [26] is planned, but other models, e.g., Whole Atmosphere Community Climate Model (WACCM) [27], Sodankylä Ion Chemistry (SIC) model [28], etc. may also considered.

The CCM SOCOL v3.0 mainly consists of the dynamical core MA-ECHAM5 and the chemical core MEZON, interacting with each other every 2 modelling hours. The model has 39 vertical levels between Earth’s surface and 0.01 hPa (~80 km). The horizontal resolution of about 2.8° × 2.8° (T42).

In the stratosphere, 10Be gets attached to stratospheric aerosols [20]. The SOCOL has a sectional scheme where the aerosol particle size distribution is represented by 40 discrete size bins. The models simulate the transport of stratospheric aerosol through sedimentation and large-scale circulation by the Brewer–Dobson circulation [29]. For our study, we need parameterizations of energetic particles effects of different origin including GCR and SPE and the extra-heating parameterization allowing a precise simulation of the 11-year cycle in the heating rates.

Important note, that our numerical needs heavy computer parallelization.

4. Implementation

Schedule of research and studies, distribution of work, and funding plan

Funding for the entire PhD project work will be provided via the ESPERA Project of the Academy of Finland (2019-2023).

As part of the work, at least four publications are planned.

2020-2021: The first publication will be devoted to a case-study whole we will test the selected model at a specially selected extreme solar event. Model data will be compared with the results of observations of cosmogenic isotopes. Perhaps it will be limited in space due to available measurements data.

2021: In the second publication, it is necessary to expand the simulation over time, capturing several centuries. These results will be for the whole globe.

2022-2023: Finally, the third and fourth articles will be devoted to conclusions throughout the work, including a comparison with other models. The advantages of the developed algorithm will be revealed and use cases offered.

Participation in several scientific conferences is planned. It is planned to visit (approximately) the GEOCOSMOS-2021, the EGU-2021 and the VCAIS-2022, CHAMOS

5. Research team, supervision, and collaboration (including mobility)

Prof. Ilya Usoskin is a supervisor.

Dr. Timo Asikainen is a second supervisor.

Research team: team of project ESPERA - Dr. Alexandr Mishev (senior scientist), Dr. Leon Kocharov (senior scientist), Dr. Stepan Poluianov (post-doc), Dr. Sergey Koldobsky (PhD 12/2020), Mr. Pauli Väisänen (PhD student).

Collaboration: Dr. Gennady Kovaltsov (senior scientist) Ioffe Physical-Technical Institute (St. Petersburg, Russia), Dr. Eugene Rozanov (senior scientist) PMOD/WRC (Davos, Switzerland), Dr.

Timofei Sukhodolov (post-doc) PMOD/WRC (Davos, Switzerland), Dr. Irina Mironova (senior scientist) SPBU (St. Petersburg, Russia).

During the work, short- and mid-term research visits are planned. Nov 2021: PMOD/WRC Davos, Switzerland. Jun 2022: SPBU Saint Petersburg, Russia.

CAREER PLAN

In four years from now, I see myself working as a researcher at a Research Institute or at the University in my homeland - Russian. The academic work requested in my present position fits well with my profile and ambition of doing high-quality research, mentoring students and achieving some administrative experience.

My scientific output is following my planned output in start of education, although there is room for improvement. Throughout my studies, I will focuse in publishing fewer but high-impact papers. I start publishing in good high-ranked journals where me as first author (GRL, JMD). An increase in research collaboration and the potential for co-supervising students should help improving my future career. In 2 years from now, I aim to have completed the necessary requirements to teach at the university level. To register for pedagogical training at the University and to finalize my teaching portfolio, which includes essays and documentation on e.g. teaching philosophy and teaching experience.

I have been little involved in administrative and management tasks throughout my studies and during my study. I prefer research and teaching work.

Literature / bibliography

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B. The Study Plan, Oodi-PSP

The doctoral degree includes a thesis and other studies representing 20–50 credits, depending on the major (http://www.oulu.fi/uniogs/studyrequirements). The Personal Study Plan (PSP) is part of the Doctoral Training Plan and is done in WebOodi. At least a draft of the PSP should be attached to the Research Plan.