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NMDB@Home2020
1st virtual symposium on cosmic ray studies with neutron detectors

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Abstract

An overview on the presentations at the first virtual symposium on cosmic ray studies with neutron detectors is given. The meeting was held online in July 2020. Neutron detectors on ground are shown to provide significant contributions to research on interactions of galactic cosmic rays with magnetic fields in the Heliosphere and on the acceleration of energetic particles, as well as to a growing range of applications, including geophysics and space weather. The advent of easily accessible databases makes original data easily available to a large user community. The present overview outlines and introduces the more detailed articles contained in the proceedings.

1. Introduction

Cosmic rays at energies between several hundreds of MeV and tens of GeV play a major role for energetic and plasma processes in the Heliosphere. Various types of neutron detectors on the Earth are used worldwide to probe neutrons produced in interactions of primary cosmic rays with the atomic nuclei of the Earth's atmosphere, and to infer information on their interaction with the magnetic fields of the Heliosphere and the magnetosphere of the Earth, and on heliospheric processes of particle acceleration. While these fields of investigation have a history over more than 70 years, they gain new interest with each new space mission launched to probe heliospheric plasma processes. Their long-standing observations allow us to monitor trends of the heliospheric magnetic field over many solar activity cycles. This is of special interest since the low levels of solar activity witnessed in recent cycles go along with a significant enhancement of the flux of galactic cosmic rays (GCR) in the inner Heliosphere.

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Besides their role as a target of fundamental research, galactic and solar cosmic rays at GeV-energies are an issue for space weather purposes. The monitoring of radiation doses, to which the aircrew of civil aviation and airline passengers are exposed, has been receiving attention since the 1990s. While spacecraft most often monitor only particles up to a few hundreds of MeV, neutron detectors on the Earth provide an adequate tool to measure the more energetic particles that become a source of radiation in the lower atmosphere. The advent of real-time space weather services is based on neutron monitor observations and on space-borne measurements.

The lack of possibilities to have scientific meetings that became clear in late winter 2020 triggered interest in the heliospheric cosmic ray community to propose an online meeting with the aim to discuss investigations in the field of cosmic ray research based on ground-based neutron detector data, the neutron detectors themselves, and the handling and distribution of data. The meeting consisted of daily, three-hour sessions between July 13 and 17, 2020. Each session was attended by 70 to 80 persons from Africa, the Americas, Asia, Australia, and Europe. The technical organisation was at the University of Kiel (Germany).

The present paper intends to give an overview on the presentations and discussions, and to set the stage for the authors' contributions that follow. Contributions are addressed in the order of their presentation at the meeting, which may be different from the order in the present proceedings.

2. Cosmic rays in the heliosphere

The advent of measurements of cosmic rays above the atmosphere, such as from the PAMELA and AMS-2 experiments, up to rigidities of several tens of GV has provided the opportunity for yield function validation and calibration for all active neutron monitors (Koldobskiy et al), for verification of the Global Survey Method (Belov et al), and for parametrization of the spectrum of galactic cosmic ray variations and the shape during negative and positive polarity periods (a power-law spectrum of variations with strong exponential attenuation at high rigidities and a pure power-law spectrum, respectively; Yanke al.).

The leader fraction, i.e., inverse neutron multiplicity, has been used as a proxy of a cosmic ray spectral index above the cutoff rigidity to enhance the high-precision spectral information from the worldwide neutron monitor network and extend it to higher rigidity (Banglieng et al.)

On short time scales, a method of defining Forbush Decreases (FDs) and an automated process for identifying FDs in neutron monitor data have been developed and a positive correlation between FD magnitude and properties of the associated Interplanetary Coronal Mass Ejection (ICME) has been found, with decreasing correlation strength as the neutron monitor cutoff rigidity increases (Light et al). The ring of stations method has been used to investigate in detail FDs and their precursors (Abunina et al.). FD precursory signals have been observed also in events without a sudden storm commencement (Lingri et al.). This emphasises the possibility to forecast the arrival of an ICME at Earth using neutron monitor observations.

A full-orbit test-particle simulation has been developed to compute the FD amplitude and time profile resulting from the particle propagation through a magnetic cloud, whose topology has been obtained with the Grad-Shafranov reconstruction. The comparison between model results and both space- and ground-based cosmic ray measurement has suggested that particle drifts across the closed field lines within magnetic clouds have a primary role in affecting the galactic cosmic ray propagation (Benella et al.).

A long and sloping decrease of cosmic ray intensity (up to $\sim 4\%$) was observed in neutron monitor data during May 2019, associated with a series of small solar eruptions following each other, although the interplanetary counterpart did not hit the Earth (Trefilova et al.).

The energy spectrum of solar-diurnal variations of cosmic rays has been derived from neutron monitor and muon telescope data. It is qualitatively well described by a flat form with an upper cutoff near 100 GeV (Gololobov et al.).

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The wavelet analysis has been applied to investigate long-term variations (Baird and MacKinnon) and mid-term periodicities (13.3 – 298 days), which were found to depend on the neutron monitor rigidity cutoff and height (López-Comazzi and Blanco).

The long-term cosmic ray modulation has been found to be much weaker in cycles 23-24 than in cycles 21-22. This can be explained by the weakening of the solar magnetic field, and consequently an increased role of particle diffusion during propagation in the Heliosphere (Yanke et al.).

The expected cosmic ray modulation has been retrieved in the observations of the CCD imagers of the Hubble Space Telescope, as well as evidence for two spatially confined regions over North America and Australia that exhibit increased particle fluxes at the 5-sigma level (Tancredi et al.).

3. Cosmic rays in the atmosphere

Cosmic-Ray Neutron Sensing for Environmental Sciences (CRNS) is a young research field that has established a technique to monitor water content in soil by measuring the flux of sub-MeV neutrons. The water content in soil, air, snow and vegetation moderates the density of neutrons above the ground. This signal represents the average water content of an area of several hectares. Hundreds of such small neutron detectors have been installed worldwide and they provide critical input for climate research, hydrological models and irrigation management. The reliability of these measurements depends on the knowledge of the incoming cosmic radiation, which has traditionally been taken from one reference neutron monitor. As these corrections do not take into account the differences between the neutron monitor and the sensor (altitude, cutoff rigidity, etc), the CRNS community is exploring the use of the neutron monitor network to improve the quality of the soil humidity prediction and to open up new opportunities for cooperation between the disciplines (Schrön and Köhli).

4. Solar energetic particle events – GLE analysis

During powerful solar events, such as flares and coronal mass ejections (CMEs), charged particles can be accelerated to high energies. These particles are known as solar energetic particles (SEPs). If their energy spectrum extends beyond 450 MeV, the primary particles, especially protons, but sometimes also neutrons, trigger atmospheric cascades that reach the surface of the Earth. Such events are called ground level enhancements (GLEs). Ground-based instruments such as the worldwide network of neutron monitors, neutron detectors and muon telescopes allow us to observe these events and to complement satellite data, which most often pertain to lower energies.

In the "GLE analysis" session Mishev, Koldobskiy and coworkers presented a new GLE analysis method based on the neutron monitor network. The method allows to compute the trajectory of particles in the simulated magnetosphere and to calculate the main parameters of relativistic solar protons (energy spectrum, direction of the anisotropy axis, pitch-angle distribution). The method is based on new neutron monitor yield functions, which were updated and cross-calibrated with the PAMELA and AMS-02 experiments.

Bütikofer and coworkers analyzed some SEPs, registered by the EPHIN detector aboard SOHO, which were comparable in magnitude with previously recorded GLEs, but had no response in the data of ground-based detectors. In addition, for some recent GLEs and sub-GLEs, the energy spectrum was modeled and compared with the satellite data.

The possibility to use radio emission of electron beams (type III bursts) as a tracer of magnetic connectivity was discussed by Klein. The analysis was applied to GLEs in order to confirm their magnetic connection to the Earth and to discuss the constraints on the acceleration region of the non thermal electrons and relativistic protons.

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5. Space weather research and services

The global neutron monitor network has a long tradition in the research on cosmic ray variations and solar energetic particles. Recently, it has been used also for space weather purposes, specifically for alerts and the related assessment of the exposure of aircrew to radiation doses caused by cosmic rays. Using neutron monitor data Gil et al. showed that the increase in the superposed averaged number of failures of Polish transmission lines appears around FDs, as well as one day after the occurrence of fast halo CMEs. Fuller and coworkers reported that data of French neutron monitors at Kerguelen Island and Terre Adélie (Antarctica) are used for the monitoring of the radiation doses received by civil aircrew in France in the framework of the SIEVERT programme. Since 2019 they support the real-time space weather service for civil aviation worldwide under the auspices of ICAO (International Civil Aviation Organization). Large enhancements in the fluxes of relativistic electrons lead to spacecraft malfunctions and have in a number of cases resulted in the failure of satellites. To estimate the state of near-Earth space during dangerous relativistic electron enhancements at geostationary orbits Kryakunova et al. suggested to use data from the world-wide neutron monitor network.

With the creation in 2009 of an international database of neutron monitors, NMDB, and its subsequent development, the opportunity appeared for the first time to use the global survey method (GSM) in real-time mode (Gololobov et al.). Authors showed that such monitoring results allow us to forecast geomagnetic disturbances with a preceding time from a few hours up to 1.5 days. Using NMDB data Papailiou et al. showed that large Forbush decreases, regardless of the heliolongitude of the solar source, are accompanied by increased geomagnetic activity and increased cosmic ray anisotropy, including anisotropy before the events, which can serve as a typical precursor of Forbush decreases and geomagnetic storms.

The network of neutron monitors should be expanded for a successful solution of space weather problems. Kato and coworkers reported that a new neutron monitor started its operation at Syowa Station in Antarctica in the frame of the 59th Japanese Antarctic Research Expedition. A distinctive feature of this neutron monitor is that it is paired with a cosmic ray muon detector. For space weather tasks it makes sense to employ different types of cosmic ray detectors, such as those installed in the Space Environment Viewing and Analysis Network (SEVAN, Armenia). The first prototype of a new directional muon telescope was shipped from Spain to Antarctica. Santos et al. reported the first observations of a cosmic ray detector based on water Cherenkov radiation, which is operated at the Marambio base, Antarctic Peninsula, by the LAGO (Latin American Giant Observatory) Collaboration.

6. Neutron detectors: instrumentation, response function

A new neutron monitor station (NEMO) was installed at the Spanish Antarctic base Juan Carlos I on Livingston Island (S 62°39'46", W 60°23'20", 12 m asl) in January 2019 as part of the Antarctic Cosmic Ray Observatory (ORCA) along with a muon telescope (MITO), and integrated into the renewable energy grid of the base (Blanco et al.). The neutron monitor at Jang Bogo (74.62S, 164.2E; Jung et al.) base has been operating since December 2015 consisting of 18 tubes of three-units transferred from McMurdo station.

Electronics of neutron monitors at DOME C (Poluianov et al.) and SANAE (Strauss et al.) have been upgraded mainly for multiplicity measurements. A novel registration system (NMRENA) has been developed for counter signals, based on an FPGA and allowing for pulse height information (Böttcher et al.). A new electronic system has been realized at Princess Sirindhorn (Thailand; Mitthumsiri et al.) and Mawson (Antarctica; Saiz et al.) for measuring cross-counter time delay distributions to obtain cross-counter leader fractions (LFs), related to cross-counter neutron multiplicity, which can used as a proxy of the cosmic ray spectrum. Complementary Monte Carlo simulations have also been performed to account for large-separation LFs, suggesting that they can be attributed to multiple atmospheric secondaries from the same primary cosmic ray.

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Differential response functions of paraffin-moderated bare counters during 1995 and 2009 latitude surveys have been determined to estimate the spectral index for GLEs of 1989 and yield functions (Nuntiyakul et al.). The comparison between bare counters and neutron monitors provided a rather precise measurement of the spectral index, and in particular the variation of the spectral index within a given event. The determination of the paraffin bare detector function will improve the quality of future estimations of the spectral index of relativistic solar particles based on measurements of the bare counter to neutron monitor count rate ratio during ground-level enhancements detected at the South Pole.

FLUKA simulations have been performed to estimate the bare detector responses in 2009 latitude survey to vertical secondary particles (Nuntiyakul et al., poster) and the processes contributing to the count rate recorded by the second neutron monitor installed at Dourbes (Belgium) during different phases of its construction (Sapundjiev and Stankov).

The importance of the pulse height (PH) analysis for checking the long-term stability of the counters was highlighted by Evenson. For instance, PH spectra have been taken annually from one of the neutron monitors used at South Pole from 1997 to 2003. Despite the broadening of the resolution, the average PH has only been reduced by 13 % over this interval with a negligible impact on the count rate from the tube degradation.

7. Neutron detectors: databases and analysis techniques

Steigies reported that a major upgrade to the database infrastructure of NMDB was performed in the fall of 2019 to ensure the availability of this data in the future. The original setup of one main MySQL server (for receiving data from the neutron monitor stations) and several distributed mirrors (for redistributing data via NEST and direct access from dedicated mirrors for other users) has been replaced by a MariaDB Galera Cluster with currently five nodes. All nodes in the cluster can be used for reading and writing data, thus greatly improving the performance of NMDB. New nodes can be quickly added to the cluster, broken nodes are removed automatically, and rejoin the cluster after they have been repaired. ProxySQL is used to access the cluster behind the firewall and to distribute the load between the different nodes. The two ProxySQL servers at different computing centers (high-availability) share a virtual IP address that is provided by Keepalived, so that the whole cluster is accessible from the outside via a constant host name (one for reading, another one for writing data) so that no users tools have to be updated, when the IP addresses of the cluster change.

The Oulu group (Väisänen et al.) conducted an extensive data survey for inter-comparison and analysis of publicly available neutron monitor datasets since 1953 to identify the best possible data sources. Data from the same stations, but different sources, are not always equivalent, which creates a problem for the reliability and reproducibility of scientific results.
Data products and data analysis tools for cosmic ray observations are available on different web sites:

- The International GLE database (http://GLE.oulu.fi, last accessed April 7, 2021) has been revised to account for the variable galactic cosmic ray background for 58 GLEs. The GLE time profiles have been detrended and the cumulative count rates have been calculated for most of the events as well as the integral omnidirectional fluences by applying the effective rigidity method (Usoskin et al.). This work could allow more precise studies of parameters of SEP events.
- An online tool has been made available at http://cosmos.hwr.arizona.edu/Util/rigidity.php (last accessed April 7, 2021) for the computation of cutoff rigidity and particle trajectories in the magnetosphere. The expected variations of effective cutoff rigidities for neutron monitors over the period 1950 – 2050 have been estimated (S. Belov et al.).
- A database of directivity functions to describe the directional sensitivity of the detector to primary protons has been made available at http://crd.yerphi.am/Directivity_Functions (Karapetyan et al., last accessed April 7, 2021).

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8. Conclusion

The NMDB@Home meeting illustrated multiple applications of neutron detectors as complements of satellite observations or independent diagnostic tools: primary research on cosmic ray acceleration and propagation, the magnetic field in the Heliosphere, but also applications for geophysics and space weather. The present proceedings contain the articles of part of the presentations and the abstracts of the contributions without submitted proceeding article. The harmonisation of data distribution especially thanks to internationally organised databases allows an easy access to the measurements for users with a variety of research interests.

Acknowledgments

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In memoriam

The participants of the symposium took note of the recent passing away of eminent members of the community.

Michel Alania passed away at the age of 85 years on May 18, 2020. He was the designer and first PI of the neutron monitor in Tbilisi, Georgia, and made long-standing contributions to cosmic ray research, especially on the solar modulation of cosmic rays, as a researcher and head of the cosmic ray group at Siedlce University, Poland. The obituary was given at the conference by Agnieszka Gil.

Roger Pyle passed away at the age of 78 years on May 21, 2020. He had been a long-standing member of the cosmic ray group at the University of Delaware, Newark, and continued working for the operation of the 'Spaceship Earth' network after his retirement in 2007. Roger Pyle undertook a dedicated effort to make neutron monitor data publicly available. The NMDB group gratefully remembers his work to integrate the University of Delaware neutron monitors into NMDB, including the provision of real-time data. The obituary was given at the conference by Paul Evenson.

While completing these proceedings, we were informed that **Evgenia A. Eroshenko** from IZMIRAN, Russia, passed away at the age of 80 years on June 3, 2021. Evgenia Eroshenko had a long-standing career with research on all aspects of cosmic ray observations with neutron monitors. She was one of the founding members of the NMDB consortium, where she ensured the participation of a wide network of neutron monitors from Russia and Asia.

We are highly indebted to the lifelong work of these colleagues whose efforts to develop research and instrumentation allow us today to pursue observations with neutron detectors for understanding cosmic rays.